COMPUTATIONAL SCIENCE (JOINT DEGREE)

FACULTY OF SCIENCE

UNIVERSITY OF AMSTERDAM
VRIJE UNIVERSITEIT AMSTERDAM

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REPORT ON THE MASTER'S PROGRAMME COMPUTATIONAL SCIENCE OF THE UNIVERSITY OF AMSTERDAM AND VRIJE UNIVERSITEIT AMSTERDAM (JOINT DEGREE)

This report takes the NVAO's Assessment Framework for the Higher Education Accreditation System of the Netherlands for limited programme assessments as a starting point (September 2018).

ADMINISTRATIVE DATA REGARDING THE PROGRAMME

Master's programme Computational Science

Name of the programme:	Computational Science
CROHO number:	65015
Level of the programme:	master's
Orientation of the programme:	academic
Number of credits:	120 EC
Specialisations or tracks:	-
Location(s):	Amsterdam
Mode of study:	full time
Language of instruction:	English
Joint programme:	
partner institutions involved:	University of Amsterdam Vrije Universiteit Amsterdam
type of degree awarded:	joint degree
Submission deadline NVAO:	01/05/2020

The visit of the assessment panel Computer Science took place at the Faculty of Science of University of Amsterdam on 4 and 5 November 2019 .

ADMINISTRATIVE DATA REGARDING THE INSTITUTIONS

Name of the institution:	University of Amsterdam
Status of the institution:	publicly funded institution
Result institutional quality assurance assessment:	positive
Name of the institution:	Vrije Universiteit Amsterdam
Status of the institution:	publicly funded institution
Result institutional quality assurance assessment:	positive

COMPOSITION OF THE ASSESSMENT PANEL

The NVAO has approved the composition of the panel on 15 april 2019. The panel that assessed the master's programme Computational Science consisted of:

- Em. prof. dr. T. (Theo) D'Hondt, emeritus professor in Software Languages and Software Engineering at the Faculty of Sciences and Bioengineering Sciences of Vrije Universiteit Brussel (Belgium) [chair];
- Prof. dr. ir. W.E.A. (Wim) van Petegem, professor and policy coordinator Learning Technologies at the Faculty of Industrial Engineering Technology of KU Leuven (Belgium);

- Prof. dr. S. (Sjouke) Mauw, professor in Security and Trust of Software Systems at the Department of Computer Science of the University of Luxembourg (Luxembourg);
- Drs. H.C. (Jeroen) Borst, senior consultant Smart Cities at TNO;
- Prof. dr. P. (Petros) Koumoutsakos, full professor Computational Science at ETH Zürich (Switzerland) [referee];
- E. (Evi) Sijben BSc, Master's student Computing Science in the specialisation track Data Science at Radboud University [student member].

The panel was supported by M. (Mark) Delmartino MA, who acted as secretary.

WORKING METHOD OF THE ASSESSMENT PANEL

The site visit to the master's programme Computational Science at the Faculty of Science of the University of Amsterdam was part of the cluster assessment Computer Science. Between June and December 2019 the panel assessed 29 programmes at 10 universities. The following universities participated in this cluster assessment: Leiden University, Delft University of Technology, University of Utrecht, Eindhoven University of Technology, Open University, University of Amsterdam, Vrije Universiteit Amsterdam, Radboud University, University of Groningen and University of Twente.

On behalf of the participating universities, quality assurance agency QANU was responsible for logistical support, panel guidance and the production of the report. P.A. (Peter) Hildering MSc. was project coordinator for QANU. P.A. (Peter) Hildering MSc. and M. (Mark) Delmartino MA acted as secretary in the cluster assessment.

During the site visit in Amsterdam the panel was supported by M. (Mark) Delmartino MA, a certified NVAO secretary.

Panel members of the cluster assessment Computer Science
The members of the assessment panel were selected based on their expertise, availability and independence. The panel consisted of the following members:
- Em. prof. dr. T. (Theo) D'Hondt, emeritus professor in Software Languages and Software Engineering at the Faculty of Sciences and Bioengineering Sciences of Vrije Universiteit Brussel (Belgium) [chair];
- Prof. dr. ir. W.E.A. (Wim) van Petegem, professor and policy coordinator Learning Technologies at the Faculty of Industrial Engineering Technology of KU Leuven (Belgium);
- Prof. dr. S. (Sjouke) Mauw, professor in Security and Trust of Software Systems at the Department of Computer Science of the University of Luxembourg (Luxembourg);
- Prof. dr. J.J. (John-Jules) Meyer, full professor Computer Science and Artificial Intelligence at the University of Utrecht;
- Drs. L. (Lennart) Herlaar, owner/director at Redbits.nl, a company specialised in software development and IT consultancy, and assistant professor Computer Science at the Faculty of Science of Utrecht University;
- T.A. (Tonny) Wildvank, owner/CEO at Wildvank, Management en Advies, specialised in IT-management and -consultancy;
- Prof. dr. J. (Jan) Aerts, full professor Visual Data Analysis at the University of Hasselt and associate professor Visual Data Analysis at the faculty of Engineering Science at KU Leuven (Belgium);
- Drs. H.C. (Jeroen) Borst, senior consultant Smart Cities at TNO;
- Prof. dr. P. (Petros) Koumoutsakos, full professor Computational Science at ETH Zürich (Switzerland);
- Prof. dr. ir. J.M.W. (Joost) Visser, Chief Product Officer at Software Improvement Group (SIG) Nederland and professor Large-scale Software Systems at the Radboud University Nijmegen;
- Ir. E.A.P. (Ewine) Smits, Senior Manager in Advanced Analytics & Big Data at KPMG Nederland;

- Prof. dr. D.P. (Danilo) Mandic, full professor Signal Processing at the department of Electrical and Electronic Engineering of Imperial College London (United Kingdom);
- Dr. ir. J.C. (Job) Oostveen, Research Manager at the Department Monitoring and Control Services at TNO;
- Prof. dr. B.A.M. (Ben) Schouten, full professor Playful Interactions at Eindhoven University of Technology;
- Dr. ir. N. (Nico) Plat, owner/CEO at Thanos IT-consultancy and architecture.
- N. (Nienke) Wessel BSc, master's student Computing Science and bachelor's student Mathematics and Linguistics at Radboud University [student member];
- E. (Evi) Sijben BSc, master's student Computing Science in the specialisation track Data Science at Radboud University [student member];
- B. (Baran) Erdogan, third-year bachelor's student Computing Science at University of Amsterdam [student member];
- M. (Martijn) Brehm, third-year bachelor's student Computing Science at University of Amsterdam [student member].

Preparation
On March 21st, 2019, the panel chair was briefed by QANU on his role, the assessment framework, the working method, and the planning of site visits and reports. A preparatory panel meeting was organised on May 9th, 2019. During this meeting, the panel members received instruction on the use of the assessment framework. The panel also discussed their working method and the planning of the site visits and reports.

The project coordinator and secretary composed a schedule for the site visit in consultation with the Faculty. Part of the visit was dedicated to the bachelor's programme Computer Science and the master's programme Software Engineering, which are organised solely by the University of Amsterdam. The panel's findings on these programmes are reported in a separate document. Prior to the site visit, the Faculty selected representative partners for the various interviews. See Appendix 4 for the final schedule.

Before the site visit to Amsterdam, QANU received the self-evaluation report of the programme and sent it to the panel. A thesis selection was made by the panel's chair and the secretary. The selection existed of 15 theses and their assessment forms, based on a provided list of graduates between 2017-2018 and 2018-2019. A variety of topics and a diversity of examiners were included in the selection. The panel secretary and chair assured that the distribution of grades in the selection matched the distribution of grades of all available theses.

After studying the self-evaluation report, theses and assessment forms, the panel members formulated their preliminary findings. The secretary collected all initial questions and remarks and distributed these amongst all panel members.

In agreement with the programme management, Professor Koumoutsakos was involved in the preparatory work of the panel, but did not attend the site visit. He reported his findings on the self-evaluation report and the theses, which were incorporated in the compilation document distributed among the panel members prior to the visit. His findings have been addressed during the respective sessions.

Site visit
The site visit to Amsterdam took place on 4 and 5 November, 2019. At the start of the site visit, the panel discussed its initial findings on the self-evaluation report and the theses, as well as the division of tasks during the site visit. During the site visit, the panel studied the additional documents provided by the programme. An overview of these materials can be found in Appendix 5. The panel conducted interviews with representatives of the programmes: students and staff members, the programme management, alumni and representatives of the Board of Examiners. It also offered

students and staff members an opportunity for confidential discussion during a consultation hour. One person made use of this opportunity.

The panel used the final part of the site visit to discuss its findings in an internal meeting. Afterwards, the panel chair publicly presented the panel's preliminary findings and general observations.

The NVAO assessment framework includes a so-called development dialogue in which panel members and programmes representatives discussed various development routes for the programmes under review. During the preparation of the visit, it was agreed that this development conversation would be organised jointly by VU and UvA and take place at the end of the panel's site visit to the Vrije Universiteit Amsterdam, on 7 November 2020. The result of this conversation is summarised in a separate report.

Consistency and calibration
In order to assure the consistency of assessment within the cluster, following measures were taken: the panel composition ensured regular attendance of (key) panel members, including the chair, and the project coordinator was present at the panel discussion leading to the preliminary findings of each programme at all site visits.

Report
After the site visit, the secretary wrote a draft report based on the panel's findings and submitted it to the project coordinator for peer assessment. Subsequently, the secretary sent the report to the panel. After processing the panel members' feedback, the project coordinator sent the draft report to the Faculty in order to have it checked for factual irregularities. The project coordinator discussed the ensuing comments with the panel's chair and changes were implemented accordingly. The report was then finalised and sent to the Faculty and University Board.

Definition of judgements standards
In accordance with the NVAO's Assessment framework for limited programme assessments, the panel used the following definitions for the assessment of the standards:

Generic quality
The quality that, from an international perspective, may reasonably be expected from a higher education Associate Degree, Bachelor's or Master's programme.

Meets the standard
The programme meets the generic quality standard.

Partially meets the standard
The programme meets the generic quality standard to a significant extent, but improvements are required in order to fully meet the standard.

Does not meet the standard
The programme does not meet the generic quality standard.

The panel used the following definitions for the assessment of the programme as a whole:

Positive
The programme meets all the standards.

Conditionally positive
The programme meets standard 1 and partially meets a maximum of two standards, with the imposition of conditions being recommended by the panel.

Negative

In the following situations:

- The programme fails to meet one or more standards;
- The programme partially meets standard 1;
- The programme partially meets one or two standards, without the imposition of conditions being recommended by the panel;
- The programme partially meets three or more standards.

SUMMARY JUDGEMENT

This evaluation concerns the master's programme Computational Science, a two-year full-time 120 EC programme that is offered as a joint degree by the University of Amsterdam and the Vrije Universiteit Amsterdam.

The master's programme combines a unique position in the Dutch higher education landscape with a specific focus on computational science and its multidisciplinary application, on scientific research, and on preparing students for research-oriented careers. These explicit objectives are reflected in the intended learning outcomes, which are formulated adequately in terms of domain, level and orientation of the programme. Moreover, the exit qualifications cover both the European-wide Dublin Descriptors and the current international consensus regarding the field of Computational Science and Engineering. The panel thinks highly of the way in which the authors of the self-evaluation report have provided insight in the rationale for a dedicated two-year Master programme on Computational Science. If anything, the programme could improve the functioning of the current Professional Advisory Board by turning it into a dedicated sounding board for computational science.

Overall, the teaching-learning environment of the programme is up to standard. The curriculum is relevant and coherent, and the courses are driven by the research agenda of the participating institutes and research groups. There is a clear relation between the learning goals at course level and the learning outcomes at programme level. The educational concept of independent supervised learning is implemented throughout the curriculum and befits the objectives of the programme. The admission procedure is effective in attracting a multi-disciplinary student body. The staff is highly qualified covering a wide range of research specialisms and is appreciated by the students for their dedication and intensive guidance and supervision. Students and staff are actively involved in safeguarding the quality of the courses and the programme. Furthermore, the panel found that four elements require attention or improvement: research skills training throughout the curriculum, the number of staff in times of growing student numbers, the attractiveness of the courses for all students including those with deficiencies and those expecting more challenges, and clear arrangements regarding joint degree students' admission to elective courses organised by other programmes. The panel appreciates that the management is not only aware of these issues but is already undertaking action.

Student assessment is organised adequately in the Master Computational Science. The policy and principles underlying course assessments are up to standard. The course assessments are valid, reliable and transparent. The programme is taking fraud seriously. Based on its own sample review, the panel considers that the assessment process of the theses is up for improvement with regard to its accountability towards external reviewers. While the process itself is robust, the motivation of the assessment is often poorly reported. The panel welcomes the new digital rubric for thesis assessment and suggests the programme management to monitor that each thesis committee completes the form in an insightful way. The members of the Examinations Board and its subcommittee for the Master Computational Science, its assessment committee and its fraud and plagiarism committee have adequate expertise to deal with their respective tasks. The panel encourages the assessment committee to verify the quality of the written feedback in its thesis review samples.

Master students who graduate from the Computational Science programme are adequately prepared for a position in both academia and industry. It is to the credit of the programme that graduates find attractive positions with a wide range of employers, be it universities, public bodies, R&D departments or (tech) companies. The panel welcomes the programme's attention to its graduates through a dedicated alumni network. Having established that overall the thesis sample meets the minimum requirements of what can be expected of a final research project at master's level, it is fair to state that the intended learning outcomes of the programme are eventually achieved at the end of the curriculum. Nonetheless, with a few outstanding exceptions the panel found the graduation projects rather disappointing in terms of academic quality and scientific approach: given the explicit

research-oriented profile of the programme and the position of the graduation project in the curriculum, the panel would have expected more theses of high quality.

Across all standards, the panel noticed that there have been many developments to the Master Computational Science in recent years and that the programme has done a great job in addressing the recommendations of the previous accreditation committee. Hence the panel's overall positive appreciation of the programme quality. Based on numerous discussions on site, the panel acknowledges the added value of the collaboration between the two universities, their staff, research institutes and faculties in the framework of this programme. The panel does not express a preference for a single programme or single degree construction, but is convinced that the advantages for students to benefit from a wide range of perspectives and expertise far outweigh the often cited problems of logistics and administration.

The panel assesses the standards from the *Assessment framework for limited programme assessments* in the following way:

Master's programme Computational Science	
Standard 1: Intended learning outcomes	meets the standard
Standard 2: Teaching-learning environment	meets the standard
Standard 3: Assessment	meets the standard
Standard 4: Achieved learning outcomes	meets the standard
General conclusion	positive

The chair, Em. Prof. Dr. T. (Theo) D'Hondt, and the secretary, M. (Mark) Delmartino MA, of the panel hereby declare that all panel members have studied this report and that they agree with the judgements laid down in the report. They confirm that the assessment has been conducted in accordance with the demands relating to independence.

Date: 17 April 2020

DESCRIPTION OF THE STANDARDS FROM THE ASSESSMENT FRAMEWORK FOR LIMITED PROGRAMME ASSESSMENTS – MASTER'S PROGRAMME COMPUTATIONAL SCIENCE

Standard 1: Intended learning outcomes
The intended learning outcomes tie in with the level and orientation of the programme; they are geared to the expectations of the professional field, the discipline, and international requirements.

Findings
The master's programme Computational Science is a joint degree offered by the University of Amsterdam (UvA) and the Vrije Universiteit Amsterdam (VU). Its origins go back to the Master Grid Computing, which was first offered solely by UvA before it became a single curriculum joint programme with VU (2012), changed its name into Computational Science (2013) and was eventually registered as a joint degree (2015). The University of Amsterdam is the "lead partner" (*penvoerder*) of the joint degree.

The development of a joint degree is part of a larger endeavour: in 2011, the Informatics departments of both UvA and VU started exploring different forms of cooperation, including the plan to form a joint Amsterdam Department of Informatics at one central location on the current VU campus and to re-organise the portfolio of degree programmes accordingly. However, these plans were abandoned when the co-decision bodies (*medezeggenschap*) at university level did not approve the envisaged merger in April 2017. While both universities have since reviewed their strategy focusing on the needs and interests of their respective departments, this master's programme—as well as the master's programme Computer Science with VU as lead partner—continues to be offered as a joint degree.

The master's programme Computational Science is embedded in the Graduate School of Informatics (GSI) of the Faculty of Science at UvA and the Computer Science Department at VU. The staff teaching in the programme belong to different research institutes at UvA and the Faculty of Science at VU. The programme director and the programme co-ordinator are both on the payroll of UvA. The panel gathered from the discussions on site that all stakeholders see an added value in the collaboration between UvA and VU, their staff, research institutes and faculties in the framework of this programme. The panel understood that the advantages for students to benefit from a wide range of perspectives and expertise far outweighs the extra efforts of logistics and administration often associated with a joint degree.

Profile
According to the insightful description in the self-evaluation report, computational science is about the modelling and simulation of complex natural or man-made systems. It is a growing and inherently multidisciplinary field that uses advanced computing techniques to understand and solve complex problems. The joint degree maximises the complementary know-how of the two institutes and their respective faculties: it covers the heart of computer science and informatics, but also reaches out to application domains to underline the multidisciplinary nature of computational science. Hence the programme aims to train students in the research and development of algorithmic and computational means to solve scientific problems, while at the same time appreciating other relevant domains.

The panel gathered from the information materials that the master's programme Computational Science has a strong research orientation: while the programme acknowledges that the skills of its graduates are in demand by the commercial sector, the students are trained to qualify for positions that involve performing scientific research, either in academic institutions or in R&D departments of business and other professional organisations.

The panel noticed that the master's programme takes up a unique position in the Netherlands: this joint degree constitutes the only programme that is entirely dedicated to Computational Science; in other universities, Computational Science is a specialisation within a broader master on e.g. applied Mathematics or Computing Science. Moreover, the programme in Amsterdam takes a computing-centric approach, while other specialisations combine Computational Science with Engineering, Visualisation or Numerical Mathematics. It also distinguishes itself by explicitly targeting a broader range of students: in order to live up to its multidisciplinary objectives, the master's programme Computational Science not only admits bachelor graduates in Computer Science or Mathematics, but also students holding a bachelor's degree in Science that demonstrates the necessary level of programming and mathematical training.

Intended learning outcomes
The panel noticed that the objectives of the programme—knowledge of computational science and the application of its methods in different fields, focus on the scientific component, preparation for research-oriented careers—are reflected in its intended learning outcomes (ILOs), which are listed in Appendix 2 to this report. The eight exit qualifications cover knowledge and skills in Computational Science, scientific research and problem solving, and communication and collaboration skills. According to the panel, the intended learning outcomes are described precisely and formulated adequately for an academic programme at master's level. The panel also learned from the thoroughly motivated section in the self-evaluation report that each learning outcome is clearly related to one or more Dublin Descriptors, and that each descriptor is addressed in several exit qualifications.

While there is no domain-specific reference framework for Computational Science, the programme provided an analysis of the current international consensus on (the field of) Computational Science and Engineering. The panel learned that the programme is using this analysis as a benchmark for the design and content of the joint degree. This analysis is presented in Appendix 1 to this report. According to the panel the objectives of the Master Computational Science are very much in line with the analysis. Moreover, the panel acknowledges the efforts of the programme and the contributing researchers/institutes in Amsterdam to do away with the reported weakness that there is no internationally approved reference framework: the institutes will organise a dedicated workshop to develop such framework when they host the next International Conference on Computational Science in 2020.

Professional field
According to the information materials, the programme educates its students first and foremost to access a PhD programme or for other scientific research-oriented positions. Graduates with such research skills are also valuable in industrial and commercial sectors. Students envisaging a career outside academia can perform their graduation research with an external company or institute. The programme reported to the panel that it would prefer to have more insight into the requirements of the professional field, but does not have the disposal over independent large-scale studies with regard to this, nor has it conducted its own market analysis. For now, it relies very much on its alumni, who indicated both in the report and to the panel that the envisaged competences/exit qualifications are very much suited for both academic and non-academic careers. Furthermore, the panel noticed that the Professional Advisory Board (PAB), which serves all degree programmes in Information Sciences, provides input in terms of market requirements and feedback on the expected graduate skills. While it appreciates the—increasingly structural—contacts of the programme with its alumni, the panel thinks that more and better use can be made of a PAB that would be dedicated to Computational Science. In that case, the programme could extend the membership of the PAB and focus its meetings on the requirements of the professional field with regard to the specific discipline of computational science and its application domains.

Considerations
The panel considers that the master's programme Computational Science combines a unique position in the Dutch higher education landscape with a specific focus on computational science and its multidisciplinary application, on scientific research, and on preparing students for research-oriented

careers. According to the panel, these explicit objectives are reflected in the intended learning outcomes, which are formulated adequately in terms of domain (computational science), level (master) and orientation (academic) of the programme. Moreover, the exit qualifications cover both the European-wide Dublin Descriptors and the current international consensus regarding the field of Computational Science and Engineering.

The panel thinks highly of the way in which the authors of the self-evaluation report have provided insight in the rationale for a dedicated two-year master's programme on Computational Science. The panel supports the plans of the programme to initiate the discussion on a domain-specific reference framework and to enhance contacts with alumni in a structural way. If anything, the programme could improve the functioning of the current Professional Advisory Board by turning it into a dedicated sounding board for computational science.

Based on numerous discussions on site, the panel acknowledges the added value of the collaboration between UvA and VU, their staff, research institutes and faculties in the framework of this programme. The panel does not express a preference for a single programme or single degree construction, but is convinced that the advantages for students to benefit from a wide range of perspectives and expertise far outweigh the extra efforts of logistics and administration often associated with a joint degree.

Conclusion
Master's programme Computational Science: the panel assesses Standard 1 as *meets the standard*

Standard 2: Teaching-learning environment
The curriculum, the teaching-learning environment and the quality of the teaching staff enable the incoming students to achieve the intended learning outcomes.

Findings

Curriculum
The master's programme Computational Science amounts to 120 EC, which are spread equally over two years of six blocks each. The curriculum consists of core courses (66 EC, including thesis), constrained choice courses (30 EC) and electives (24 EC). Appendix 3 to this report provides an overview of the curriculum.

The panel obtained extensive information on the master's programme and its curriculum in the self-evaluation report and the annexes. Studying the materials, the panel found that the curriculum is both relevant and coherent. The core courses are mandatory for all students and reflect the central body of knowledge: modelling, simulation and computing. In the extensive Graduation Project (42 EC) students perform independent research either internally at a UvA/VU research group or externally in a scientific institute or at an R&D department in industry. The constrained choice offers a limited choice of courses related to the core of the programme, so that students can adjust their mix and focus on different areas of the core knowledge. The electives allow students to place particular emphasis on a specific knowledge area, a range of areas or to deepen their knowledge on the core domain of computational science. The core and constrained choice courses ensure that each student is exposed to the whole spectrum of core knowledge identified in the benchmark analysis. Furthermore, the programme has identified combinations of constrained choice and elective courses which allow students to tailor their curriculum towards a particular specialisation, such as computational finance, biology, chemistry or biomedicine. The panel noticed with appreciation that the courses—core, constrained choice and electives—are driven by the research agenda of the participating institutes and research groups.

Moreover, the panel gathered from the detailed information materials on the link between curriculum and programme objectives/exit qualifications, that there is a clear relation between the learning

goals at course level and the learning outcomes at programme level. This finding was confirmed when the panel looked into several course files during the visit: the panel found that these materials are of good quality and at the proper level for an academic master's programme. Based on the sample review and the self-evaluation report, the panel is confident that altogether the curriculum allows students to achieve the intended learning outcomes of the master's programme Computational Science.

An important topic of discussion during the site visit was the attention in the curriculum to academic skills. The panel had noticed when reviewing the graduation projects (see Standard 4) that the overall quality of the theses was up to standard and in a few cases really good. However, the panel also noticed that in several cases, the level of academic skills (such as the use of scientific methodology, writing skills) was lower than would be expected from a programme that explicitly aims to prepare students for a PhD programme or scientific research-oriented positions. The panel gathered from the discussions with management, teaching staff and students that all stakeholders were aware of the issue, that it had been reported among others through the evaluation questionnaires and by the programme committee and that several actions had been undertaken since.

All interviewees indicated that an important feature of the programme is the heterogeneous intake of students: this diversity creates a challenge in bringing all incoming students up to the expected minimum levels of knowledge and skills, and from there on to have them acquire the exit qualifications at the expected academic master level of achievement. This challenge also applies to some extent to the expected level of academic and research skills, notably in the case of some students with a bachelor's degree from abroad.

Following the above-mentioned reports, the programme has adjusted the contents of the core course Seminars Computational Sciences, which is taught across the entire first year and in which students acquire and practice academic research skills which they collect in a portfolio. Students also apply what they have learned in the Seminars and in other core and constrained choice courses, such as Introduction to Computational Science or Complex System Simulation. Before they embark on the graduation project, students have practiced their academic writing skills several times and have also been assessed on the English language component of their deliverables. Moreover, the supervisors in the graduation project accompany students individually during the entire trajectory and monitor the entire research cycle.

The panel understood from the discussions that there has always been attention in the programme to academic skills but that the increased attention is too recent to have found its way to the sample of graduation projects the panel has reviewed. Students indicated that there have been issues with the academic skills part of the programme in the recent past, but that the problems have been taken up in the meantime and that they are addressed properly in the Seminars course and other courses. The students whom the panel spoke to during the site visit all emphasised that they feel properly equipped to do the master's thesis. The panel appreciates the additional attention to research skills in the curriculum and advises the programme to monitor how the acquired skills are demonstrated in the graduation projects in the near future.

Language of instruction
In line with all other master's programmes in the Graduate School of Informatics, the Faculty of Science and the corresponding programmes at VU, the language of instruction in the master's programme Computational Science is English. The panel understands from the self-evaluation report that apart from alignment, there are also other merits for this choice: the programme wants students to reach a level that grants access to PhD programmes or other scientific research-oriented positions with a computational science component. Given that the field of computational modelling has been dominated by the English language since its inception and that the standard language for scientific research is English, it is crucial that students in computational science develop their English communication skills in order to pursue a meaningful career. Students from their side indicated that they are satisfied with the level of English of the teaching staff. The panel subscribes to the rationale

for offering the programme in English. The discussions on site, moreover, have demonstrated according to the panel that the international student and staff body has added value for the programme.

Educational concept
In the self-evaluation report, the didactic concept of the master's programme Computational Science is described as 'independent supervised learning'. The panel noticed from the report and the discussions with management, teaching staff and students that the programme indeed implements this concept in the day-to-day delivery of the curriculum: students are expected to have/develop an independent learning style, while the teaching staff and the graduation project supervisors support them during lectures and practical lab sessions. Moreover, the variety of teaching and examination methods challenges the students to an independent learning and working style, while the programme has built in checks and balances to monitor and assess the progress of students towards fulfilling the course learning goals and the exit qualifications.

Given its explicit choice to admit students with a broad range of educational backgrounds, the programme organises additional extra-curricular moments of independent supervised learning: mathematics and programming tutors help students with a deficiency in one of these areas and support their independent learning. The panel learned that many students make use of these tutoring services.

Furthermore, students indicated to the panel that they are challenged by the programme and at the same time supported by the teaching staff to complete this challenge. The panel noticed that this approach is even more explicit and visible in the graduation project, which resembles a trajectory of a starting PhD student where supervisors and students enter into a master-apprentice relation: during the visit, the students confirmed that they are expected to identify a topic and formulate their own research question, but are supported—e.g. through spending time with the research group—to identify the most relevant and interesting topic. They also appreciated the quality and intensity of the supervision by their 'master'.

Further to its findings on the relevance and coherence of the curriculum, the panel noticed that from an educational point of view the curriculum structure is sound. The first year is dedicated to core and constrained choice courses which set the scene, while the second year features electives and allows students to specialise in a particular (application) domain of computational science and demonstrate the acquisition of new learning skills in the graduation project. Based on the information materials and the discussions, the panel found the educational concept to be relevant for this particular programme.

Intake
Further to the recommendation of the previous accreditation committee, the programme has increased its outreach activities, among others by hiring a dedicated communications expert to help promote the master's programme Computational Science and understand the reservations of potential students. The input from students had led to a less complex programme structure and to promoting the curriculum with a broader range of Science bachelor's programmes at both UvA and VU. The panel learned that since 2013, the number of enrolments has been growing and has almost doubled from 44 (in 2015-2016) to 81 (in 2019-2020), with about 150 students applying to enter the programme in September 2019. According to the data provided, the number/share of female students is growing (more than 20% in 2018-2019) and so are the students who obtained their bachelor's degree abroad (30% in 2019-2020).

The programme management indicated that the current size of the cohort still suits the character and educational concept of the programme. However, any further growth should be met with additional staffing to maintain the quality of the education and safeguard in particular the master-apprentice approach in the graduation project. The panel understands the concern of the

management in this regard and supports the intention of the programme to maintain its master-apprenticeship concept in thesis supervision.

Furthermore, the panel obtained detailed information on the admission criteria and the specific entry requirements. All applications are handled by a dedicated admissions board. Bachelor's graduates in computer science from a Dutch university have direct access to the programme. Students who obtained a similar bachelor's degree abroad submit their diploma for review and should fulfil additional requirements in terms of university ranking, grade point average and proficiency in English. Given the interdisciplinary character of the programme, several students enrol with different bachelor degrees such as physics, chemistry, psycho-biology or economics. In all cases students should demonstrate sufficient knowledge in mathematics, modelling & simulation, and computing skills. Dutch bachelor students intending to apply for this master's programme can take the minor Computational Science, which is recognised as a valid pre-master programme. Accepted students complete a self-assessment survey, which generates a report and a set of recommended study materials to overcome identified deficiencies. Each student also takes part in an intake interview to discuss among others the results of the survey. According to the panel, this survey is a useful initiative that addresses the concern of the previous accreditation committee to help students with deficiencies prepare prior to the start of the programme. Moreover, the panel thinks the admission procedure is extensive and relevant in view of the explicit objective of the programme to emphasise the multi-disciplinary character of computational sciences and to have this reflected in the student body. Further to the panel's finding on academic skills, the admissions board may want to check through the survey and the interview prior academic and research skills training of the accepted students.

Feasibility
The panel gathered from the information materials and the discussions that the individual courses are feasible and that there are no specific courses that systematically hinder a smooth and timely realisation of the curriculum. The panel learned from students that some struggle with the independent learning approach at the start of the programme but that they all appreciate the guidance they receive from the teaching staff and the programme coordination and management. Hence, students consider that the overall programme is feasible. The panel noticed that this is partly confirmed by the data available on success rate: roughly one third of the students graduate within the nominal period of two years. Nonetheless, about 10% of the students drop out and another 20% spend a considerably longer period on the programme. In this regard, the panel appreciates the initiatives of the programme to impose a thesis limit time and to have the study advisor reach out to students who are still in the programme after three years. Given the share of students concerned, the panel advises the programme to monitor its initiatives and take additional measures when relevant.

As students enrol with a heterogeneous study background and because the programme reported that it is difficult to match the content of the courses to each student, the panel discussed with students if and to what extent the programme in general and the different courses in particular are sufficiently challenging. Students first and foremost indicated that they appreciate the programme, its combination of compulsory and elective courses, the multidisciplinary student body, the attention and commitment of the teaching staff and supervisors and the opportunities this programme offers through the specialisation paths to apply computational methods in other domains. The panel gathered furthermore from students who spoke also on behalf of their colleagues that several students noticed during the first months of the programme that they had (minor) deficiencies which they could overcome but which also made the first part of their study sufficiently challenging. However, some of the—often Dutch—students with a background in computer science, mathematics or physics found the level of the courses rather easy and had expected to be challenged more. The panel understands—and appreciates—the explicit objective of the programme to attract diverse student cohorts. Moreover, the panel has looked into a number of course files and found these to be of appropriate level. Nonetheless, it advises the programme to look for ways to make the courses (even more) attractive for all students, including those students who have covered all required

domains extensively in their bachelor's programme. This finding and recommendation is all the more relevant according to the panel if the Faculty wants to maintain or even increase the number/share of computer science bachelor graduates who stay at UvA for a master's programme, e.g. in computational science.

Staff
The self-evaluation report provides an overview of the 15 staff members who are involved as course coordinators in the Computational Science programme. According to the tables, 6 are on the payroll of VU, 7 belong to UvA and two staff are connected to external research institutes. All staff have a PhD, 11 have a teaching qualification (BKO) while the others are in the process of obtaining the BKO. While almost all staff have a full-time appointment, the contribution of a course coordinator to the programme is calculated as 0.15 FTE. In addition to teaching courses, 25 staff have supervised or examined one or more graduation projects in 2017-2018 and 2018-2019.

The panel gathered from the discussions that students appreciate the quality of the staff, their dedication to the educational concept of independent supervised learning and the intensity of the graduation project supervision. Based on its meetings with the enthusiastic teaching and support staff, the panel fully subscribes to this appreciation. Several staff indicated moreover that VU and UvA colleagues work in good cooperation, notwithstanding the failed plans to merge the institutes. According to the panel, the programme draws much added value from the involvement of teaching staff who are linked to different research institutes; students also appreciate the opportunity to choose from a wide variety of electives/specialisations.

According to the panel, the current number of staff and their contribution to the programme is sufficient. However, the programme is growing and this is likely to impact first on the thesis supervision and then on the organisation and delivery of the courses. The panel gathered that a yearly intake of around 70 students would allow to maintain the quality of education and therefore understands the programme's rationale for not aiming at a further growth of student numbers.

Facilities
Lectures, tutorials and lab courses are given at UvA Science Park and on the VU campus. Both UVA and VU computer science departments are in the process of moving to new buildings on their respective campuses. Students indicated that they very much appreciate the building and the (atmosphere on) campus at UvA.

Scheduling is done independently but core and constrained courses are scheduled on specific UvA and VU days. The panel gathered from the information materials and the discussions that due to the current student numbers within both faculties, room availability can be difficult. Moreover, several elective courses are owned by other programmes, which sometimes poses challenges in terms of attendance or admission. Students indicated that they could not enrol for 'popular' electives that are mandatory for other programmes, or had to follow courses in crowded lecture halls. The panel advises the programme management to look into these issues, make arrangements with the course owners, and inform students accordingly.

The panel gathered from the information materials and the discussions that students play an important role in the quality system of the programme. They fill in course evaluations and are an active part of the programme committee. At several occasions during the visit, the panel noticed that this committee of students and staff takes its role seriously and has grown in stature compared to the previous visit of the accreditation committee. Moreover, students indicated that because of the approachable—and safe—education environment they feel taken seriously by the teaching staff and the programme management, and are at ease to address issues of concern.

Considerations
The panel considers that the teaching-learning environment of the master's programme Computational Science is up to standard. In fact, the panel thinks highly about several components

of this standard: the curriculum is relevant and coherent, and the courses are driven by the research agenda of the participating institutes and research groups; there is a clear relation between the learning goals at course level and the learning outcomes at programme level; the educational concept of independent supervised learning is implemented throughout the curriculum and befits the objectives of the programme; the admission procedure is effective in attracting a multi-disciplinary student body; the staff is highly qualified covering a wide range of research specialisms and is appreciated by the students for their dedication and intensive guidance and supervision; students and staff are actively involved in safeguarding the quality of the courses and the programme.

In addition to these positive elements, the panel found that four elements require attention or improvement. It appreciates however that the management is not only aware of these issues at stake but is already monitoring or even undertaking action. First and foremost, given its findings on the thesis quality, the panel appreciates the additional attention to research skills throughout the curriculum and advises the programme to monitor that the acquired skills are effectively demonstrated in the graduation project. Secondly, the time staff can dedicate to the programme is sufficient for now, but should be monitored carefully as the number of students has grown and may impact on the quality of the course delivery and the intensity of thesis supervision. Thirdly, the panel appreciates the explicit objective of the programme to admit students with a heterogeneous study background, but considers that the programme should do more to make its courses attractive for all students, including those at different ends of the challenge spectrum. This finding and recommendation is all the more relevant according to the panel if the Faculty wants to maintain or even increase the number/share of computer science bachelor graduates who stay with UvA for a master's programme. Finally, the growing number of students in both faculties makes it sometimes difficult for joint degree students to get admitted to popular electives which are mandatory for students from other programmes; the panel advises the programme management to make arrangements with the course owners, and inform students accordingly.

Conclusion
Master's programme Computational Science: the panel assesses Standard 2 as *meets the standard*

Standard 3: Student assessment
The programme has an adequate system of student assessment in place.

Findings

Assessment system
The panel noticed that the assessment system of the master's programme Computational Science is based on the provisions set by the framework policy of the university. The organisation of student assessment is stipulated in the Teaching and Education Regulations (TER). The specific assessment rules that apply in the master's programme are described in a dedicated assessment policy document, which serves as a clarification for both teaching staff and students. Moreover, the study guide (*studiewijzer*) describes per course the contents, the organisation and the assessment method(s). The panel noticed in an annex to the self-evaluation report that the programme is using a variety of assessment methods—ranging from written exams to practical assignments, oral presentations, written reports and group work. All courses have several ways to assess whether students have acquired the learning goals.

Course and thesis assessments
The panel noticed that the assessment principles underlying the master's programme are sound and have been implemented in all courses. On site the panel looked into course files and their respective assessment forms and found these to be appropriate: the questions were valid and reliable. Students indicated during the visit that assessment is transparent: they know in advance what they need to prepare for the exam and how they will be assessed. Furthermore, students informed the panel that rules and regulations relating to fraud and plagiarism are addressed in several courses.

As part of its thesis review, the panel studied a sample of 15 master's theses and their respective assessment forms. Every thesis is assessed by a thesis committee that consists of at least three people: the daily supervisor, the examiner and the second reader. The final grade is the responsibility of the examiner, who is proposed by the programme director and appointed by the Examinations Board. Every thesis is assessed on 19 criteria clustered around three elements: research work, thesis product, and presentation/defence. The criteria require an appreciation ranging from excellent to insufficient, while the three elements each receive a score; there is an indicative but not mandatory weighing of the three elements in setting the final score. Assessors can provide written clarification on the form to motivate their scores on implementation, thesis and presentation. Until now, the evaluation form was filled in manually.

While in principle the thesis evaluation form is appropriate, the panel found that in a majority of cases the thesis committee had not made optimum use of the form. Only a small number of evaluation forms contained insightful comments clarifying why the committee had given a certain score. Qualitative feedback to motivate the appreciation of the criteria or the score of the respective elements was especially lacking in cases where the panel did not agree with the final grade (see Standard 4) and would have liked to understand the reasoning of the thesis committee. Furthermore, the panel noticed that the form did not invite the individual thesis committee members to express an independent opinion on the respective criteria/components.

Confronted with these findings, the programme management indicated that students are getting more extensive formative feedback when working on the thesis, as well as orally at the thesis defence. Moreover, the management agreed that the format did not invite thesis committees to provide much qualitative feedback; it acknowledged also that there had been no strict rules with regard to providing such feedback beyond completing ticking criteria boxes, giving scores per element and establishing a final grade.

The panel was informed, however, that as of 2019-2020, a new format based on the same elements but with criteria rubrics will be used. This form is made available digitally, contains a fixed weighting per element and requires thesis committees to motivate the scores with qualitative feedback. The panel has studied the new digital rubric and thinks it constitutes a considerable improvement: the rubrics for instance provide useful pointers for the assessors to reflect on their appreciation per criterion. The panel strongly recommends the management to monitor that the new forms are completed properly and contain per element an insightful motivation of the score. Furthermore, the programme management may want to reflect if and how the respective thesis committee members could issue an independent opinion on the thesis elements.

Examinations Board

The quality of assessment and the end level of the master's programme Computational Science are safeguarded by a subcommittee of the Examinations Board at faculty level. This subcommittee consists of four members, including a representative of VU who also sits on the Examinations Board of the other joint degree led by VU. In order to safeguard the quality of assessment, the central Examinations Board has established an assessment committee which is composed of one delegated member per subcommittee. Each committee checks 10% of all regular courses per year and reviews two theses. The central Board also established a fraud and plagiarism committee, which exchanges its findings with the assessment committee.

The panel gathered from the discussion with representatives of the Examinations Board and assessment committee that the quality assurance of student assessment is organised properly and that the individual members have adequate experience to fulfil their various tasks. The panel was somewhat surprised to notice that the assessment committee's check of the thesis sample had not given rise to action with regard to the use of the assessment forms within the programme. The representatives, however, agreed with the panel that the (former) thesis evaluation form was not used in an optimum way, and indicated that the new form should resolve many of the issues the panel had spotted. Further to its recommendation to the programme management, the panel

suggests that the assessment committee, when reviewing master theses, pays specific attention to the quality of the written feedback and reports any flaws in this regard.

Considerations
The panel considers that student assessment is organised adequately in the master's programme Computational Science. The policy and principles underlying course assessments are up to standard. The course assessments are valid, reliable and transparent. Moreover, the panel appreciates that the programme is taking fraud seriously.

Based on its own sample review, the panel considers that the assessment process of the thesis is up for improvement with regard to its use for quality assurance purposes. While the process itself is robust, the motivation of the assessment is often poorly reported. In this regard, the panel welcomes the new digital rubric for thesis assessment and strongly suggests the programme management to monitor that each thesis committee completes the form in an insightful way. Furthermore, the panel invites the management to reflect if and how the respective thesis committee members could form an independent opinion on the thesis product and report this separately on the evaluation form.

According to the panel, the quality of the assessment is safeguarded properly by the faculty-wide Examinations Board and its subcommittee for the master's programme Computational Science, its assessment committee and its fraud and plagiarism committee. The individual members have good expertise to deal with their respective tasks. The panel encourages the assessment committee to verify in its thesis review sample the quality of the written feedback and to report any flaws.

Conclusion
Master's programme Computational Science: the panel assesses Standard 3 as *meets the standard*

Standard 4: Achieved learning outcomes
The programme demonstrates that the intended learning outcomes are achieved.

Findings

Thesis quality
In order to establish whether students achieve the intended learning outcomes, the panel has reviewed a sample of 15 master's theses that were accepted in the academic years 2017-2018 and 2018-2019. The thesis is an individual research project of 42 EC and the main way in which the exit qualifications of students are tested. According to the self-evaluation report, the graduation project should lead to an addition to the body of knowledge in Computational Science, demonstrating the ability of students to be able to perform original scientific research and communicating that to their peers.

The panel found that 14 out of 15 theses were of a quality that can be expected of a final project at master's level. In a few cases the panel thought that the quality of the thesis was really good. In a previous section, the panel considered that through the individual courses, the curriculum allows students to acquire the programme's intended learning outcomes. Having reviewed a selection of master's theses, the panel considers that the thesis quality is sufficient overall and that students who successfully pass the graduation project have indeed achieved all intended learning outcomes.

Notwithstanding this positive finding, the panel was rather disappointed about the overall quality of the graduation projects. The panel found that in several cases the academic quality of the thesis and the scientific approach adopted by the students were not as strong as expected. While the panel did not question the basic threshold level of quality of these theses, it did notice that several graduation projects were receiving relatively high grades: across the sample, the panel would have given a lower grade in a majority of cases. Moreover, the panel found that only a handful of graduation projects lived up to the very ambitious claims of the programme that it should add to the body of knowledge

with students performing original scientific research. The panel was somewhat surprised by its findings, given that the master's programme Computational Science has an outspoken scientific research oriented profile with high expectations regarding the career of its graduates. Moreover, the curriculum contents are very much attuned to this profile and so is the position of the graduation thesis, which takes up a considerable study load and features intensive supervision.

During the visit, the panel learned that the programme has started enhancing the academic skills component in the curriculum. Furthermore, the revised thesis evaluation form includes rubrics on the respective criteria providing clear pointers with regard to the expected levels of performance and the scores associated with these levels. The panel understood that it is too early to already notice the impact of these measures. However, the discussions demonstrated according to the panel that the programme management, the course coordinators and the Examinations Board are implementing adequate measures to enhance the overall quality of the thesis projects and will follow-up the results. Students who are currently on the programme, moreover, indicated that they have received extensive academic skills training, that they apply these skills in several ways throughout the curriculum and that they feel well prepared for the graduation project.

Alumni
In addition to verifying the quality of the final deliverables, the academic and/or labour market performance of master graduates is another way to establish whether students achieve the intended learning outcomes upon completion of the programme. Both the information materials and the discussions indicated that the master's graduates are effective in pursuing a career in both academia and industry. In this regard the panel noticed that the programme is delivering on its double ambition, i.e. to prepare its students for entering a PhD trajectory and for taking up a research-oriented position in industry.

The panel noticed furthermore that the programme has enhanced its contacts with alumni, as recommended by the previous accreditation committee. In addition to graduates joining the UvA-wide alumni organisation, the programme actively seeks to establish a network of Computational Science alumni through LinkedIn. The network is then used to ask for input, to keep graduates informed about colloquia and symposia and to promote the master's programme. As a concrete output of this engagement, the panel received an overview of current positions and companies of 24 alumni who graduated between 2015 and 2019: it confirms that Computational Science graduates end up with higher education institutions, research institutes, public authorities and industry companies. In so far as it can be deducted from the combination of employers and positions in the overview, several graduates seem to be professionally active using the multi-disciplinary component of their study.

If anything, the panel found that there is a slight mismatch between the emphasis put in the self-evaluation report on the preparation for scientific research-oriented positions in academia and research institutes on the one hand, and the number of graduates on the other hand who are now in data science or software engineering positions in industry. This finding is linked to both expectation management and programme profiling and may need to find its way in the communication to (potential) students.

Considerations
Based on its review of the graduation projects and the discussions on site, the panel considers that master's students who graduate from the Computational Science programme are adequately prepared for a position in both academia and industry. It is to the credit of the programme that graduates find attractive positions with a wide range of employers, be it universities, public bodies, R&D departments or (tech) companies. The panel, moreover, welcomes the programme's attention to its graduates through a dedicated alumni network.

Having established that overall the thesis sample meets the minimum requirements of what can be expected of a final research project at master level, the panel concludes that the intended learning outcomes of the programme are eventually achieved at the end of the master's curriculum.

Notwithstanding a few outstanding exceptions, the panel would have expected more theses of excellent quality with regard to academic quality and scientific approach, given the explicit research-oriented profile of the programme and the position of the graduation project in the curriculum. The panel therefore welcomes the increased attention in the curriculum to academic skills training and its applications in the domain-specific courses.

Conclusion
Master's programme Computational Science: the panel assesses Standard 4 as *meets the standard*

GENERAL CONCLUSION

In the previous sections, the panel has come to the conclusion that the master's programme Computational Science, which is offered as a joint degree by the University of Amsterdam and the Vrije Universiteit Amsterdam, fulfils the quality requirements with regard to each of the four standards set by the NVAO's Assessment Framework for the higher Education Accreditation System of The Netherlands for limited programme assessments: intended learning outcomes, teaching-learning environment, student assessment, and achieved learning outcomes. Hence, the panel's overall assessment of the *master's programme Computational Science* as 'positive'.

APPENDICES

APPENDIX 1: DOMAIN-SPECIFIC FRAMEWORK OF REFERENCE

In an appendix to the self-evaluation report, the programme provides an analysis of the current international consensus on the field of Computational Science and Engineering, the need for graduate programmes in this field, and the construction of a degree course in Computational Science.

1. Introduction

This Appendix provides an analysis of current international consensus on the field of Computational Science and Engineering, on the need for graduate programmes in this field, and on the high-level construction of a degree course in Computational Science. This analysis serves as the benchmark against which we will measure the design and content of the Master Computational Science at the University of Amsterdam. Next, we describe how we have translated this benchmark into goals for the program, and a set of specific learning outcomes that we aim to achieve.

2. Third pillar of science

Computational Science has established itself as the third pillar of science, alongside theory and experimentation. The influential document from the USA PITAC (the President's Information Technology Advisory Committee) entitled "Computational Science, ensuring America's competitiveness', delivered as a report to the USA president in June 2005, describes Computational Science as: "Computational science is a rapidly growing multidisciplinary field that uses advanced computing capabilities to understand and solve complex problems. Computational science fuses three distinct elements:

1. Algorithms (numerical and non-numerical) and modelling and simulation software developed to solve science (e.g., biological, physical, and social), engineering, and humanities problems;
2. Computer and information science that develops and optimises the advanced system hardware, software, networking, and data management components needed to solve computationally demanding problems;
3. The computing infrastructure that supports both the science and engineering problem solving and the developmental computer and information science."

Or in short, "the multidisciplinary combination of computational techniques, tools, and knowledge needed to solve modern scientific and engineering problems" [1]. The impact of Computational Science on science and society is substantial. The PITAC report provides numerous examples, ranging from the Social Sciences to the Physical sciences and Engineering disciplines.

There are other influential reports and events that stress the importance of Computational Science:

- The 2009 World Technology Evaluation Centre (WTEC) Panel Report on International Assessment of Research and Development in Simulation Based Engineering and Science.
- The proceedings of the ICCS conferences, each year more than 3500 pages.
- The "Towards 2020 Science" report and the associated special issue in Nature [2].

Finally, 'Computing in Science & Engineering' and the Journal of Computational Science, key journals in this field, supply numerous examples of state-of-the-art Computational Science, as well as many papers and discussions on Computational Science education. In the Netherlands, the Royal Academy of Science KNAW took the initiative for an advisory committee Computational Science under the chairmanship of Prof. Rutger van Santen from the Technical University Eindhoven. They advised to further strengthen Computational Science in the Netherlands, and to foster the strong multidisciplinary potential available in the Netherlands. This culminated in the establishment of a Dutch Computational Science council, chaired by Prof. Frenkel from Cambridge University, and with Prof. Peter Sloot as vice-chair.

3. The Need for Computational Science Education

Based on the current status of the field of Computational Science, and the overwhelming need for professionals with an academic training in the Computational Sciences, there is a clear impetus for Academic programmes, both on the graduate and undergraduate level [1, 3]. The PITAC report writes: "Universities must implement new multidisciplinary structures and organisations that provide

rigorous, multifaceted educational preparation for the growing ranks of computational scientists […].” The WTEC report on SBE&S writes: “Demand exceeds supply. There is a huge demand in the European Union and Asia for qualified SBE&S students who get hired immediately after their MSc degrees by industry or finance.” The recent PRACE report “The Scientific Case for High Performance Computing in Europe 2012-2020”28 also clearly states the need for academic education in the Computational Sciences.

On a Dutch National level, the Dutch Science Foundation NWO financed a special research programme on Computational Science. This programme was formally ended, yet acknowledging that we do not train a sufficient number of graduates in the Computational Sciences. SIAM provides a list of current graduate programmes in Computational Science [4].

4. Computational Science Curricula

There is an international consensus that a Computational Science curriculum is inherently multidisciplinary in nature, with a core of Computational Science, and applications in science or engineering [1, 3, 5-10]. Yasar and Landau have summarised this quite well in the following six general areas of knowledge [1]:

- Computational Tools;
- High Performance Computing;
- Applied Mathematics and Computational Methods;
- Simulation and Modelling;
- Visualisation;
- Applications in Science or Engineering.

They also analysed a number of Computational Science programmes, showing that each of them contains this list of areas of knowledge, albeit with slightly different weights. The SIAM working group report [3] reaches the same conclusion. Most important is that all these six areas of knowledge are “essential and should be covered either in dedicated courses or in the context of other courses” [1]. It would be interesting to have statistics on the percentage that each knowledge area takes in an overall curriculum. We are however not aware of an in-depth study to this, and we have not attempted such study ourselves. However, Yasar and Landau do provide some very crude metrics for a small sample of programmes, and find that in the subjects “Computing”, “Mathematics”, “Applications” and “Other” the balance was 20%, 25%, 25% and 30% respectively [1].

References

[1] Osman Yasar and Rubin H. Landau, Elements of Computational Science and Engineering Education, Siam Review 45, 787-805, 2003.
[2] Special Issue 2020 Computing, Nature 440, March 23, 2006.
[3] SIAM Working Group on CSE Education, Graduate Education for Computational Science and Engineering, SIAM Review 43, 163-177, 2001.
[4] http://www.siam.org/students/resources/cse_programs.php
[5] Leigh J. Little, The Computational Science major at SUNY Brockport, Fut. Gen. Comput. Sys. 19, 1285-1292, 2003.
[6] Osman Yasar, Kulathus S. Rajasethupathy, Robert E. Tuzun, R. Alan McCoy, and Joseph Harkin, A New Perspective of Computational Science Education, Computing in Science & Enginereering 2 (September/October), 74-79, 2000.
[7] Martin Bernreuther and Hans-Joachim Bungartz, First Experiences with Group Projects in CSE Education, Computing in Science & Engineering 8 (July/Augus), 16-25, 2006.
[8] W. Wiechert, The role of modelling in computational science education, Fut. Gen. Comput. Sys. 19, 1363-1374, 2003.
[9] Hans-Joachim Bungartz, Computational science and engineering: a new master’s program at the Technische Universität München, Fut. Gen. Comput. Sys. 19, 1267-1274, 2003.
[10] Sverker Holmgren, and Anders Ynnerman, The Swedish National Graduate School in Scientific Computing, Fut. Gen. Comput. Sys. 19, 1275-1283, 2003.

APPENDIX 2: INTENDED LEARNING OUTCOMES

Our objectives have been rationalised into the following exit qualifications of the programme:

1. The graduate in Computational Science has thorough knowledge of modelling and simulation of complex systems, computational methods and techniques, and the application of computational methodologies in application fields (ranging from e.g. physics or biology to medical sciences or psychology).
2. The graduate is able to contribute to scientific research in the field of computational science or in other fields using a computational science approach.
3. The graduate can formulate and solve problems with the aid of abstraction and model forming.
4. The graduate is able to formulate problems both in general terms and in mathematical and
5. technical terms.
6. The graduate is able to clearly express himself/herself both orally and in writing.
7. The graduate is able to analyse, design and implement as part of a team.
8. The graduate has given thought to the societal and scientific impact of computational science.
9. The graduate is able to independently perform research projects and acquire the necessary information and concepts.

These exit qualifications fall into three categories: Computational Science knowledge and skills; scientific research and problem solving; and communication and collaboration skills.

APPENDIX 3: OVERVIEW OF THE CURRICULUM

Curriculum Master programme Computational Science 2018-2019

	Semester 1			Semester 2		
	block 1 September October	block 2 November December	block 3 January	block 4 February March	block 5 April May	block 6 June
Core (year 1) 24 EC	Introduction Computational Science (UvA)	Numerical Algorithms (UvA)		Seminars Computational Science (UvA)		Complex System Simulation (UvA)
Constrained Choice Courses 30 EC	Evolutionary Computing (VU)	Stochastic Simulation (UvA)	Agent-Based Modelling (UvA)	Computational Finance (UvA)	Computational Biology (UvA)	
	Introduction to Systems Biology (VU)		Biosystems Data Analysis (UvA)	Performance of Networked Systems (VU)	Data Mining Techniques (VU)	
	Large Scale Data Engingeering (VU)		Parallel Programming Practical (VU)	Scientific Computing (UvA)		
	Programming Large-scale Parallel Systems (VU)					
Recommended Electives 24 EC	Bioinformatics I (UvA)	Algorithms in Sequence Analysis (VU)	Understanding Molecular Simulation (UvA)	Biomolecular Simulations (UvA)	Advanced topics in Computational Finance (UvA)	Machine Learning for the Quantified Self (VU)
	Biomedical Modelling and Simulation (VU)	Behaviour Dynamics in social Networks (VU)		Parameter Estimation Applied to Medical and Biological Sciences (VU)	Bioinformatics II (UvA)	
	Concurrency and Multithreading (VU)	Bounded Rationality (UvA)		The Social Web (VU)	Bioinformatics for Translational Medicine (VU)	
	Fundamentals of Bioinformatics (VU)	Distributed Systems (VU)			Experimental Design and Data Analysis (VU)	
	Internet Programming (VU)	Information Theory (UvA)			Knowledge Representation on the Web (UvA)	
	Non-linear Economic Dynamics (UvA)	Machine Learning I (UvA)			Quantitative Financial Risk Management (VU)	
	Physics of Organs 1: Cardio-Pulmonary Physics (UvA)			Stochastic Calculus (UvA)		
	Scientific Visualisation & Virtual Reality (UvA)					
	Statistical Theory of Complex Molecular Systems (UvA)					
	Stochastic Processes for Finance (VU)					
	Uncertainty Quantification and Data Assimilation (UvA)					
Core Course year 2 - 42 EC		Master Thesis Computational Science				

APPENDIX 4: PROGRAMME OF THE SITE VISIT

Venue: University of Amsterdam, Science Park 904, Beta Lounge (room B1.25)

Monday 4 November 2019

10.30 Arrival panel, internal preparatory meeting + lunch
13.00 Session with management UvA (including representative VU)
13.30 Session with programme management
14.30 Session with bachelor students
15.30 Session with lecturers bachelor programme
16.30 Session with Examinations Board
17.30 Session with Alumni and Advisory Board
18.30 Internal panel meeting
19.00 End of day one

Tuesday 5 November 2019

08.30 Open consultation hour
09.30 Session with master students Computational Science
10.30 Session with lecturers Computational Science
11.30 Session with master students Software Engineering
12.30 Session with lecturers Software Engineering
13.30 Internal panel meeting + lunch
14.30 Session with programme management
15.15 Internal panel meeting
17.30 Plenary feedback
18.00 End of site visit

APPENDIX 5: THESES AND DOCUMENTS STUDIED BY THE PANEL

Critical Reflection Master Programme Computational Science, University of Amsterdam & Vrije Universiteit Amsterdam 2019.

Prior to the site visit, the panel studied 15 theses of the master's programme Computational Science. Information on the selected theses is available from QANU upon request.

In addition to the numerous appendices that were part of the self-evaluation report, following materials were made available by the Graduate School of Informatics during the site visit, either as hard copy or in digital format through the faculty's electronic learning environment:

Annual Reports

- OC Computational Science 2017-2018
- Examencommissie IW/EW

List study material courses MSc Computational Science

Introduction to Computational Science (2018/2019) course code 5284ITCS6Y

- Exam and answer model (available in course record Datanose + printed version)
- Reading material (available on CANVAS)
- Lecture slides (available on CANVAS)
- Exercises and assignments (available on CANVAS)

Computational Finance (2018/2019) course code 5284COFI6Y

- Exam and answer model (available in course record Datanose + printed version)
- Reading material (available on CANVAS)
- Lecture slides (available on CANVAS)
- Assignments (available on CANVAS)

Stochastic Simulation (2018/2019) course code 5284STSI6Y

- Exam and answer model (available in course record Datanose + printed version)
- Reading material (available on CANVAS)
- Lecture slides (available on CANVAS)
- Lecture notes (available on CANVAS)
- Assignments (available on CANVAS)

Complex System Simulation (2018/2019) course code 5284COSS6Y

- Exam and answer model (available in course record Datanose + printed version)
- Reading material (available on CANVAS)
- Lecture slides (available on CANVAS)
- Assignments (available on CANVAS)