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Aims and Scope
The manifestos from Dagstuhl Perspectives Workshops are published in the *Dagstuhl Manifestos* journal. Each manifesto aims for describing the state-of-the-art in a field along with its shortcomings and strengths. Based on this, position statements and perspectives for the future are illustrated. A manifesto typically has a less technical character; instead it provides guidelines and roadmaps for a sustainable organisation of future progress.

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Manifesto from Dagstuhl Perspectives Workshop 14112

Massive Open Online Courses: Current State and Perspectives

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Abstract

The rapid emergence and adoption of *Massive Open Online Courses* (MOOCs) has raised new questions and rekindled old debates in higher education. Academic leaders are concerned about educational quality, access to content, privacy protection for learner data, production costs and the proper relationship between MOOCs and residential instruction, among other matters. At the same time, these same leaders see opportunities for the scale of MOOCs to support learning: faculty interest in teaching innovation, better learner engagement through personalization, increased understanding of learner behavior through large-scale data analytics, wider access for continuing education learners and other nonresidential learners, and the possibility to enhance revenue or lower educational costs. Two years after "the year of the MOOC", this report summarizes the state of the art and the future directions of greatest interest as seen by an international group of academic leaders. Eight provocative positions are put forward, in hopes of aiding policy-makers, academics, administrators, and learners regarding the potential future of MOOCs in higher education. The recommendations span a variety of topics including financial considerations, pedagogical quality, and the social fabric.

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Executive Summary

Online education is not new; Massive Open Online Courses (MOOCs) are. Their uniquely powerful combination of classical digital teaching tools (videos, audios, graphics or slides), individualized tools for acquiring and validating knowledge, and appropriate use of dedicated social networks makes them a new and powerful means of accessing knowledge and education. If backed up with scientific and pedagogical excellence, MOOCs allow one to reach and teach simultaneously tens of thousands and even hundreds of thousands of learners in a new pedagogical dynamic.

The computer science and informatics community has long collaborated with the teaching and knowledge dissemination community through the creation and deployment of technology for teaching and learning. However, MOOCs represent a new level of engagement between these communities because of their scale, their links to economic and production systems in

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higher education, and the conversations about teaching that they have provoked, some of which may induce radical changes in teaching and learning mechanisms. The consequences on transmission of culture and educational content, and on society as a whole, will be deep.

The Perspectives Workshop on "Massive Open Online Courses: Current State and Perspectives" took place at Schloss Dagstuhl on March 10–13, 2014. Twenty-three leading researchers and practitioners from informatics and pedagogical sciences presented and discussed current experiences and future directions, challenges, and visions for the influence of MOOCs on university teaching and learning. The first day of the workshop consisted of a series of presentations in which each participant presented those topics and developments he or she considered most relevant for the future development of MOOCs. On the second and third day the participants divided into several working groups according to the main thematic areas that had been identified on the first day.

This manifesto summarizes the key findings of the workshop and provides a collection of research topics for MOOCs. The eight theses presented in this report can be divided into three categories: the integration of MOOCs into university education, quality assurance and measures of success, and policies for access and privacy.

The working group chose to make specific recommendations that are intended to provoke discussion and to lead to better understanding of the core issues. This document represents the editors' best effort to capture the main positions put forward during the meeting, but may vary from the opinions of individual participants. The eight positions identified and explored by participants are:

Integration of MOOCs Into University Education

1. Universities should restructure residential education using MOOCs.
2. New pedagogical approaches should be developed to take advantage of scale.
3. Universities should move towards providing official credit for MOOCs.

Quality Assurance and Measures of Success

4. Quality criteria for MOOCs should be developed.
5. Standards should be developed for measuring participation in MOOCs.
6. Return on investment in MOOCs is heavily university-dependent.

Data Access and Privacy

7. MOOCs should provide universal access.
8. New data policies should be collectively negotiated.

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1 State of the Art

Massive Open Online Courses (MOOCs) have emerged in a period of only a few years from 2008 into a much-discussed component of higher education worldwide, despite a very small scale of educational provision in comparison to traditional university education (∼700 short MOOCs at the start of 2014 versus 100.000s of degrees). Their nature distinguishes them from mainstream university education: they are entirely online courses which are open for enrolment regardless of previous educational attainment and free of charge to anyone with an internet connection, with large enrolments (10.000s to 100.000s of learners[1]) but very few teachers/tutors, and studied almost entirely without the option of formal university credits being awarded.

We do not review MOOCs in great detail here, as much has been written about them in numerous recent reports and recommendations [10, 12, 18, 5, 15, 9, 14], but instead summarise the state of the art as of March 2014 when we met at Dagstuhl. We focus mainly on university-provided MOOCs rather than the growing number of MOOCs from corporates, governmental and non-governmental agencies and organisations, and from schools or VET (vocational education and training) colleges (e. g. http://vetcollege.in).

MOOCs take multiple forms. At one end of the spectrum is the xMOOC, which is characterised by a rather tight structure, little social interaction and mainly computer-marked assessments. At the other end is the cMOOC or Connectionist MOOC, which is almost entirely free of pre-provided content and relies instead on very high social interactivity to produce the course content and outcomes. Most current MOOCs lie between these extremes, with some structure (weekly content in the form of video and quizzes) and some important social interactions (discussions, peer-review of work, and so on).

Although the "year of the MOOC" (2012) launched intense interest in MOOCs with the launch of xMOOCs from computer science departments at US universities, at present there are more MOOCs in humanities and social science subjects than in the sciences, and new MOOCs appear weekly in new subjects. One relatively constant feature has been the focus on "end of high school – first year of university," with few MOOCs offered above or below this level. Various companies and organisations have been created to act as "platforms" for MOOCs, and few universities host their own MOOCs. These platforms include commercial for-profit (Coursera, USA), commercial not-for-profit (FutureLearn[2], UK), noncommercial not-for-profit (edX, USA), and governmental (FUN, France).

Very popular MOOCs can attract more than 100.000 initial enrolments. This scale has led to intense press and political interest in MOOCs, but the lack of retention of the great majority of those enrollees has led to criticism about drop-out levels and MOOC quality. DeBoer and others have argued, however, that the concept of "retention" should be reconceptualized for MOOCs [6], given the very different risk/benefit profile that MOOCs offer relative to traditional credit-bearing courses that charge a fee or tuition. Data shows that enrollees come from all countries, but mainly from the educated adult population, contradicting (for the present) early expectations of reaching the disadvantaged or under-represented in higher education. Despite this overall preponderance of an educated learner base, MOOCs clearly do reach some learners for whom they represent an important educational opportunity, such as learners in remote regions or with various disabilities.

[1] Note that in all the Manifesto, we name MOOC participants as 'learners' and retain the word 'student' for enrolled students in universities.

[2] FutureLearn is formally a commercial for-profit organisation but wholly owned by a not-for-profit University, and therefore any profits will be put back into the organisation.

The large scale of enrolments and engagement with the online learning materials and activities generates large amounts of data about the learners' behaviour online. The availability of such data has driven great interest in the educational research community in learning analytics, and the possibility of helping learners through better understanding of how they are learning and what challenges they are facing. However alongside this positive view of the data is a "darker side" of concerns about privacy of learner behaviour online and the ethics of research and data-sharing. The presence of commercial companies, funded by venture capital, increases this sense of discomfort for some in the academic and learner communities.

Tackling difficult questions about supporting learning at large scale has spurred a steady pace of innovation in technology solutions. Tools for managing small groups in a large cohort, for large-scale peer review and assessment, for visualising analytics of a course and of individuals, and for providing targeted feedback to learners have all emerged in the past two years.

The co-presence of MOOCs and traditional teaching in universities has inevitably led to cross-fertilisation, and in particular to explorations of how to use MOOCs with students enrolled on degree programmes in particular. Examples include "MOOCs as books", flipped or inverted classrooms, Small Private Online Courses (SPOCs) based on open MOOCs, and credit for students enrolled in external MOOCs.

The group that met at Dagstuhl came together with all these developments and more in mind, to discuss trends in MOOCs and to share their experiences from their own universities. We wished to inform not only researchers and instructors, but also learners, policy-makers, and leaders in higher education. The first day of the workshop was spent brainstorming a set of questions and topic areas based on position statements provided by each participant. Subsequent days were spent discussing these topics, summarizing the discussions and presenting them to the group, and drafting recommendations based on these discussions. Our hope is to influence the creation of an agenda that will not only improve the quality and availability of MOOCs, but also address fundamental questions about the relationship between MOOCs and traditional education from the perspectives of pedagogy, administration, cost, and learner privacy. Given the composition of our group, our discussion has a strong focus on the roles of computer science, artificial intelligence, and the learning sciences.

2 Universities Should Restructure Residential Education Using MOOCs

The MOOC-accelerated paradigm shift in education, comparable to shifts in the news media and the music industry, is forcing an unbundling and rebundling of educational components. In the case of higher education, we must rethink long-established modes of interaction, teaching roles, and structures in a way that recognizes that the sources of knowledge, and therefore the roles of instructors and campuses, have changed.

We see the most important shifts as follows:

- With the wide availability of high-quality, (often) free, and easy-to-reuse content online, most instructors' primary responsibility shifts *from creating content to creating context.*
- Rearrangements of residential course elements (lectures, recitations, labs, and so on) and new teaching roles beyond simply "instructor" and "teaching assistant" will better fit this new instructional modality. One challenge of this reorganization is changes to campus infrastructure, but one facilitator is that inexpensive video production will empower domain experts to create better materials to prepare and train the new teaching roles.

- The absence of the "sage on the stage" will open new ways to foster teacher and learner commitment. Campuses should focus less on conveying content-oriented skills and more on social/professional skills, such as collaborative work and perspective-broadening activities, to complement independent study and discovery.

2.1 Teacher Responsibilities: Context Versus Content

The abundance of learning material online – instructional videos, slides, discussion forums, open educational resources (e. g. https://oerknowledgecloud.org), Wikipedia – challenges the traditional role of teachers and lecturers as content creators, a role rooted in times when such materials were not easily available. Today, lecturer-authored content competes with hundreds of alternatives, some better and some worse than his own, and the lecturer loses the content monopoly he has had since classical times. MOOC-driven learning materials may supplant lectures for the first two learning steps in Bloom's taxonomy [2]: remembering and understanding the content presented by the lecturer.

In this new scenario, the instructor's role focuses on contextualizing existing content. Numerous metaphors have been used to describe this role: creating a narrative, connecting the dots, acting as an expert tour guide, or as in Vannevar Bush's prescient Memex vision, blazing a trail. Instructors present their personal views on the content based on domain expertise and puts them into perspective with examples, applications, analogies or anything else they deem useful. Lecturers question the content's assumptions and perspectives, helping learners evaluate alternative explanations of content and thereby guiding them in applying the material (the third step in Bloom's taxonomy). The role of contextualization is especially important across disciplines: a course on "building user-friendly and secure databases" requires interweaving expertise in databases, human-computer interaction, software engineering, and security. The abundance of online material in each topic suggests that with a skilled guide, such a course could be offered without requiring three different professors to teach it.

One key ingredient of this new role is the ability of the professor to skillfully select and remix existing content into a coherent story, as a film editor reduces hundreds of hours of film footage into a coherent 90-minute movie presenting a specific point of view. We note, however, that this activity brings the lecturer's role into direct conflict with restrictions on remixing imposed by copyright issues, as discussed in Right to Remix (http://right2remix.org) and other forums.

Campuses should also capitalize on their social and professional networking benefits, teaching skills that are less content-oriented and more crosscutting such as teamwork and collaboration. In the sciences, clinical and other practical subjects, they will remain essential places for learning, although even here changes to digital alternatives are becoming viable. Campuses should also focus on their ability to competitively place students in perspective-broadening activities, such as premium internships or international collaborations.

Interestingly, instructor guidance around inquiry-based use of existing materials combined with teamwork and collaboration are the underlying format for another kind of education many universities already practice: graduate research. While undergraduates would be mainly exploring an existing body of knowledge rather than discovering new knowledge, it is possible that the undergraduate educational process could become more like graduate research and less like the unidirectional presentation of information that dominates much of undergraduate education today.

2.2 Inexpensive Video Creation and the Reorganization of Courses and Teaching Roles

Most residential courses today are offered in a "one size fits all" model: a single lecture, a single set of assignments or labs, and so on. Yet as demand for higher education drives enrolments, we observe that not all aspects of offering a course scale equally well in terms of instructor resources. Larger enrolments expose more obvious variance across learner cohorts. Combining flexible teaching staff with MOOC-like "self-service" resources can help tailor instruction to smaller groups within the large cohort. For example, peer and social learning techniques enable strong learners to help their colleagues, while learners in difficulty benefit from mastery learning and other MOOC benefits resulting from inexpensive computing power. This restructuring of course elements into more-scalable and less-scalable components will leave instructors more time to conduct interaction-intensive learning activities such as small-group discussions and design projects.

At the other extreme, MOOCs could provide an opportunity to save highly-specialized "boutique" courses and curricula. In Europe, after the Bologna Declaration, highly specialized courses and curricula such as Indian Studies or Albanology (the study of Albanian culture) had to be integrated into more general Bachelors' or Masters' curricula such as Asian Studies or Mediterranean Studies, threatening the existence of important building blocks for certain cultures. Several professors around the world could collaboratively produce a series of specialized MOOCs that would form the basis of "boutique" degree programs that would enable continued deep scholarship in such areas despite limited resources at any single university.

Both scenarios call for new teaching roles beyond just the traditional roles of instructor and teaching assistant as they exist today. How will these new roles receive training in order to be effective? It is already well known that some skills are better demonstrated by video than explained in text; two examples are narrated screencasts showing how to use digital tools and videos showing how to play an instrument or perform physical tasks. Inexpensive video creation and distribution allows the domain expert to author such materials directly, eliminating the "translation gap" that might arise when working with a video producer who is not a domain expert and accelerating the creation and deployment of these assets. The potential benefit of this change is the ability to easily create training materials *for other instructors* that are richer and more interactive than a textbook, such as a SPOC (Small Private Online Course) targeted not at learners but at other instructors becoming involved with a course. These materials could familiarize staff with particular course topics, give guidance on resolving common learner problems, and so on. By exploiting the ability to create such materials, it becomes possible to train new strata of teaching staff that further leverage the effectiveness of the lead instructor, potentially allowing us to educate more learners with a sublinear increase in instructor resources.

Finally, campus infrastructure today, both physical and digital, is highly optimized around traditional delivery models and lecture/section formats. Campuses may have to rethink facilities in light of the increasing role of personal devices such as smartphones and tablets in and out of class, the greater importance of social learning and interaction, and the increasing use of collaborative spaces with new kinds of teaching staff in preference to existing computer labs and individual study spaces.

2.3 Teacher and Learner Commitment in New Learning Modes

Recent meta-analyses [13] have examined what makes teaching effective and how the best teachers activate learners with feedback, challenging goals, direct instruction, and frequent testing, acting as behavioral organizers rather than facilitating learners to digest learning material and fulfill tasks. Just as the 2-sigma finding of tutorial instruction [3] inspired intelligent cognitive tutors, these meta-analyses may inspire the improvement of MOOCs or whatever follows them.

How can we motivate MOOC learners and teachers when the teachers may be both geographically distant and socially disconnected from the learners? MOOCs could, for example, support reciprocal teaching, direct instruction, mastery learning, peer assessment and instruction, small-group/community interactions such as dynamic regrouping of learners to match learning styles and paces, and so on. One promising property of MOOCs is that their delivery vehicle, large-scale software-as-a-service, allows research-supported best practices to be quickly deployed to teachers and learners. The large scale of MOOCs enables 'citizen science' approaches to be incorporated, which involve the learners in live research and stimulates them to very active participation, especially in introductory classes.

3 New Pedagogical Approaches Should Be Developed to Take Advantage of Scale

MOOCs offer new opportunities for scaling up some parts of education to very large numbers of learners: they can reach up to 200.000 learners, compared with the approximately 500 in a typical lecture or seminar room. This scale is made possible in part by the "open" features of MOOCs and their worldwide accessibility. The drawback is that scaling up could come at the expense of pedagogical richness. Typically, the range of pedagogies for xMOOCs is limited primarily to delivery of content and computer-based assessment. This may include effective learning tools such as simulations or modelling tools, as well as peer-review and group work. Nonetheless, today we see scale primarily as a limitation: some rich learning activities are difficult to scale up. In this section we consider how to use these rich methods despite scale, and we explore a complementary perspective – that some activities work better when conducted at large scale. In these cases scale is an opportunity. We therefore divide our discussion into MOOC elements that are *rich despite scale* and those that are *rich because of scale*.

3.1 Rich Despite Scale

An example of pedagogical approach that is difficult to scale is small group activities oriented to joint production of artifacts like essays or design documents in project-based learning, as well their interplay with large group activities. Which categories of pedagogical methods do not scale up very well? While there are many categorizations of pedagogies for online learning, a framework developed for the Capital project (http://www.naace.co.uk/capital) can be considered as a valid reference. The modes of learning are described by multiple keywords, such as reflective, collaborative, simulation, construction, inquiry-driven, problem-based, project-based, case-based, cross-context, game-based, anchored, performative, conversational, networked, and embodied. Each of these methods is mediated in practice through location, process, topic, technology, representation and actors. So, for example, inquiry-driven learning might be enacted at home, by self-directed processes, using mobile technology, with a representation of the inquiry process, through communicating peers.

In the diversity of pedagogical methods, those that are difficult to conduct at scale tend to be those that scaffold high order thinking skills or competencies such as creativity, critical thinking, collaboration skills, and scientific rigour. The importance of these skills explains why we care about pedagogical diversity at scale and leads us to the following recommendation expressed as a research question: How can we create a broad range of effective pedagogies at massive scale, and thereby efficiently contribute to achieving 21st century competencies? The challenge is to explore which of these pedagogies can work effectively at massive scale or what we need to do to deal with scale (new services, metrics, and so on) in technology-enabled environments, while retaining their educational power and accessibility. Researchers have already recognized the importance of scale as a new first-class aspect of pedagogy, as evidenced by new scholarly conferences such as Learning At Scale (http://learningatscale.acm.org).

Such research should focus on the orchestration functions that depend heavily on scale. These functions include creating breakout groups, delivering extra content and personal coaching as in SPOCs, monitoring progress, surveying learner status, guiding and scaffolding the different learning activities, peer reviewing or peer assessment. Thus, one would need to provide orchestration and analytic methods for educators to manage important problems of scale for purposes of preparation, monitoring, grouping, surveying, directing, and coaching. The ultimate goal would be to reduce and distribute efficiently the associated orchestration load on educators, learners, and software agents. Then, orchestration bottlenecks should be identified and effective load balancing schemes should be provided. An analogy consists is the human or virtual game masters who effectively act as community managers in modern massive multiplayer games.

3.2 Rich Because of Scale

To understand the effects of massive scale, we can invoke Metcalfe's Law, which states that the value of a networked system increases in proportion to the square of the number of connected users. For example, a telephone system becomes quadratically more effective with the number of subscribers able to communicate. But as Stephen Downes observes [7], learners are not simply nodes in a communication network – they engage in discussion and collaboration, and these interactions should be useful, new, salient, timely, understandable, trusted, and coherent. The new technological opportunities for multiple degrees of scale create new challenges, which should benefit from studies and lessons learnt regarding scale in telematics engineering, human networks, as well as networked learning.

The mere existence of a scaled up number of learners may have a direct effect on the scale of interactions, and especially on the quantity and quality of messages and other emerging learning objects which are produced and propagated through the networked participants (learners, teachers and other stakeholders). Also, the larger the network, the more opportunities there are for direct learner-to-learner communication. For instance, learners involved in reflective learning may benefit from being aware of the annotations of large numbers of other co-learners, observe the heat maps of these annotations, and consequently focus on the critical topics. However, such a major opportunity requires the provision of adequate filters and advanced semantic and lexical processing methods, that will make peer annotations meaningful. Other significant modes such as collaborative learning benefit from the crowdsourcing effects, especially in terms of timely peer reviews, or data analytics using big data can feed effective algorithms for appropriate groupings.

We therefore recommend that research efforts be directed to invent new pedagogical approaches that are intrinsically designed to take advantage of scale. We believe these two approaches of (a) scaling rich activities initially designed for low scale and (b) inventing new scale-powered activities, are complementary to the construction of new landscapes of learning through ambitious research programs.

3.3 Scaling Both Up and Down

Lastly, even when large scale can be managed successfully, scaling down can still be very relevant, as Section 2.2 of [9] describes. Scale-down is necessary, for example, when the number of participants decreases drastically over the lifetime of a MOOC, or when a MOOC must be adapted for a smaller-scale context such as a SPOC. Moreover, massive scale can sometimes be best achieved by aggregating a massive number of small learning cohorts, again highlighting the importance of small group dynamics and the importance of scale-down. Therefore, there is a need for flexible and elastic mechanisms that enable the most effective and efficient pedagogies when scaling both up and down.

4 Universities Should Move Towards Providing Official Credit for MOOCs

4.1 Why Credits?

In a nutshell, credits are a necessary condition for MOOCs to have a significant impact on the European or worldwide educational landscape.

Currently, most universities do not provide official credits towards an on-campus degree for MOOC completion certificates. This is especially important in Europe where credits are formally defined in terms of learners workload and serve as an exchange currency, thereby allowing mobility among curricula within an institution and among institutions. If MOOCs were recognized with official credits, this current physical mobility would be enhanced with virtual mobility. This would complement parallel developments towards virtual mobility in taught online courses. Physical plus virtual mobility would both allow and motivate the construction of cross-institutional curricula, something that already occurs in practice but is hampered by many institutional, technical and logistical constraints.

Technical constraints include the issue of interoperability in particular since MOOCs are running on different platforms. We hence propose that credits should be offered by universities for MOOC achievement if the two following conditions are met: (1) the identity of the learner has been verified and (2) there exists a valid measure of the target knowledge and skills. Identity verification in an online context is an area of intense development in which appropriate solutions are starting to emerge. The validity of the assessment is the responsibility of the teacher and is part of the quality control that universities and platforms are expected to exercise anyhow.

Offering credit has potentially deep consequences on the MOOC ecosystem, for example on the high attrition rate of MOOCs. Actually, the current drop-out rates are overestimated:

up to 30% of registered learners never even show up. In addition, some participants only register in order to be able to access the content provided by the MOOC but with no intention of taking the full course. Even taking into account these two elements, the rate of drop-out remains high, which may interfere with a credit system. Credit can help because it increases the responsibilities of both learners and teachers: Learners may feel more motivated to complete a MOOC if the certificate is useful for the rest of their studies, and universities may feel more concerned in bringing learners to a designated level of achievement if the credits are necessary for a longer educational process. To reach a more reasonable completion rate, we can pursue two strategies: (a) carefully select participants based on their mastery of prerequisites, and (b) better support them during the MOOC, especially those facing difficulties.

4.2 MOOCs and Prerequisites

MOOCs highlight a tension between effectiveness and openness. On the one hand, one meaning of "open" is that MOOCs are accessible to any person independently of her or his background. On the other hand, if those lacking the proper prerequisites were filtered out early on, the MOOC achievement rate might be higher. This might especially be an issue if the failing learner happens to be an alumnus of the institution providing the MOOC: his or her frustration may be detrimental to university, and many universities are substantially funded by their alumni.

This is a general issue in academia, which runs on a combination of training and selection: we are willing to accept more learners in our universities but afraid that this could lower overall excellence or learner achievement. Different universities already take different positions on this continuum. However, for MOOCs we favor the former option – accepting more learners – for the following reasons. First, learners without prerequisites nonetheless do succeed sometimes, due to higher engagement. Second, admission criteria may be somewhat imprecise and based on limited information. Hence, it is appealing to allow everyone the chance to try for success. Therefore, we suggest that learners should have the right to take the risk of enrolling in a MOOC despite lacking some prerequisites.

This openness should, however, be accompanied by initiatives through which more learners could achieve a MOOC and obtain credits, while keeping both the current policy of universal access and the level of expectation on final outcomes. These initiatives could explore richer individual support, social dynamics such as meet-up groups, analytics for drop-out prediction, increased time flexibility, and so on. In general, we hypothesize that a strong investment in the quality of teaching will contribute to lower attrition; we want learners to feel that teachers are there to help them navigate difficult learning processes.

The rate of achievement is an even more important concern with credits when credits are accumulated in order to get degrees: if 50% of the learners pass the first MOOC, and among them 50% pass the second MOOC, only 25% of the original cohort are still on track towards a degree. Moreover, a degree usually covers higher-order learning outcomes that are rarely addressed in MOOCs, such as creativity, sense of rigour, critical analytic skills, skills of synthesis, reflection, ability to identify problems, social skills, and so on. We recommend research on MOOC activities that support the development of these high-level skills. Replacing exams by projects or even capstone projects are examples of such activities.

4.3 Universities' Role in Credit-Articulation Systems

Will universities retain their relative monopoly of issuing credits and certificates for advanced study, or will a broader variety of actors, such as professional or accreditation organisations, also decide to give credits? For example, in Europe, the European Credit Transfer and Accumulation System (ECTS) could regulate the development of the campus+MOOC academic landscape. Some open universities such as iVersity already offer ECTS credits for some MOOCs (https://iversity.org/pages/moocs-for-credit). In the USA, the American Council on Education has recommended a number of MOOCs for undergraduate credit, although each university ultimately decides which transfer credits it is willing to accept. The undergraduate-credit MOOCs are offered by Coursera, whose "Signature Track" option gives learners the option to undergo a series of identity-verification measures and take a proctored online exam after the course ends. If the accreditation ecosystem evolves in a natural way, the value of MOOC credits will depend upon the reputation of the institution that delivers them.

We expect that universities may take an incremental approach, initially offering credit for separate versions of MOOC material that serve a large, but not necessarily massive or open, population. For example, learners who sign up for "verified" enrollment, such as Coursera's Signature Track or edX Verified Certificates, might be put into separate discussion groups from the others. Similarly, some faculty are exercising their discretion as instructors, by allowing MOOC to informally satisfy one or more prerequisites for courses they teach, thus enabling students to jump more immediately into advanced courses; such bottom-up decision making may have influence on institutional policies. Should universities identify and tackle the obstacles to pursuing such scenarios? Reasons not to do so could include decreasing the educational value of residential credit, interfering with the schools' business model, or the need for a proctored follow-on activity on campus to weed out individuals who had cheated egregiously in the MOOC. On the positive side, such an activity would also be a way to build affinity to the brick-and-mortar university, which could be a net win for both the learner and the university.

5 Quality Criteria for MOOCs Should Be Developed

Although the question of quality of a MOOC should, in principle, be no different than the question of quality applied to any course produced by an educational provider, MOOCs have additional properties that make the question of MOOC quality unique. First, MOOCs are usually free or very low cost to the learner. Second, the massive scale has meant that the offering institutions have seen MOOCs as a vehicle for publicity and reputational enhancement as much as an educational device.

5.1 Dimensions of Quality Depend on Context and Actor

Several dimensions of quality depend largely on the MOOC's context, the perspective of a particular actor, or both. For example, one important element is the perception of the MOOC by enrolled learners, which is difficult to pin down as the learners are a heterogeneous group with varying expectations. The learners' perceptions are even more important if fees are associated with MOOCs. As another example, the MOOC style (cMOOC vs. xMOOC vs. blended learning) may determine whether greater emphasis is placed on learner cohort quality; for example, learners in a cMOOC might be more engaged than learners in an xMOOC.

Other dimensions of MOOC quality include the following:

1. Learning effectiveness, fulfilment of learning objectives
2. Engagement of learners
3. Professionalism of preparation and execution
4. Quality of the learner cohort

Note that (1) and (2) may be in conflict and may receive different emphasis from different groups. For instance, university administrators may want to emphasise retention and reputational outcome, leading to an emphasis on engagement and few challenges, while the MOOC creator may want to emphasise pedagogical integrity, which may push the learners beyond their comfort zone.

A particular quality risk with MOOCs is to focus on points (2) and (3) at the expense of point (1): that is, providing overpolished, entertaining video-material with expensive, professionally-animated graphics, while paying less attention to the actual learning objectives, which might or might not have been properly defined in the first place. In general, designers of MOOC courses and platforms should first think about the pedagogy of their course and after that worry about the technology that is required to implement their pedagogy. Pedagogy should drive technology and not vice versa.

5.2 Existing Quality Problems

Some current MOOC offerings have already grappled with problems that could be considered issues of quality, for example:

1. Video/content quality problems: poor presentation, poor or inappropriate material, poor quizzes
2. MOOC not based on any pedagogical underpinning
3. MOOC not clear or accurate about learning goals and outcomes
4. Technical problems: poor sound, unreadable slides, poor video quality or delivery, audio and video out of sync, learner-facing technology that collapses at large scale or is a poor fit to the teaching material

Most universities already have processes ensuring their traditional course offerings meet particular quality criteria, both for accreditation and to maintain internal standards. These processes should be extended to include MOOC offerings as well. Even if they do so, however, official certifying bodies, such as the Association for Computing Machinery, may want to certify course offerings as well. For example, the Quality Matters (QM) Program (http://qualitymatters.org) describes itself as "an international organization representing broad inter-institutional collaboration and a shared understanding of online course quality." A recent Gates Foundation program to fund MOOC development required the creators to self-evaluate their MOOCs using the QM rubric, which measures specific course properties (such as whether learning goals are clearly stated) rather than relying on learners' subjective appraisals of the MOOC. A summary of the initial results of this review [1] showed that while most supported MOOCs did fairly well in meeting the quality criteria, the most common areas of weakness were institutional responsibilities that are quite different in a MOOC than in a residential course, such as articulation of course support services and of policies regarding accessibility issues. As well, a challenge reported by many of the reviewers was the mixture of for-credit and non-for-credit learners in MOOCs – two cohorts with different sets of expectations. In Europe, metrics for assessing quality of online learning provision have been in existence for several years, and EFQUEL has recently extended theirs to encompass MOOCs (http://efquel.org).

6 Standards Should Be Developed for Measuring Participation in MOOCs

When governments, university administrators, instructors, learners, and the general public consider a MOOC, measures of participation are critical in their perceptions and attitudes about the MOOC's educational value. For example, when participation is measured in terms of number of videos watched and assessments taken, there appears to be large attrition over time with virtually all MOOCs to date, regardless of form or initial enrollment. Interpreted naïvely, these observations can be taken as a negative aspect of MOOCs, but such measures fail to consider the goals of the learner and other factors that might distinguish subpopulations with very different participation patterns. Participation measures will inform assessments of (a) individual people learning outcomes, which is perhaps primary. But through these assessments, participation measures will also inform assessment of (b) cohorts of learners; (c) resources, the utility of which depends in part on use of these resources, and the learner outcomes that result; (d) instructors, whose quality depends on the outcomes of courses they teach; and (e) the quality of the MOOCs themselves and higher-level administrative and educational structures. As yet, we know of no consensus, detailed inventory of variables for measuring participation in MOOCs, which could guide pedagogy, practice, and policy. There is important research to be done on defining measures of participation and other educational variables for MOOCs [6], studying the effect of these measures on the perceptions of different stakeholders, and on how best to obtain and protect the learner data needed for highly nuanced, conditionalized measures of participation.

6.1 Building Blocks for Deriving Participation Measures

A starting point for a more comprehensive picture of participation is measuring learners' actions regarding:

- MOOC resources, such as videos, assessments, readings and so on;
- assessments, both formative and summative, both attempted and completed;
- resource annotation, to include tagging video and textual sources;
- resource creation (common in connectionist MOOCs), such as video and text; and
- communications with the instructors, assistants, MOOC platform company, and with other learners.

These categories are not mutually exclusive: a discussion board post in response to another learner post is both a communication action and a resource annotation, where the initial post is a resource. Neither are these categories complete. Finally, each category includes many sub-categories, as with formative vs. summative assessment. A rich assessment inventory will almost certainly be hierarchically structured, with many categories and sub-categories, and with fine grained measures possible, if not desirable.

Importantly, within this rich set of variables will be *base variables*, which are nonnormalized and often continuous (for example, how many videos watched, total quiz score); and interpreted variables, which are often discrete, even binary, and convey value or judgement about a participant's activity in a MOOC (for example, pass/fail). Here, we are most interested in the possibilities for participation within a multidimensional space of base variables, with the understanding that interpreted variables can be introduced with thresholds that are particular to differing conditions, preferences, constraints, and goals.

While independent measurements of and correlational analysis between different variables enable important statistical relationships to be found – for example, correlating number of video hours watched with final course score – more causal interpretations can be aided by capturing *traces* of learner activities. A trace is a sequential or tree-based representation of a learner's activities, and enables analysis beyond pairwise associations (e. g., "`user1` read a post by `user2` directing them to `resource25`, and `user1` followed the recommendation"). By comparing learner traces, for example through graph clustering or inductive logic programming, more complicated patterns of activities can be found across a population of learners. While recording a learner's behavior as a vector of variable values is a popular representation in data mining generally, traces and other higher-order representations need to be developed and explored further, for example as in [11].

6.2 The Wealth of Conditioning Information

Participation patterns undoubtedly vary with many factors, and we should strive to capture, and explain variance on participation variables based on these many factors. Let us briefly consider the MOOC design, attributes of individual learners and learner cohorts, and time, as major categories of independent variables that will condition findings on MOOC participation. An important insight presented in [9] and elsewhere is that participation is a value or region in a rich and continuous multidimensional space.

MOOC Designs. Even today, there are several recognized kinds of MOOCs, e. g., xMOOC, cMOOC, iMOOC (implementing inquiry-based learning), to say nothing of the MOOC types that will emerge in the coming years. Rather than standardizing measures across diverse MOOC formats, harmonisation of measures that are best suited to the different types of MOOCs seems the better view. For example, resource creation by learners will be relevant measures of participation to some MOOCs. Some MOOCs will be inherently more social, with requirements for collaboration, whereas others will not. Some measure simply will not apply to every type of MOOC. Thus, measures will apply differentially across MOOCs, and garnering a comprehensive set of measures across current and future MOOC formats will be a challenge. We recommend a catalog of such measures, perhaps in wiki form, which can be open to the research and practitioner communities and easily linked to other sources. In addition to cataloging measures that may vary with format, there will hopefully be "canonical" measures that are independent of MOOC types, with the simplest of these being "time spent" by the learner on the MOOC (e. g., watching its videos, taking assessments, doing projects). While this is a simple measure to state, it may be very challenging to capture, because much of the time spent on a MOOC probably happens off the MOOC platform.

Learner Characteristics. Learner characteristics influence participation. Primary among these characteristics are the motivations that the learner has for taking a MOOC – does the learner intend to complete, or is the learner there to sample the content only? Related to completion versus sampling goals, but distinct, is the level of mastery that a learner hopes to achieve. If a learner wishes to complete a course, can we capture information on whether a learner returns to the MOOC after "dropping" it previously? In addition to being critical for a descriptive understanding of learner participation under many nuanced conditions, a rich characterization of learners will inform prescriptions (e. g., suggestions) of how learners might best work their way through MOOC material; who might be the best partners, peer reviewers, mentors, and instructors for learners in different contexts; thus influencing participation patterns actively through recommender and other help systems. In other words, the many affordances that we want to create for learners will drive the conditioning variables that will be measured.

Time and Other Continuous Dimensions. Although participation at a single point in time is of value, it is the detailed and real-time participation information that will be most relevant to both the educator and learner. These data can be used to improve the learner experience and inform MOOC design making it more responsive and adaptive. This is especially the case in identifying different user types amongst MOOC learners and potentially factoring this into the overall way the MOOC adapts to the different needs of individual learners and the groups they belong to. Thus, for each of the dependent and conditioning variables that we alluded to above, we will want measures over time, annotated by events that have predictive value. Attention to the time dimension also invites analysis using traces, which was mentioned above. For example, learner actions at one time point influence actions and outcomes at subsequent time points, all of which can be represented, processed, and compared by computational means. Time is a primary, but certainly not the only, continuous dimension for which various measures of participation will be continuous functions rather than simply point values!

6.3 Challenges in Assessing and Improving Participation

There are many challenges in defining participation, in obtaining data on participation, assessing it, reporting it, and eventually comparing participation analyses across MOOCs and MOOC-hosting platforms. A main challenge, described in the previous paragraphs, is the diversity of MOOCs and the diversity of types of participants. Another obvious challenge are privacy concerns that will stem from heavy instrumentation of MOOCs and MOOC platforms to collect data. The measurement of learner activity may become intrusive for learners concerned. What happens to participation measures if learners are required to agree to be measured? How do we safeguard unintended privacy leaks through the use of detail at this level? Despite these challenges, we believe important for our community to develop participation metrics.

Despite the challenges, a greater and more nuanced understanding of MOOC participation in light of many contextual factors (e. g., the subject matter of the MOOC, its duration and pace, lecturer, institutions and sponsors behind the MOOC, fees if any, transparency in students' data collection and use, and the availability of credits or certificates for completion) promises to increase benefits for learners, educators, institutions, and policy-makers.

7 Return on Investment in MOOCs is Heavily University-dependent

MOOCs require considerable investment of capital and human resources. Whether this investment will yield effective return is heavily dependent on each institution's situation and priorities; a corollary is that there is no single formula for computing return on investment or determining the point of diminishing returns.

Universities operate in different contexts and so the opportunities open to any single university may be different to those of others, due to differences in funding (fees vs. no fees), legal frameworks (whether online learning is recognised as legitimate higher education), competiveness of their student recruitment against other universities, and so on. Each university must assess its own possible ROI by balancing these constraints against the costs of developing and delivering MOOCs. A recent report [14] offers a rich set of interview-based perspectives on the costs and benefits of MOOCs as perceived and experienced by over 80 faculty, administrators, researchers, and other actors from over 60 institutions in North America, Europe, and China.

We survey possible outcomes for a university of offering MOOCs – that is, types of return they might hope to achieve – and then discuss benefits specific to research vs. teaching universities as well as possible negative returns on investment.

7.1 Potential Benefits and Pitfalls of Investing in MOOCs

Universities may pursue MOOCs to meet any of several goals, including:

- Contributing to the wider mission of universities to reach more potential learners for its education;
- Enhancing the university's reputation amongst key stakeholders, including politicians, peer universities, potential learners, and the media;
- Improved teaching efficiency by using MOOCs as part of courses for enrolled learners;
- Increased recruitment of learners to credit-bearing and fee-bearing courses;
- Raising the university's internationalisation profile by engaging learners worldwide;
- Raising the university's outreach to those socioeconomically or geographically unable to access residential higher education;
- Raising expectations for on-campus teaching;
- Training teachers and learners to work in this new medium, as well as teaching future professionals who need collaborative skills for lifelong learning.

However, MOOC investments are not without pitfalls. At universities that rely heavily on tuition income, the considerable expense of creating MOOCs may cut into other opportunities or contribute to a negative perception that students' tuition money is being "wasted" on giving away free content. Enrolled learners, trustees, and funding agencies with such perceptions may be indisposed to provide additional resources to these universities. The attractiveness of investing in MOOCs may also draw funds away from less innovative developments, and in particular from improving the quality of existing but deficient-quality courses.

For all open-ended investments such as MOOCs, where the number of investment opportunities is effectively unlimited, a very difficult decision will be to decide at what point the return on investment moves from positive to neutral or even to negative. Can the same return be obtained from 10 times or 100 times more MOOCs?

ROI can be improved if ways can be found to reduce the cost of production, and the same applies for MOOCs. Can these be produced more cheaply ("MOOC factory") or is the cost inevitably high due to the human skill and time required to design and execute?

7.2 Research Universities Versus Teaching Universities

For research universities, MOOCs offer research materials and settings for large scale research, with rapidly changing and evolving settings. Research grants can flow from this opportunity. As well, MOOCs can be a way of maximizing and accelerating the impact of research, and may become a routine part of grant proposals, thus incentivising universities to support their production as part of research efforts MOOCs may become CV items for professors and junior faculty giving them a direct, and very personal return on their investment of time and effort.

For example, at Vanderbilt University in the US, the Institute for Digital Learning provides matching support for faculty members to create a MOOC if that MOOC is part of the proposed strategy for disseminating research results, or is the major education component, in a successful research proposal to the National Science Foundation or other funding agencies, foundations, or industry sponsors.

Beyond research on pedagogy and learner engagement, numerous attractive opportunities for research about the wider effects and context of MOOCs are immediately evident. For example, researchers might:

- investigate of the effectiveness of MOOCs on outreach and access;
- analyse the economics of MOOCs at all stages (creation, delivery, re-use, cessation) and the value proposition of possible returns on investment in a variety of contexts;
- investigate the impact of MOOCs on "traditional" university education and develop measures of those impacts that can be used for comparative and longitudinal analyses;
- gather evidence from MOOC uses that can inform the effectiveness of policy implementations, both during policy formulation and also policy evaluation.

What about the incentives for teaching-centric universities that de-emphasize educational research? At these institutions, informal explorations of teaching innovations can still get the attention of others, and may lead to improved teaching with higher retention and pass rates. For example, in a widely reported experiment at California's San Jose State University, learners taking a blended format digital course using edX-provided materials scored 5 to 6 percentage points better on exams, and 91% of learners ultimately passed the course, compared with 59% of learners using the conventional format only. Of course, like research institutions, teaching institutions should accept that not every experiment will be equally successful: the same institution's attempt to provide remedial maths courses through Udacity was less successful [4].

7.3 How Policy-makers Can Help

MOOCs have potential benefits as well as potential pitfalls for both research-intensive and teaching-focused universities, and policy-makers can help in several ways:

- Be generally supportive of universities' efforts to develop MOOCs or reduce barriers to doing so where necessary, but with the understanding that bold experiments are both necessary and risky;
- As described in Section 4, reduce barriers to universities offering credit for MOOCs *should they wish to do so,* subject to normal quality assurance processes;
- Ensure that legal and compliance frameworks enable learners to use MOOCs for university entry and credit transfer, should universities wish to accept such credits;
- Ensure that universities within their jurisdiction share knowledge, expertise, and best practices, so that they may learn from each others' mistakes as well as their successes.

We caution policy-makers against mandating which options universities must pursue with respect to MOOCs, at least without a careful advance study of the complicated ecosystems in which universities operate, the variety of factors listed above both supporting and opposing investment in MOOCs, and the other dimensions of MOOC benefits and pitfalls discussed in this report. We similarly urge university leaders to take proactive roles in such discussions rather than abdicating this responsibility.

8 MOOCs Should Provide Universal Access

By 2014 the world is expected to have more mobile-device accounts than it has inhabitants [17]. It is therefore safe to assume that many learners will have them: user data from FutureLearn shows about 20% of access to its courses comes from mobile devices.

Techniques such as Responsive Web Design can help provide an optimal viewing experience across a variety of devices. However, more important are the new affordances of these emerging devices, such as smartwatches, smartbands, smartsensors, and so on. Besides offering "anytime, anywhere" access to learning materials such as podcasts and videos, mobile, wearable and ubiquitous technologies can link physical and virtual environments and support continuous learner engagement through notifications and instant messaging. In technology-enhanced learning, such devices can not only provide information access, but also produce or collect content and communicate with each other. We therefore see an opportunity to provide continuity in time and space to promote seamless learning, allowing online and technology-enhanced learning to "break free" of classroom constraints.

We consider three categories of potential benefits to MOOCs from mobile and ubiquitous computing: information access, production and collection of data by learners, and communication.

Information Access. Timely access to educational information is necessary no matter the learning type or pedagogical approach. The widespread and growing use of mobile technology to access learning materials means there is an imperative to provide access to learning materials on these devices. But there is no evidence that learning is enhanced by mobile access, so the design challenge is to enable ubiquitous access without impairing the learning experience.

Production and Collection of Data by Learners. There are several learning situations that are facilitated by mobile and ubiquitous technologies. In contextual learning and situated learning, different items of the context information can be retrieved, processed, communicated and shared by other learners. For example, the iSpot environment (http://ispotnature.org) enables learners to make observations of birds, animals, plants, and so on, sharing photos and initial identifications online. Then others in the community, including wildlife experts, provide additional information and a more accurate identification. Such learner-created materials can be especially important in MOOCs with large numbers of participants.

Mobile devices enable the teacher to organise active learning activities that rely on mobile devices, such as cultural outings, field trips, and excursions to meet local residents. For example, in a hypothetical MOOC on the Renaissance in Florence, learners in the online MOOC environment might be in contact with residents of the City of Florence, asking them questions or commissioning "localised investigations" such as photographing buildings or interviewing museum curators. In general, we can use the expertise of the crowd for powerful learning from differing perspectives and cultures. For example, in the FutureLearn course

"The Secret Power of Brands", participants from many countries brought their differing cultural and national perspectives to the discussions. Other possibilities include crowd-sociology, crowd-psychology, and crowd-demographics. Such situated learning can take place in inquiry-based learning, mastery learning, case-based learning, problem-based learning, and project-based learning, among other pedagogical approaches.

Communication. Mobile devices enable learners and other stakeholders to have continuous social interactions and to be continuously involved in their learning activity. Participants can receive notifications during commuting time, exchange short messages, stay abreast of the learning activities of their peers, and so on. Some classic pedagogies can be revisited with these affordances in mind; for example, spaced repetition, which is especially good for vocabulary language learning, could exploit mobile devices to deliver reinforcers at timed intervals.

New opportunities are possible in MOOCs from crowd learning, crowd sensing, crowd-sourcing, and crowd commissioning, all of which rely on data produced by "the masses." Crowd learning describes the process of learning from the expertise and opinions of others, shared through online social spaces, websites, and activities [16]. Crowd sensing is a new sensing paradigm based on various mobile devices, wearable devices, connected objects, and so on, using these devices' sensors for crowdsourced data creation and analysis that contribute to learning analytics with authentic data and situations. Crowdsourcing is a way to solicit needed services, ideas, or information from a large group of people. Crowd Commissioning commissions learners to do tasks according to learning goals.

MOOCs in different domains have already shown the promise of authentic data and situated learning to give the learner a continuous connection to a MOOC and to link virtual and physical spaces. The access and creation of authentic data by crowds can enhance the learning experience in MOOCs. These innovations, anchored firmly on a suitable pedagogical foundation, can provide sustained motivation and personal relevance for learners.

9 New Data Policies Should Be Collectively Negotiated

MOOCs generate vast amounts of data: data about the content of the course (videos, quizzes, exercises, slides, ...), data about the learners (clickstream data, answers to questions, discussion forums, ...) and data about the professor and his or her pedagogical team. This section is concerned with the last two points, i. e. user data. As with any user data collected by other online platforms, MOOCs raise serious concerns on possible breaches of the user's privacy. These are addressed in the first point. Nonetheless, these datasets do also constitute great opportunities. At the individual level, this data is necessary for adapting learning activities to individual needs. At the collective level, the data supports extracting knowledge about the effectiveness of the MOOC components, in order to improve the concerned MOOC or to acquire general pedagogical knowledge. These opportunities are emphasized in the second point.

9.1 Data Collection Transparency and Learner Privacy

Data privacy is a complex issue that cannot be fully developed here, but we cannot help but point out the current opacity of data in MOOC platforms. To know what is being recorded, users must read the "terms of service" document between the MOOC platform and the learner or between the MOOC platform and the universities providing courses. These are complex documents that few users have the stamina to read and that do not always clearly state what is being recorded. There are many reasons learners might care about the retention of their data. For example, a learner might be concerned if a potential employer could access that learner's performance data in a MOOC. Another concern is that a record of failure may reduce the teacher's expectations about a learner that consequently may adapt to these lower expectations by working less hard (the "Rosenthal effect").

We therefore propose a general principle: a learner's data belongs to the learner. According to this principle, learners should be able to easily access and visualize any data recorded about them, such as interaction traces. Learners should be able to share their data with others as well as analyze it themselves, with access to the same analysis tools that MOOC platforms or instructors use. And a learner should be allowed to delete any subset of her or his data: he or she will lose the advantages of having it analyzed, but that would be a personal choice.

This proposal can be compared with the medical field, where a patient's digital healthcare record contains highly sensitive data for which any breach in confidentiality may have medical, social, or economic consequences to the patient, such as stigmatisation or impact on health insurance. In most countries, patients' data are owned by the patients themselves, with legal instruments providing guarantees of security, reliability, and confidentiality. Patients may elect to share their data with medical personnel, and with informed prior consent, may choose to share their data for scientific purposes, such as participation in a clinical study. But informed consent in these cases is much more transparent than clicking the "I Accept" link at the end of a long list of conditions often written in impenetrable legal terms. And even patients who refuse to participate in the clinical study retain their right to the highest quality care. MOOC learners should enjoy a similar benefit: they should be the unique owners of their data, and should be able to opt-out of sharing their data without sacrificing the quality of their educational experience.

Finally, MOOCs can produce an unprecedented degree of transparency in teaching: the log files also contain data about the teachers or the teaching team, for instance, the average response time for forum postings. While this data constitutes a potential source of analytics that might contribute to quality management, labor unions may object to the direct use of such measurements of productivity and work quality. An alternative might be to monitor for problems related to resources for which the teacher is responsible, for example, ensuring that learner questions are always answered in a timely way and alerting the teacher when this is not the case. The teacher would then be evaluated on the effectiveness of the learner experience rather than on direct metrics such as number of hours spent online.

9.2 Sharing MOOC Data Across Institutions and Platforms

Currently, each university receives data associated with its own MOOCs. However, the research community would be very interested in the possibility of making data from MOOCs in some form available to all. Many scientific domains have benefited from becoming "data driven" once large datasets were made available. We therefore recommend active exploration of technological and legal frameworks under which MOOC data can be shared to support research.

One possibility would be that the terms of service include the possibility to provide data to non-profit educational institutions for research purposes. Such an agreement would need to be added to the contracts that universities have with MOOC providers. Some MOOC providers' terms of service already include a clause stipulating that learner data may be made available to researchers. There is still the potential for abuse, however: consider that most whales today are nominally killed for research purposes. Fortunately, most universities have an internal review boards, such as Committees for the Protection of Human Subjects, who could monitor for responsible data use.

Sharing data requires de-identification, a hard problem in computer science in both principle and practice, as Netflix and AOL discovered to their dismay when researchers were able to recover individual identities from supposedly anonymised datasets that those companies voluntarily provided for research. While it is easy to remove names from log files, the forum postings may include information that enables third parties to directly or indirectly (e. g. "a female chemist from Lausanne") identify the learner. While learners should be responsible for keeping confidential data out of public forums, users often cannot foresee all the ways in which their "public" information may lead to privacy leaks.

Some research and pedagogy requires learner identification. For instance, in a teacher training MOOC, a pre-service teacher would hardly be able to describe an example of classroom conflict without providing any confidential information. From an analytics point of view it is important that anonymisation maintains all data from the same learner associated to the same ID. This, in turn, would imply that user identity resolved from a forum posting would also allow for de-anonymising test results later on. We recommend both new research and new institutional policy exploration regarding the trade-offs between privacy concerns and the research and teaching benefits of data sharing.

One condition for sharing data across MOOCs and across platforms is that the context-specific meaning of collected should not be lost during that transfer. For example, MOOCs contain many different types of quizzes: some attention-enhancer quizzes simply check the understanding of the last video segment and can be answered in a few seconds, while other quizzes may propose several solutions to a complex problem that may require several hours of work. It would not make sense to compare the success rate of such two quizzes or to compute an average response rate across them. Sharing MOOC data will only be useful if the data is accompanied by a semantic description of what was collected, that is, what each piece of data meant in its original context. Such a description would also be necessary to address the ethical issues already raised.

Currently, universities negotiate one-by-one with MOOC platforms, which puts them in a rather weak position, despite the fact that they provide content that in has been developed over many years with their own (often public) funding. Universities and learners would be better served if universities could move towards a collective negotiation, perhaps even at a national level for countries that have specific privacy laws. We therefore recommend that associations of universities collect data privacy and data ownership concerns across their members institutions.

10 Research Questions

Today a MOOC is primarily organized around lectures by a university instructor; it is taught as an xMOOC in a traditional lecture-oriented format. One consequence is that MOOCs have a rather rigid structure and suffer from high drop-out rates. Future MOOCs should provide better learning experiences; they should be more enjoyable, adaptive, evaluable, accessible, usable by handicapped learners, aware of cultural diversity and ethical context, and so on.

These requirements create new research problems and new methods to address some of them. We briefly present some example research questions around these issues; this list is not meant to be exhaustive.

MOOC platforms should provide computer support for a large variety of pedagogical methods and should be accessible to the broad diversity of learners. This leads to two initial sets of research questions:

- **Better Support for Pedagogical Methods:**
  Responsive: more research is needed to give the learners more feedback, such as via machine grading or peer grading of exercises, and also to evaluate their success and deliver certificates.
  Adapting to the learner: in classroom pedagogy, there is little room for offering each learner a particular sequence of exercises adapted to his level and difficulties. With MOOCs, such adaptation becomes possible, but research is needed to understand which algorithms foster this adaptation.
  Enjoyable: children learn much by playing games; learning itself is also often an enjoyable activity. These observations suggest investigating how courses could be "gamified", or transformed into educational games.
  Pedagogy at scale: more generally, research is needed for new pedagogical approaches that are intrinsically designed to take advantage of scale. Pedagogical activities initially designed for small scale should be examined for the possibility of adapting to massive numbers of learners, and opportunities for novel scale-powered pedagogical activities, such as direct learner-to-learner communication, should be investigated.
- **Better Support for Learner Diversity:**
  Accessible: current MOOC platforms are difficult to use by deaf, blind, and other disabled learners. More research is needed to understand how to make them accessible.
  Usable by underserved learners: MOOCs have been presented as a possible way to improve literacy rates and school retention for underserved learners, but such MOOCs must use strategies, interfaces, and learning techniques appropriate for these specific learners.
  Aware of cultural diversity: offering courses in different languages is essential for offering education to everyone. Besides the diversity of languages, more research is needed to present the courses and the exercises in a way that is compatible with the different (academic) cultures.

The history of any science can be divided into two eras separated by the appearance of effective measuring instruments. Astronomy began with the naked eye but has had good instruments since Galileo's telescope. Biology has been instrumented since van Leeuwenhoek's microscope. Mathematics has been instrumented only since the middle of the 1970s, when a computer was used to help prove the four-color theorem. If the computer is the mathematician's telescope, the network may be the social scientist's telescope, as it affords the observation of social interaction on a large scale. This is particularly the case with pedagogy: MOOCs afford observation at large scale of how people teach, how they learn, and so on. Thus MOOC platforms can serve as a novel measuring instrument in pedagogy. On the other hand, access to detailed MOOCs data traces requires respecting the personal rights of learners and teachers. Research is needed on the ethics as well as the algorithms of evaluating the quality of a MOOC and measuring the activities of its learners:

- **Better Analytics of Course Data:**
  Evaluating quality: more research is needed to evaluate the quality of a MOOC: Besides the number of learners, the drop-out rate, and the reputation of the course, factors such as learning effectiveness, fulfilment of learning objectives, or the quality of the learners cohort must be investigated.
  Measuring learner activities: developing instrumented pedagogy requires improving learning analytics; for example, analyzing the data traces of the learners in order to understand and predict the progress of learners or to help teachers in planning supporting interventions and in improving the content of a course.
  Ethical: more research on the ethical use of MOOCs data is needed to understand which kind of information should be accessible to whom, focusing on the privacy issues related to the data produced by the learners. Besides defining goals, research is also needed to understand their implementation in MOOC platforms, requiring, for instance, the development of privacy models and methods to develop MOOC platforms so that privacy is enforced by design.

Finally, more research is needed to understand the societal and economic impact of MOOCs. Some interesting research questions include how to transform on-line communities into geographically confined ones, and what MOOC business models will balance the efforts of private industry and public services.

11 Conclusions

The invention of the printing press led to a technical-intellectual ecosystem consisting of print shops, skilled laborers, authors, editors, readers, publishers, and investors, motivated by both profit and intellectual pride [8]. The universities that successfully embraced this disruptive technology – Frankfurt, Paris, Strasbourg, Leiden, Venice – became the most influential of their time, as the ideas and writings of their faculty gained wide visibility.

Similarly, we believe modern universities must embrace the disruptive technology of MOOCs as vigorously as European Renaissance universities embraced printing to enhance and cement their intellectual leadership. Like the printing press, MOOCs provide not only new financial opportunities, but new ways to enhance reputation. They can help attract the best learners and faculty, provide them with modern learning environments, and in so doing, contribute to the success of both learners and institutions. These characteristics will make MOOCs an essential component of success and visibility in today's higher education. Universities wishing to retain their intellectual prominence ignore this technology at their peril.

Finally, we close with an observation. 2013 marked the 75th anniversary of xerography, the dry-photoimaging process that revolutionized business. In 1938, few believed that xerography would ever displace carbon paper, a time-tested and extremely inexpensive way of making multiple originals. As in many similar examples, they did not see that the fundamentally new ability to quickly copy *existing* documents would enable entirely new markets and practices that were literally inconceivable with carbon paper.

We similarly caution university leaders and policy-makers not to limit their appraisal of MOOCs to comparison with existing techniques only. New educational modalities, markets, and opportunities will arise that were previously inconceivable. Each university should be empowered to explore and seize the opportunities that seem most consistent with its institutional situation and goals, but with the realistic understanding that not every experiment will end in success, and that failures should be regarded as opportunities for learning rather than reasons to turn back.

12 Acknowledgments

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References

1 Deb Adair. QM for MOOCs: Results of QM reviews of Gates Foundation-funded MOOCs, September 2013.
2 Lorin W. Anderson, David R. Krathwohl, Peter W. Airasian, Kathleen A. Cruikshank, Richard E. Mayer, Paul R. Pintrich, James Raths, and Merlin C. Wittrock. *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives, Abridged Edition*. Pearson, 2000.
3 Benjamin Bloom. The 2 sigma problem: The search for methods of group instruction as effective as one-to-one tutoring. *Educational Researcher*, 13(6):4–16, 1984.
4 Catheryn Cheal. Creating MOOCs for college credit: SJSU's partnership with edX and Udacity (research bulletin). Technical report, EDUCAUSE Center for Analysis and Research, August 2013.
5 President's council of advisors on science and technology. Letter about MOOCs, December 2013.
6 Jennifer DeBoer, Andrew D. Ho, Glenda S. Stump, and Lori Breslow. Changing "course": Reconceptualizing educational variables for massive open online courses. *Educational Researcher*, 2014.
7 Stephen Downes. The personal network effect, November 2007.
8 Lucien Febvre and Henri-Jean Martin. *The Coming of the book: The Impact of Printing, 1450–1800*. Verso World History Series, 2010.
9 Douglas H. Fisher and Armando Fox, editors. *CCC-CRA Workshop on Multidisciplinary Research in Online Education (MROE)*, Washington, DC, February 2013. Computing Research Association.
10 Michael Gaebel. MOOCs – Massive Open Online Courses, an update of EUA's first paper (January 2013). EUA occasional papers, European University Association, January 2014.
11 Olivier L. Georgeon, Alain Mille, Thierry Bellet, Benoit Mathern, and Frank E. Ritter. Supporting activity modelling from activity traces. *Expert Sys: J. Knowl. Eng.*, 29(3):261–275, July 2012.
12 Stephen Haggard and co-authors. The maturing of the MOOC: Literature review of massive open online courses and other forms of online distance learning. BIS research paper number 130, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/240193/13-1173-maturing-of-the-mooc.pdf, Department for Business, Innovation and Skills (http://www.gov.uk/bis), September 2013.
13 John Hattie. *Visible Learning: A Synthesis of Over 800 Meta-Analyses Relating to Achievement*. Routledge, 2008.
14 Fiona M. Hollands and Devayani Tirthali. *MOOCs: Expectations and Reality*. Center for Benefit-Cost Studies of Education, Teachers College, Columbia University, New York, NY, May 2014.
15 Steven D. Krause and Charles Lowe, editors. *Invasion of the MOOCs: The Promises and Perils of Massive Open Online Courses*. Parlor Press; Anderson, South Carolina, 2014.
16 Mike Sharples, Patrick McAndrew, Martin Weller, Rebecca Ferguson, Elizabeth FitzGerald, Tony Hirst, and Mark Gaved. *Innovating Pedagogy 2013: Open University Innovation Report 2*. Institute of Educational Technology, The Open University, Milton Keynes, UK, 2013.
17 SiliconIndia Team. World to have more cell phone accounts than people by 2014. http://www.siliconindia.com/magazine_articles/World_to_have_more_cell_phone_accounts_than_people_by_2014-DASD767476836.html, Jan 2013.
18 UUK. Massive open online courses massive open online courses: Higher education's digital moment? Report, May 2013.

Manifesto from Dagstuhl Perspectives Workshop 12212

Co-Design of Systems and Applications for Exascale

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Abstract
The Dagstuhl Perspectives Workshop 12212 on "Co-Design of Systems and Applications for Exascale" is reaching into the future, where exascale systems with their capabilities provide new possibilities and challenges. The goal of the workshop has been to identify concrete barriers and obstacles, and to discuss ideas on how to overcome them. It is a common agreement that co-design across all layers, algorithms, applications, programming models, run-time systems, architectures, and infrastructures, will be required. The discussion between the experts identified a series of requirements on exascale co-design efforts, as well as concrete recommendations and open questions for future research.

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Executive Summary

The term "exascale" itself describes not only the performance of future systems in terms of "ExaFLOPS" (10^{18} Floating Point Operations Per Second), but instead covers all areas of High Performance Computing (HPC), starting from the fact that future systems will continue to scale up on all characteristics from todays leading supercomputers. Consequently, the endeveaour towards exascale computing faces challenges not only in fundamental, methodical aspects, but also practical aspects when operating these machines.

Correspondingly, the development and operation of exascale systems faces a series of different problems, starting from the concurrency and complexity of future systems, through reliability and corresponding resilience, towards power consumption and total cost of ownership. It is expected that future exascale systems will consist of hundreds of millions of processor cores and billions of parallel executable threads, which should work together as efficiently as possible for a wide range of scientific applications.

The joint vision of the experts participating in the workshop has therefore been described as follows:

> "To provide exascale capabilities to scientific and engineering applications."

The role of the experts and thus their mission is to "co-design systems, such that they reach exascale capabilities within the given technological and non-technical boundaries". The activity “co-design” itself can be defined as „two or more distinct activities collaborating on and across different layers to design a system architecture for a specific goal“.

On the way to exascale systems, co-design across all layers has been idenfitied as the most important approach. It requires collaboration of experts on exascale systems design and operation, and across all layers, from algorithms, applications, programming models, run-time systems, architectures and infrastructures. More specifically, the most important requirements for exascale co-design have been identified as follows:

Requirement 1: Co-design requires collaboration between tool developers, software developers and users to allow post-mortem analysis for tuning and online introspection.

Requirement 2: Co-design requires collaboration between the HPC computer architecture community and the realiability/resilience community to coordinate all levels of resiliency throughout the entire exascale stack.

Requirement 3: Co-design requires the joint development of computer center infrastructures, computer systems architecture, software, and application development.

Today, there are already a number of initiatives targeting each of these requirements, mostly in isolation. However, it might be necessary to address all or a large subset of the requirements together to enable exascale computing.

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1 Introduction

Ever since the beginning of computing, performance has been an important issue. Faster and faster computing has been the goal. Today, petascale computing is a reality, and the focus has shifted to the next barrier: exascale computing. With future systems even more powerful by orders of magnitude, new possibilities and challenges are approaching. This Dagstuhl workshop has addressed the many scientific, technological, and financial challenges of exascale-level computing with the hypothesis that exascale computing is only possible by co-designing across different levels of software, hardware, and the surrounding infrastructure.

The vision as derived during the workshop and based on the requirements of the scientific community is thus "to provide exascale capabilities to scientific and engineering applications", where it is important to notice that exascale means extreme scale or large scale, not the particular barrier of exaFLOPS performance looming ahead.

With this vision at hand, the participating experts identified their particular role and mission as follows: "to co-design systems such that they reach exascale capabilities within the given technological and non-technical (social,...) boundaries". While each expert has been knowledgeable on a distinct layer of the exascale architecture, the mission requires expertise combined across all layers (algorithms, applications, programming models, run-time systems, architectures and infrastructures). Exascale computing requires involvement from a number of different and even distinct areas of computer science in order to perform exascale co-design of hard- and software, including also different levels of software working closely together with hardware and the interfacing to the underlying infrastructure. This has lead to the definition of co-design, where two or more distinct activities collaborate on and across different layers of an exascale architecture to design a system for a specific goal.

In summary, the workshop has reflected on the current state of petascale machines providing multiple examples from world-leading machines and using them to derive the barriers on the road towards exascale computing. Looking beyond the current research into the future, where exascale computing will become feasible, the roadmap to exascale needs to be identified with intermediate goals and pitfalls, and leveraging the combined forces of computer science to overcome them.

2 Challenges and Requirements

The main challenges of exascale computing can be grouped into development, operation, application, and usage. An additional important challenge is the organization and training of user skills, which is of course included as a result of the above mentioned tasks. The requirements to effectively and efficiently use exascale systems in the area of computer architecture, systems software and application and algorithm design call for solutions potentially well beyond the observable scientific evolution.

At first glance, the lion's share of the discussed challenges seems to be not new, but instead well known for several years. In fact, some of these challenges are already solved for petascale systems. Nevertheless, there is a very special and new aspect of exascale systems that demands new solutions: all areas pass a certain limit of scale, whereby a new dimension of existing problems or entirely new problems are introduced.

Remark: It is important to note that "exascale" must not be confused with "exaFLOPS", because the latter focuses only on a very narrow aspect of HPC, i. e. number of operations per second, whereby "exascale" covers all areas of HPC. Hence, not only challenges while increasing floating point operations per second (FLOPS) should be analysed, but the challenges of all HPC areas, including for instance storage or interconnect. As a consequence, the challenges to consider range from fundamental, methodical aspects (like programming models) to very practical problems (like the number and size of log-files being produced on such machines).

2.1 Critical System Level Parameters

As mentioned in the International Exascale Software Project roadmap (IESP) [1] regarding the technology trends, the following three critical system level parameters have been defined, that relate directly to the development of exascale system architectures and their operation:

- Concurrency and complexity of the systems
- Reliability / resilience of the systems
- Power consumption and costs

Each of these aspects is described in more detail below.

2.1.1 Concurrency and complexity of the systems

Analyzing the development of the number of processors and functional units can be done with the systems listed on the TOP500 [2] supercomputers list. Already in 2012/2013, first systems with more than a million processor cores and in the order 10 millions of functional units have been brought into existence. By the time of the first implementation of an exascale computer architecture, systems with hundreds of millions of processor cores and billions of parallel executable threads must be expected.

These numbers indicate that solutions for system parameters such as reduced interconnectivity between processor cores and the development of new highly scalable algorithms and programming technologies are needed. Each of these parameters must not only be seen in isolation, but affects other parameters as well. For example, reduced interconnectivity of the architecture will require applications that are latency tolerant for communication and synchronization.

The expected complexity, heterogeneity, and failure behavior of exascale computer systems will introduce working conditions for the entire software stack, which will have to react appropriately to the behavior of the system's hardware. For each individual element of the exascale software stack as well as for the entire cooperation model of the stack, it will be necessary to develop new powerful tools to help software developers and the application users in mastering these complex systems.

Requirement 1. Co-design is required between tool developers, software developers, and users to allow post mortem analysis for tuning (required to obtain a maximum of performance) as well as online tools for introspection and direct links to adaptive runtime systems to support the decision making processes.

2.1.2 Reliability / Resilience of the systems

System dependability comprises several aspects, but within the workshop, we focused mainly on reliability, resilience, and logging. These three aspects face new challenges on exascale systems as described below.

Simplified, a component's reliability can be quantified by the "Mean Time Between Failures" (MTBF) and the total reliability of a system is evaluated as a combination of individual component values. Consequently, the aforementioned significant growth in component count results in correspondingly higher error rates. Due to the adding of system components (such as more cores, more memory, and more disks), the probability of failure increases proportionally to the number of components. This aspect is critical for exascale systems, since they comprise significant more components than todays petascale systems and hence, probability of failure is much higher. With current technologies, MTBF would be decreased down from hours to minutes or even less on exascale systems. Extrapolating system complexity from petascale systems predicts that the probability of failures will grow with at least three orders of magnitude.

Besides the new challenge of extreme scale in exascale systems, system's reliability is additionally faced with problems induced by power constraints. Smaller circuit sizes and lower voltages increase soft error vulnerability, for instance bit flips caused by thermal and voltage variations as well as radiation. Additionally, power management cycling as offered by a number of microprocessors already today decreases component lifetimes due to increased thermal and mechanical stresses. Summarizing, problems appear more often in terms of magnitude due to scale and power constraints. Therefore, reliability and resilience of exascale systems will not be realizable by common approaches. In fact, a number of additional problems is emerging.

Redundancy or checkpointing as applied on petascale systems is also not feasible due to scale, complexity and power constraints: redundancy means more running components (increases power consumption) and overhead (increases runtime and thereby again power consumption). Conducting root cause analysis by checking log files is nearly infeasible due to file sizes. The absence of strategies for silent data and code corruption will cause applications to produce erroneous results, hangups, or crashes.

Exascale systems and software will be of a complexity in hard- and software that has never been realized and tested before. Consequently, applications must be inherent fault tolerant, and this requires not only solutions for applications and algorithms, but also for the basic system software.

Future research and development in exascale systems resiliency requires that the results obtained for general purpose computer architectures regarding reliability and resiliency must be transferred and extended.

Requirement 2. Co-design between the HPC computer architecture community and the reliability/resilience communities is required to analyse how to coordinate all levels of resiliency throughout the entire exascale hard- and software stack.

2.1.3 Power consumption and costs

Since electric power consumption became a hot-topic within the last years, several approaches and improvements in order to lower energy consumption were developed. Examples include adaptive clock speed, low voltage technologies [3], and new cooling concepts such as hot-water colling in SuperMUC [4].

Nevertheless, with the cost of power increasing (often dramatically) in most parts of the world, the power budget for any high performance computing system will be limited. For this reason, DARPA suggested a maximum value of 25 MWatt for top-level supercomputers. Based on the electricity cost in most of the western countries, this figure would already represent costs well over 100 million US$ to cover the running period of 4–5 years. Yet, as shown in several analyses, scaling today's architectures to exascale will lead to power consumptions in dimensions ranging from hundreds of megawatts to over a gigawatt [5, 6]. This includes the electricity required for cooling and operating infrastructure.

As a consequence, the limitation for power is one of the most important barriers for the development of future supercomputers. In fact, there is an urgent need to decrease power consumption of today's petascale systems in order to gain more expertise and knowledge for lower energy consumption. Advances in the following areas are expected to contribute to the reduction of power consumption:

- Energy efficient computer architecture
- Energy efficient data center implementation
- Systems software supporting application programs in minimizing energy to solution
- Energy aware efficient algorithms making best use of hardware resources and specific power features

Despite the fact that there are selective and effective optimizations in each of the aforementioned areas, overall energy savings are still far behind the required levels. A reason for this stems from the lack of synchronisation of improvement and optimization efforts. For instance, scheduling algorithms cannot be optimal if applications do not provide all necessary information to the scheduler.

An important example emphasizing the urgent need to combine the above mentioned areas of research and development is the design of the computer center infrastructure itself, which must be taken into account similar as the other hard- and software factors [4].

Requirement 3. Co-design must be extended to the joint development of computer center infrastructures, computer systems architecture, software, and application development.

2.2 Applications of Co-Design

During co-design, two or more factors are optimized in concert to achieve better solutions. For exascale systems and applications, the performance and the requirements above define a multidimensional space of optimization. A number of important factors in co-design contributing to the optimization of performance, power and reliability are:

Algorithms: Multiple algorithms or mathematical techniques can be used for a calculation, and may exhibit different computational characteristics. For instance, using a uniform resolution of a data grid may lead to an implementation with regular memory and corresponding communication characteristics but with computation exceeding that of a more complex adaptive refinement implementation.

Applications: The application represents the implementation of a particular method and comprises a component of the overall workload of interest. Multiple applications may be used in concert to explore multiple aspects of a physical system, such as climate simulations considering land, sea, and atmospheric components in conjunction.

Programming Models: The programming model underlies the application and defines the way in which computation is expressed. Two common approaches are used for expressing parallelism: process-centric such as the Message Passing Interface (MPI) in which the inter-process communication is explicitly expressed, and data-centric in which access to any data across the system may occur from any location e. g. Global Arrays, Unified Parallel C (UPC), and Co-Array Fortran (CAF).

Runtime system: The runtime is responsible for ensuring that application requirements are dynamically satisfied and mapped onto the system resources. This includes process and data management and migration.

Architecture: This includes the micro-architecture of a processor-core, arrangement of cores within a chip, memory hierarchy, system interconnect, and storage subsystem. Advances in technology are continually allowing innovations.

Until today, no co-design process has covered all factors in a comprehensive fashion. However some notable cases have addressed a subset of factors and the corresponding tradeoffs. Several existing co-design experiences have been presented at the workshop, which resulted in improved performance, power efficiency, and reliability. An overview of observations is included below:

Optimization of "application to architecture": For a system architecture already implemented, this process requires mapping of application workload onto architecture characteristics. This process is commonplace in application development and software engineering and is not considered co-design.

Optimization of "architecture to application": Given applications that have already been implemented, the process here is to steer the design of the architecture so as to achieve high performance. Given that only one factor is optimized this is also not considered co-design.

Co-design for performance: Enabling application and architecture to best match each other unlocks the potential to achieve the highest performance on a new system. (This process has been illustrated at the workshop in a presentation describing the design of an application and of the first peta-flop system – the IBM Roadrunner machine.)

Co-design for energy efficiency: The energy consumed by extreme-scale systems will increasingly become a design constraint and notable cost factor – see above. Co-design for energy means designing an application to provide information on expected periods of idleness, and defining the runtime to lower overall power consumption.

Co-design for fault-tolerance: A critical factor in the operation of extreme-scale systems is the detection and handling of faults. Traditional methods using checkpoint-restart mechanisms do not scale well with future system sizes. Selective checkpointing methods, such as replicating only critical data across system memory, can be used to reconstruct state from failed nodes and enable job execution to continue.

Co-design is driven by modeling (or modeling is the tool of co-design).

The complexity of the aspects described above leads to the necessity of optimization to multiple criteria. This requires sophisticated modeling and simulation (modsim) methodologies and tools.[1]

3 Recommendations and Open Questions

The above discussed challenges and roadblocks on the way to enabling exascale systems are addressed with three necessary activities as identified during the Dagstuhl workshop:

- Application of co-design across all layers
- Simplification of HPC system usage
- Education of HPC users

[1] A significant area of emphasis in co-design continues to be related to modsim activities. Some of the important future directions along these lines have been mapped by the modsim community and available in the Report on the ASCR Workshop on Modeling and Simulation of Exascale Systems and Applications.

All three activities focus on strategic aspects and synergies of different fields. The Dagstuhl workshop participants agree that the three activities should be employed conjointly to facilitate development, operations, and usage of exascale systems. Guided by a common pattern, the following subsections describe the three activities: For each of them, the general findings are discussed in terms of concepts, thoughts, and involved technologies. Afterwards, a list of the most interesting and promising research questions is provided, which cover not only technical, but also economical and organizational aspects.

3.1 Application of Co-Design

Applying the co-design methodology was considered as the most important approach and as a vital element on the way to exascale systems. Co-design vehicles are required because there are several possible paths to exascale system with many associated design choices along the way. The main objective is to bring different aspects together, and to develop a common solution, where aspects can (positively) influence each other. Because of its generality, the definition of co-design can be used within different topics as well as spanning several topics, e. g., co-design of software and tools, or co-design of hardware and software. Additionally, it is not restrained to realms, but it can cope with different timelines, teams, and organizational aspects.

In fact, the definition of co-design raises a double-edged sword: On the one hand, all aspects, topics, and realms can be covered. On the other hand, the severe question of trade-offs between generality, performance, and costs arises. Hence, the first open research question is:

On which aspects, topics, and realms should co-design be applied to optimize the trade-off between generality, performance, and costs?

The following, non-exhaustive list outlines a few possible combinations for the application of the co-design methodology:

- Performance, power, reliability – co-design of capabilities
- Applications, hardware, software – co-design of disciplines
- Algorithms, software, hardware, applications – co-design of disciplines and domains
- Applications, software-stack/execution-stack – co-design of domains and paradigms
- Teams – co-design of people

After having selected the elements for the application of co-design, the next group of questions investigates how to bring the selected elements together, especially in terms of synchronisation and interfaces. An exemplary question in the realm of co-design of disciplines would be as follows:

How can the short life cycle of hardware be synchronized with the relatively long life cycle of software?

Again, a lot of possible follow-up questions are generated on the realm of co-design of paradigms, in particular of the software stack and performance monitoring. A non-exhaustive list of possible questions is as follows:

- What is the right kind of interface for performance introspection?
- What kind of data flows between the layers?

- What kind of monitoring, first-person or third-person, is more suitable, and how can both approaches be integrated?
- How can system monitoring be included in an overall approach?
- What part of the software stack is missing for exascale?
- How can application developers be encouraged to adopt exascale and corresponding technologies?
- Which metrics other than performance are needed on exascale systems, e. g. energy consumption?
- Which abstractions and layered design approaches are convenient, keeping in mind their costs in performance?

Bringing all these questions into context leads to a group of research questions that can be summarized as follows:

How to co-design two different elements of an exascale system?

The above described group of research questions introduces one very special situation, which is considered here separately because it heavily involves psychology, social, and organizational science:

What to do with partners, who contribute fundamental elements to the co-design process, but are not willing to comply with the policies and restrictions of the co-design process?

Clearly, this issue jeopardizes the overall co-design benefits, and it is crucial to investigate solutions. An example for this situation, which became prominent within the last years, is the involvement of HPC hardware vendors and the issue of not influencing the hardware part of HPC systems through science.

After dealing with strategic aspects of co-design, the last group of research questions focuses on the concrete (technical) operations of co-design methodology, e. g., "What kind of tools are missing and how to make them work?". This group of research questions can be summarized as follows:

How to support the application of the co-design methodology operationally?

All these research questions will need to be addressed in order to enable exascale computing. The Dagstuhl workshop initiated many discussion and established a basis for further investigations on the way to exascale.

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References

1 Jack Dongarra, Pete Beckman, Terry Moore, Patrick Aerts, Giovanni Aloisio, Jean-Claude Andre, David Barkai, Jean-Yves Berthou, Taisuke Boku, Bertrand Braunschweig, Franck Cappello, Barbara Chapman, Xuebin Chi, Alok Choudhary, Sudip Dosanjh, Thom Dunning, Sandro Fiore, Al Geist, Bill Gropp, Robert Harrison, Mark Hereld, Michael Heroux, Adolfy Hoisie, Koh Hotta, Zhong Jin, Yutaka Ishikawa, Fred Johnson, Sanjay Kale, Richard Kenway, David Keyes, Bill Kramer, Jesus Labarta, Alain Lichnewsky, Thomas Lippert, Bob Lucas, Barney Maccabe, Satoshi Matsuoka, Paul Messina, Peter Michielse, Bernd Mohr, Matthias S. Mueller, Wolfgang E. Nagel, Hiroshi Nakashima, Michael E Papka, Dan Reed, Mitsuhisa Sato, Ed Seidel, John Shalf, David Skinner, Marc Snir, Thomas Sterling, Rick Stevens, Fred Streitz, Bob Sugar, Shinji Sumimoto, William Tang, John Taylor, Rajeev Thakur, Anne Trefethen, Mateo Valero, Aad van der Steen, Jeffrey Vetter, Peg Williams, Robert Wisniewski, and Kathy Yelick. *The International Exascale Software Roadmap*. International Journal of High Performance Computer Applications, 25(1):3–60, 2011. DOI: 10.1177/1094342010391989

2 http://www.top500.org

3 Ram K. Krishnamurthy and Himanshu Kaul. *Ultra-Low Voltage Technologies for Energy-Efficient Special-Purpose Hardware Accelerators*. Intel Technology Journal, 13(4):100–117, 2009.

4 Ludger Palm. *LRZ awarded German Data Centre Prize*. Inside – Innovatives Supercomputing in Deutschland, 10(1), 2012. http://inside.hlrs.de/_old/htm/Edition_01_12/article_04.html

5 David Jensen and Arun Rodrigues. *Embedded Systems and Exascale Computing*. Computing in Science Engineering, 12(6):20–29, 2010. DOI: 10.1109/MCSE.2010.95

6 Daniel A. Hitchcock and Lucy Nowell. *Advanced Architectures and Critical Technologies for Exascale Computing*, U.S. Department of Energy – Office of Science – Office of Advanced Scientific Computing Research, Program Announcement to DOE National Laboratories LAB 10-255, 2010. http://science.energy.gov/~/media/grants/pdf/lab-announcements/2010/LAB_10-255.pdf

7 Darren J. Kerbyson, Abhinav Vishnu, Kevin J. Barker and Adolfy Hoisie. *Codesign Challenges for Exascale Systems: Performance, Power, and Reliability*. Computer, 44(11):37–43, 2011. DOI: 10.1109/MC.2011.298

8 Adolfy Hoisie, Darren Kerbyson, Robert Lucas, Arun Rodrigues, John Shalf, Jefffrey Vetter, William Harrod, and Sonia R. Sachs. *Report on the ASCR Workshop on Modeling and Simulation of Exascale Systems and Applications*. U.S. Department of Energy – Office of Science, 2012. http://science.energy.gov/~/media/ascr/pdf/program-documents/docs/ModSim_Report-2012_AH_5.pdf