Cloud Computing: Developing Contemporary Computer Science Curriculum for a Cloud-First Future

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ABSTRACT

Cloud Computing adoption has seen significant growth over the last five years. It offers a diverse range of scalable and redundant service deployment models, including Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), Software-as-a-Service (SaaS), and Containers-as-a-Service (CaaS). These models are applied to areas such as IoT, Cyber-Physical Systems, Social Media, Data Science, Media Streaming, Ecommerce, and Health Informatics. The growth in cloud presents challenges for companies to source cloud expertise to support their business, particularly small and medium-sized enterprises with limited resources. The UK Government recently published the *Digital Skills Crisis* report, identifying skill-set challenges facing industry, with a shortage in cloud skills negatively impacting business. While cloud technologies have evolved at significant pace, the development of Computer Science curriculum in the further and higher education sector has lagged behind. The challenges faced in the sector includes the training of educators, institutional gaps (software and hardware policies), regulatory constraints, and access to cloud platforms. By embedding fundamental cloud skills throughout the educator and student journey, both stakeholders will be better positioned to understand and practically apply the use of appropriate cloud services, and produce graduates to support the needs of industry. This working group has carried out work to: i) assess current cloud computing curricula in CS and similar programs, ii) document industry needs for in-demand cloud skills, iii) identify issues and gaps around cloud curriculum uptake, and iv) develop solutions to meet the skill demands on core Cloud Computing topics, technical skills exercises, and modules for integration with contemporary Computer Science curricula.

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CCS CONCEPTS

• **Social and professional topics** → **CS1**; • **Computer systems organization** → *Cloud computing*;

KEYWORDS

Cloud Computing, Education, Computer Science, Curriculum Development, Distributed Computing

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1 WORKING GROUP OBJECTIVES AND INTRODUCTION

Cloud Computing is commonly referred to as service models such as PaaS, IaaS, and SaaS, offered as pay-as-you-go utility computing

[6]. These service models are rapidly being adopted by companies to ease the burden on traditional on-premises hardware and software, as well as quickly enabling scaling and redundancy through the elasticity of compute resources. This working group (WG) aims to identify areas of Cloud Computing that are in demand by relevant industry sectors [46, 64], and develop contemporary Higher Education (HE) curriculum that supports addressing these needs. The foci of interest in the context of HE institutions are Computer Science degree programs, and how relevant cloud skills can be instilled in graduates moving into industry, benefiting their career opportunities, as well as supporting industry needs. The UK Government recently published the report *Digital Skills Crisis* [12] identifying key skill-set challenges facing industry, with a shortage of cloud-based skills negatively impacting business and competitiveness, and the wider economy. Recent academic work investigates the impact cloud resource adoption has on corporate growth [59], with findings indicating when a business creates key competencies and skill-sets in cloud integration, the result is increased competitiveness. Cloud is viewed as a key development area for many small businesses and can facilitate a competitive edge [68], though the challenges associated with migrating digital services can be a risk to business continuity, and the drivers for migrations are not necessarily the same as those of larger organizations [34, 43].

Cloud Computing has also been identified as one of the nine Industry 4.0 (ID 4.0) digital technology pillars and enablers that are transforming industry for the next wave of digital innovation [7, 46, 64, 65, 71]. In a 2017 report, the World Economic Forum identified a global market $ 100 trillion opportunity for both industry and society through the adoption of these technologies [22]. The Internet of Things (IoT) is an example of an emergent technology pillar that relies on supporting cloud services [62], such as IoT hubs and analytics for scale and redundancy. Where digital technologies have a requirement for scalability, redundancy, and performance for compute and storage, the underlying enabler is commonly cloud resources. In order to develop and grow economies across the ID 4.0 pillars, cloud skills must be a priority area to develop industry workforce skills.

A shortage of cloud skills is not exclusively a UK phenomena. A recent global research survey was conducted in collaboration with academics and industry, designed to collect data from IT decision makers on the business impact of the technical cloud skills shortage. The survey received over 950 global responses, from organizations with over 1,000 employees, with key findings of the survey indicating organizations are losing revenue due to a cloud expertise deficiency, and a shortage of cloud expertise is holding businesses back [73]. It can be assumed that the deficiency in cloud skills can at least in part be attributed to a lack of skilled graduates coming through the employment pipeline. Promisingly, in the UK at least, there is a government-led drive to develop shorter degree-apprenticeship programmes that aim to address key skills shortages over the short term [11]. Such programmes are designed for employees to undertake block study release over at least two years whilst still playing a key role in their place of employment. The main benefit is that employees receive training and education to degree level standard and can instantly take those skills back into the workplace, whereas with traditional degree programmes students will not be part of the workforce for the three to four years of study required to obtain their traditional route degree. The degree apprenticeship in the UK is also driven by an enforced apprenticeship 'levy', where businesses with a pay threshold over a specified amount pay into the fund, which they can then draw from to develop their own degree-apprenticeship programmes [27].

With the focus of this WG on understanding cloud industry skills needs, and academic curricula development to support these needs, the work presented in this report is designed for educators to quickly ramp up the delivery of cloud curricula as part of established or planned courses and programs. For example, an educator can select the most relevant Knowledge Area (KA) and Learning Objectives (LO) that are pertinent to their course needs, with a list of the KAs and LOs produced as part of this work available in Section 5.

The authors of this WG are comprised of academics and industry leaders with Cloud expertise, and significant experience in developing cloud content for delivery in further and higher education sectors. Four main areas of work have been investigated as part of the WG: i) current cloud curricula in HE, ii) industry skills in demand, iii) gaps in curricula, and iv) proposed skills, exercises and modules to meet gaps. These areas will now be presented as a summary overview before discussing in more detail.

1.1 Educational Goals for Cloud Computing Curricula in CS, CIS, IT, and Similar Programs

1.1.1 *Current Cloud Curricula in Higher Education.*

- Objective: Understand the current state of cloud-curriculum from a sample of Higher Education institutions across different regions

In order to understand the current uptake of Cloud Computing at the degree level, and to some extent the granular module units of degree programs, a survey will be undertaken across at least two distinct regions, targeting the United States and at least two countries in the European Union. This will provide the WG with a meaningful snapshot of Cloud Computing exposure for undergraduate and postgraduate students, and an understanding of specific areas of cloud currently being taught. The survey will also yield data on HE institutions who currently do not offer core cloud content as part of their Computer Science program portfolio, presenting an opportunity for collaboration in the deployment of new cloud curricula generated as part of the WG objectives.

1.1.2 *Industry Skills in Demand.*

- Objective: Identify key cloud skills gap in industry for supporting business processes

A significant number of businesses, particularly SMEs, who offer digital services will require in-house expertise of cloud resources in order to remain competitive. A sustainable pipeline of qualified graduates is key to this, and would further support addressing the issue of skills-shortage 'Salary Inflation', where smaller companies simply cannot compete on salaries in the employment market for in-demand skills such as cloud. Given the general cloud skills gap identified (see introduction), a WG objective will be to explore this further to understand what the key industry areas are where cloud skills are in short supply. Further to this, the objective will explore how curricula can be developed to meet industry demand, whilst ensuring students have the opportunity, in the first instance, to learn the fundamental theory and concepts of cloud computing, with specialization and/or certification coming afterward. Finally, a key component will be understanding best practices for faculty and industry engagement - a vital link for reacting to emergent areas/needs for adoption into programs.

1.1.3 Gaps in Curricula.

- Objective: Identify internal and external facing issues in the uptake of cloud-based curriculum in HE institutions

Issues around the uptake of cloud curriculum in CS-focused degree programs can be classed as either internal or external facing. Internal issues can be identified as a lack of resource in terms of educator expertise and skills. Another internal factor is that programs are validated with a specific set of learning objectives, this is problematic for enabling a timely response for industry needs. The WG will explore the potential efficacy of low-barrier certification as part of academic programmes, presented as value-add using extra-curricular approaches, effectively dealing with the issue of set program outcomes that are time constrained for modifications. External issues include appropriate and continuous access to a suitable cloud vendor to support the practical application of cloud concepts. The main cloud vendors such as Google Cloud Platform, Microsoft Azure, and Amazon Web Services currently offer limited, free educator and student access in order to support the delivery of cloud curricula. This WG aims to initiate a dialogue with the aforementioned cloud vendors with a specific focus on moving toward an open-source cloud platform standardization approach. This approach could be enabled by providing full-stack implementations based on existing open-source cloud platforms (e.g., OpenStack) as envisioned both in industry and in academia [18, 20, 40]. Such an approach would provide an understanding of potential platform solutions for longer-term cloud adoption in HE institutions.

1.1.4 Proposed Skills, Exercises and Modules to Meet Gaps.

- Objective: Develop accessible, industry-informed cloud curriculum

The aim is to develop a modular learning framework comprised of suitably themed KAs and LOs, with learning objectives underpinned by fundamental Cloud Computing concepts and theory that are applicable to all major cloud vendors and open-source cloud platforms (e.g., OpenStack), and further supported by academic research. This approach would produce modular pathways, facilitating specialization to support industry needs. An additional part of this objective would be to initiate discussion on how the use of contemporary and future clouds would differ in the future to support enhanced Machine Learning and Artificial Intelligence infrastructures.

2 CURRENT CLOUD CURRICULA IN HIGHER EDUCATION

The section discusses the findings of a survey to support the framing of the WG in moving forward, specifically in understanding the current state of cloud-curriculum from a sample of Higher Education institutions across different regions.

In order to widen the capture of data to understand the current uptake of Cloud Computing in further education and above institutions, the survey was designed for global participation. The survey results provided the WG with a meaningful snapshot of Cloud Computing exposure for college undergraduate and postgraduate students, and an understanding of specific areas of cloud currently being taught. The survey also yielded data from institutions who currently do not offer core cloud content as part of their Computer Science program portfolio, presenting an opportunity for collaboration in the deployment of new cloud curricula generated as part of the WG objective findings.

2.1 Cloud Survey Design

The objective of the survey was to assess the current scope of adoption of cloud computing in computer science and related programs at various types of higher education institutions in different geographic regions. The survey was motivated by the fact that despite plenty of anecdotal evidence, there is only a handful of published reports documenting the process of adopting cloud computing in the curriculum. On the other hand, there are a number of large scale surveys reporting on the adoption of cloud computing in higher education [1, 8, 29]. These reports, however, focus exclusively on adoption of cloud-enabled services in technical areas supporting the educational process, such as enrolment management systems, learning management systems, email and office suites, etc.

The survey design focused on collecting information from educators in computer science and related fields focusing on the below constructs.

Institutional construct:

- Geographic location.
- Institution type.

Technology construct:

- Cloud platform used.
- Party who is paying for the services consumed.

Adoption construct:

- Scope of adoption.
- List of courses that have adopted a cloud platform.
- Date of first offering.
- Number of students enrolled.
- Delivery modality of course.

Content/program construct:

- Primary technologies/skills being taught.
- Professional certifications offered.

Dissemination construct:

- Relevant website(s) with amplifying information.
- Willingness to make materials open source.
- Whether individual has any publications describing their experience with adopting cloud computing in the curriculum.

2.2 Cloud Survey Results

The survey was distributed via a diverse range of channels between April and July 2018.

Distribution channels included a SIGCSE mailing list with approximately 1300 recipients, a mailing list for computer science educators, a Google+ community for Google Cloud Platform Educational Grants recipients with approximately 600 members, and a Jisc mailing list. Jisc (formerly the Joint Information Systems Committee) is a UK non-profit supporting tertiary education.

The survey was also shared with education departments at major cloud service providers. The working group has not received feedback as to what degree the survey has been disseminated within or beyond the recipients.

By August 4th 2018, a total of 50 individuals provided responses to the survey.

Geographic distribution:

- USA: 25
- UK: 8
- Other Europe: 6
- Canada: 2
- South America: 1
- Asia: 7
- Other: 2

Institution types:

- 20 (40%) PhD granting institutions
- 10 (20%) MS granting institutions
- 17 (34%) BS/BA granting institutions
- 3 (6%) Hybrid or Other type of Institution

Platforms (multiple options allowed):

- 19 (38%) Amazon
- 29 (58%) Google
- 20 (40%) Microsoft
- 5 (10%) OpenStack

Scope (multiple options allowed):

- 38 (76%) Assignments/labs/projects
- 20 (40%) Standalone course
- 5 (10%) Certificate program
- 16 (32%) Undergraduate or graduate program

Date of adoption:

- 2010: 1
- 2012: 1
- 2013: 5
- 2014: 4
- 2015: 3
- 2016: 10
- 2017: 12
- 2018: 13
- 2019: 1 (planned)

Delivery mode (multiple options allowed):

- 35 (75%) face-to-face
- 4 (9%) online
- 7 (15%) blended/hybrid

Professional certifications:

- 38 (86%) none offered/required
- 2 Amazon
- 2 Microsoft

Who pays:

- 14 (30%) free tier
- 21 (44%) educational grant from the cloud vendor
- 9 (19%) institution
- 6 (8.4%) other

2.3 Survey Discussion

Although the scope of our survey was limited, it identified a number of interesting trends.

A significant number of respondents (44%) take advantage of the grant programs offered by the cloud providers to facilitate using their services in various educational offerings. At the same time, 30% of educators indicated that they prefer to use the free tier, which, depending on the provider, limits the scope of cloud platform features available to the users.

By far, the most popular (76%) reported venue for introducing cloud computing techniques is through a standalone assignment or a project. This appears as a logical first step to take for any educator to ease the way for adding cloud computing into the curriculum. However, it would be a disservice to the students if their exposure to cloud computing was limited at that. 40% of respondents indicated that they offer a standalone course on cloud computing with 32% offering an undergraduate or graduate program and 10% offering a certificate (note that respondents were allowed to select more than one response to this question).

According to the information available from the National Center for Education Statistics, there are a total of 1848 institutions of higher education classified as Baccalaureate, Master's, or Doctoral institutions in the United States using the Carnegie Classification of Institutions of Higher Education [48]. Out of these, 41.13% are primarily BS/BA-granting, 40.8% are MS-granting, and 18.07% are PhD-granting institutions. Our survey reflected the data gathered from the global audience reaching far beyond the confines of the United States, which makes it difficult to directly compare these percentages with those reflecting cloud adoption among different types of institutions throughout the rest of the world.

Interestingly, the adopters of cloud computing technologies are concentrated either in PhD-granting institutions (40%) or BS/BA-granting institutions (34%). Only 20% of responders who said that they have adopted cloud computing in their curriculum were from MS-granting institutions, with the remaining respondents identifying their institutions as "other." This could be indicative that institutions with a lot of resources (including technical support staff), such as PhD-granting institutions, are more adept at adopting the cloud because they can attract faculty with the relevant expertise and hire technical support staff to offer system administration services.

Survey respondents mentioned a broad range of courses that include cloud computing coverage at their institutions. The most frequently mentioned courses included Big Data and Data Science, Computer Security and related courses, Internet/Web Development, Artificial Intelligence and Machine Learning, Mobile Computing, and Parallel Computing. A standalone course on cloud computing was mentioned by all respondents whose institutions offered a cloud computing degree program or certificate.

According to results we received from our survey, a typical standalone course on cloud computing includes the following topics:

- The paradigm of cloud computing: its fundamentals, evolution, applicability, benefits and challenges.

- Principles of cloud management techniques and cloud software deployment.
- Compute, network, and storage virtualization techniques.
- Cloud storage and distributed file systems.
- Cloud computing programming models.

Additionally, a number of standalone cloud computing courses included the following topics:

- Networking fundamentals and protocols.
- Cloud-enabled artificial and machine intelligence applications.
- Computer security, privacy, and policy compliance issues.
- DevOps in cloud computing, including continuous integration, continuous delivery, and continuous monitoring tools.

3 IDENTIFYING CLOUD SKILLS IN DEMAND

Findings presented in this section were a result of carrying out the WG objective described in section 1.1.2, to identify key cloud skills gap in industry for supporting business processes. Identifying cloud industry skills currently in demand, and those projected to be supportive of growth areas, was informed by Industry 4.0 (ID 4.0) research and industry development work [7, 35, 45, 64, 65, 71]. The opportunities provided by future, untapped ID 4.0 technology areas will be key to the improvement of UK (and global) industrial productivity, however the current UK workforce is not well equipped to meet the challenge, particularly in technology areas such as Cloud [12]. The discussion presented has a primary focus on the UK, however as stated ID 4.0 is a global concern with rapid adoption evident in the US, Europe, and Asia [64].

3.1 Cloud Computing and Industry

To maximize the potential for industrial digitalization in the context of Cloud, awareness and capability will have to be fostered and developed through providing further and higher education graduates with the advanced skills necessary to support business growth and market competitiveness. In manufacturing and engineering for example, industrial digitalization is thought to be driving ID 4.0 technology embodied through the identification of nine technology 'pillars' such as Industrial Internet (sensors), Autonomous Robots, Big Data, and the Cloud [64] as shown in figure 1. For many of the nine pillars of ID 4.0, cloud-based platforms act as the primary enabling technologies. Industrial digitalization also has huge potential for driving productivity and improving outcomes in other areas such as food production and supply-chain, with cloud-driven IoT technologies as the technical enablers [42]. In the aforementioned industry areas, the cloud is a common supporting enabler for both Small-Medium Enterprises (SMEs) and large organizations.

The Made Smarter Review (Oct 2017) [46], commissioned under the UK Government Industrial Strategy, has concluded that the potential value to the UK economy of digitalization over the next 10 years could boost UK manufacturing by £455 bn. As such, the importance of developing cloud curricula that are informed by significant industry requirements is critical for a nation's digitalization strategy. Such strategies would ensure there is a pool of graduates with the required skill-sets. In summary the cloud can be viewed as an enabling suite of technologies that are threaded throughout ID 4.0 technology pillars.

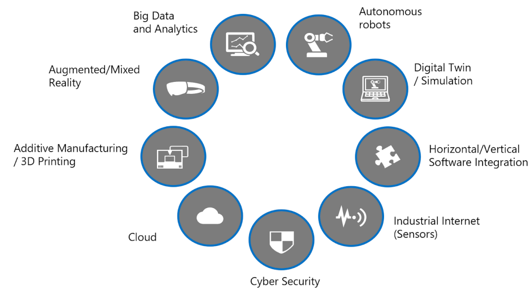

Figure 1: The nine ID 4.0 technology pillars

Cloud in industry will continue to be a highly disruptive force, reshaping applications and datacenter and computing architectures, transforming the way IT uses resources, and how services and applications are created and managed. For the next generation of Information Technology (IT) professionals and developers, education institutions will need to recognize the opportunities created by cloud. Institutions who recognize the importance of cloud to their students and raise awareness, training and exposure to the services will position themselves at the intersection of the new trends and their business requirements, providing students with industry opportunities. Graduates who can clearly demonstrate proficiencies in cloud will have more influence in activities relevant during cloud deployment and expansion projects, and therefore be ultimately more recruitable. In addition to student academic programs, industry certification also plays a role in recruitment.

The industry white paper *Cloud Skills and Organizational Influence: How Cloud Skills Are Accelerating the Careers of IT Professionals* [19] provides evidence that IT professionals with professional certifications related to cloud development and operations have dramatically more influence over their organization's adoption and expansion of cloud services than IT professionals without relevant certifications. IT professionals with more than three relevant certifications have 5.5 times more influence during initial deployment of cloud services than IT professionals without cloud related certifications. This highlights the value of certification when making technical decisions that impact business. In another industry white paper that ran a survey, almost half (48%) of the respondents said they would expect to pay more for personal resources with relevant cloud certifications [2]. In the same report, UK organizations who were surveyed stated that Cloud Skills are critical to transformational success: more than 80% of respondents thought that having the right cloud skills will be important or critical to their digital transformation.

In summary, academic institutions face significant challenges in preparing their graduates to meet the needs of industry, particularly in the context of ID 4.0 technology areas.

3.2 Identifying Core Technologies for Cloud Skills

A significant number of businesses, particularly SMEs, who offer digital services will require in-house expertise of cloud resources as part of the value chains of their market areas to remain competitive. These cloud resources can be robustly framed in the context of the primary technology pillars identified in the previously discussed ID 4.0 literature, where they are interwoven as technology enablers. For the purposes of this work, figure 2 presents an extrapolated view of the original nine ID 4.0 pillars reconfigured to six, suitable for inclusion as topical curricula headings. For each technology, a sample of the supporting cloud services that are currently available are identified. Addressing the future need and capacity of ID 4.0

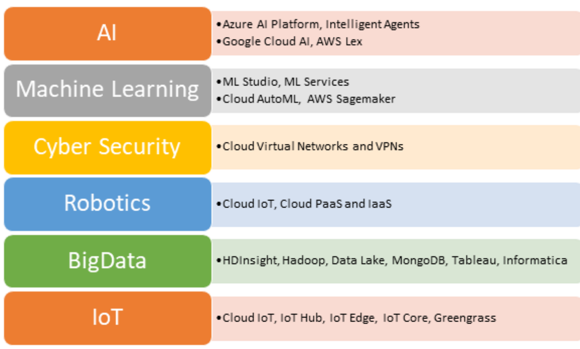

Figure 2: ID 4.0 Pillars with supporting cloud service examples

technology pillars is challenging, and demands strategies at a national level, one of which is providing students of FE/HE institutions with opportunities to learn cloud skills that can be readily applied when they move into industry. A sustainable pipeline of qualified graduates is key to supporting an ID 4.0 strategy, and would further support addressing the issue of skills-shortage 'Salary Inflation', where smaller companies find it challenging to be competitive in the job market for in-demand cloud skills. Given the ID 4.0 technology pillars identified and the significant pace of growth, it is important for educational institutions to design and map their cloud curricula to these pillars to better align with industry needs.

3.3 Case Studies for Demand in Cloud

Two short case studies will now be outlined that help to frame and underpin the importance of cloud curricula development from a small and large scale perspective.

3.3.1 Cloud Computing and the SME Perspective. An SME in the electro-mechanical lock industry had the goal of innovating around the emergent market area of cloud-connected smart locking systems [24], a relatively untapped space with significant growth potential in the IoT space. The company was well established in providing hardened mechanical lock systems for several decades for critical infrastructure deployments and utilities, and made the decision to explore the space of cloud-connected locking systems with a view to entering new deployment scenarios. An experienced web developer was currently employed to support basic auditing systems of lock systems and was tasked with exploring cloud and IoT systems. Quickly realizing the significant expertise required the company went to market with limited resources in terms of salary to source cloud expertise. Unfortunately the role proved challenging to fill in the salary range, as well as a shortage of cloud skill-sets in the company's geographical area. An alternative strategy was pursued, involving the adoption of a Knowledge Transfer Partnership (KTP) [69], where the company was supported financially as well as provided with expertise from a University (termed the Knowledge Base Partner) in the same region as the company. The KTP approach allowed the company to tap into expertise at the university and facilitated the design and development of cloud infrastructure to a production ready state, resulting in a commercially viable solution. A graduate from the knowledge base university was also employed at the company, taking with them cloud computing skills learned whilst at the knowledge base partner university.

In this case study example it is clear that universities can play a significant supporting role for SMEs with limited resources and expertise, particularly at a local level and where skills such as cloud are in short supply. Without this support, the SME in this instance would not have been able to innovate and take their envisaged product forward to the market. This supporting role could either be in the form of a knowledge base partner or consultancy, or through providing a pipeline of talent through graduates. The key here is cloud curricula is integrated and well established with the university, with SMEs in the local area fully informed of the skillsets generated at the university.

3.3.2 Cloud Computing and the Large Organization Perspective. Many large institutions have commercial aims to migrate current services [73] or develop new ones, in order to improve their market competitiveness. In this case study, a large organization (UK University) had the goal of migrating their backup services for Virtual Machine image snapshots (400 distinct operating system instances), as well as SQL server mirroring for a hybrid on-premises/cloud approach. Automation was a critical part of this using shell scripts to manage digital service infrastructure such as large scale backups. The organization went to the employment market to recruit two cloud developers and failed to attract interest from suitable candidates with the required skill-sets. This could be attributed to a number of reasons, the skills shortage in this space and the competitiveness of the salary offered. The structure of the organization's pay bands did not accommodate salaries for developer roles that surpass that of senior roles, with the average cloud developer salary in this instance higher than the organizational pay structures allowed. Another consideration in this respect was contracted consultancy, which would be at significant cost, with the expertise gone when the contract ends.

Similar to the previous SME case study in 3.3.1, attention was turned to CS students at the university who were about to graduate. After discussions between academics and IT staff within the organization, it was identified that students had the skill-sets that met the job requirements and suitable candidates were recruited.

3.4 Curriculum Design and Implementation

Rapid advances in cloud computing and related technologies have made incorporating cloud into an existing curriculum a challenging task. Moreover, contemporary approaches to CS education in HE institutions, as well as the emerging Computational Thinking movement in K12 education worldwide have been challenging educators, particularly in their efforts to ensure students acquire relevant knowledge and skills in the cloud space.

One core reason for the challenges is the extent of cloud-related concepts, and the plethora of choices to implement among cloud tools and technologies. Another reason may simply be stated as the overall reluctance of instructors to complete steep learning curve(s) in tackling the use of many tools on modern cloud infrastructure; not to mention the rapid evolution of such tools and requirement to keep skills refreshed.

The classical instructional approach to 'start from a rough set of curricular content, and then work on the same content as the student feedback is received after each semester is complete' does not really work for cloud curricula, because each semester typically brings multiple changes in the field. These changes may be due to mere competition among providers, improvements on design and implementation, new concepts implemented as additional offerings, or retiring certain product offerings. At the very least, even when there are no changes in existing cloud tools and technologies, both command-line and graphical interfaces (CLI, and GUI, respectively) get updated frequently. It is very common for cloud-related instructional materials, particularly the visual ones, to become obsolete by the next academic term, if not in the middle of the current term. There are also very few good cloud textbooks because of these issues and many faculty members want to teach their courses with a textbook.

Thus, cloud curricula implementers have to tackle this reality by fundamentally changing their approach that they might employ within other courses. Traditional lecture content may be less successful for cloud concepts. Instead, students should be encouraged to explore and experiment through practical activities. A practical approach would explore the core cloud knowledge areas in Section 5 that students should be aware of. In fact, cloud computing is fundamentally suited to incorporating active learning exercises into curriculum design, an approach that is well received by students, who achieve higher education ranks having already acquired a variety of STEM skills in high-school if not in earlier grades. In other words, current students starting higher education, are ready to learn cloud computing concepts using active learning early in their studies; however, most academic programmes do not necessarily reciprocate and facilitate such opportunities.

3.5 Cloud Affordances

Adopting the cloud in university-level courses enables a multitude of affordances from geographical reach, scale, and consistency to the methods of delivery. The global availability of cloud services widens the reach of a course. Cloud-enabled offerings increase the scale in terms of the number of students who can participate in a course, the number of, and size of datasets and resources in a particular project. Furthermore, adopting the cloud provides a level of consistency in its service offerings, which in turn enables an enhanced level of technology adoption in learning, compared to varying performance of on-premises and student-provided resources.

Further, the cloud can be tied into an educational technology tool, which enables several pedagogical models. Blended, flipped, remote and distance learning, among others, use technology to combine in-class and out-of-class learning, maximizing the educational impact for residential and remote students as a result. This approach breaks the 'one-size-fits-all' model by taking education beyond the physical classroom and allowing students to learn anytime, anywhere, and more importantly at their own pace. This is extremely important in realizing not all students learn the same content in the same amount of time.

Almost all cloud-based pedagogical methods can be seen as natural extensions to the novel online / group collaboration movement that followed Berners-Lee's Web 2.0 envisioning [10]. Service-oriented approaches enable fast creation of user-generated content, ease of use, and interoperability (of interacting web services) for end users. This early vision was immediately followed by disruptive implementations of many modern technological tools, that include popular sites for social networking, video sharing, hosted services, and collaborative consumption [9], as well as both classical and hybrid web applications (i.e., mashups [75]).

One main methodology is expanding the collaboration space from single service-based offerings, that are typically limited to the implementation of a particular learning management system (LMS) to a much larger scale, with references from a staging/summary page (such as a Syllabus, or a main page) on LMS. In addition to using the LMS as a glue for incorporating active learning exercises, many instructors have also opted to use a simple web page as the starting point, with course outline and links to relevant cloud-based tools as well as LMS content as separate links from that web page.

Instructors typically utilize one or more of the following approaches:

- Incorporating cloud computing tools and technologies as active learning exercises as external modules into an LMS.
- Providing educational materials (documents, videos, excerpts, and so on) for students to follow outside classroom.
- Providing external references to specialized labs (QwikLabs, codelabs, etc.) to enhance learning experiences with tutorials.
- Using cloud-based scientific computational environments (e.g., Project Jupyter) as a scientific mashup.

Additionally, other third-party cloud services are commonly used as stand-alone tools for the following:

- Communication (e.g., Slack, Remind.com).
- Collaboration ('Suite' applications, e.g., GSuite and Office365).
- Student Engagement (e.g., FlipGrid, Menti, Kahoot!).
- Mashups (e.g., cloud-based customized geolocation/mapping).
- Micro-dataflows (e.g., IFTTT, Google Firebase).

3.6 Cloud Educational Resources and Certifications

There are numerous educational resources available from cloud providers and cloud communities, including various tutorials and other documentation for educators to gather materials for presenting entire courses, starting with introductory fundamentals, all the way up to advanced development and deployment of complex cloud orchestration. In addition, there are professional certification levels offered by many providers. We highlight several specific examples in this section to provide the reader with a good starting point and frame of reference, but this is by no means an exhaustive or complete list. New material is frequently published.

3.6.1 Platform Documentation. All cloud platforms have online documentation available. Documentation often includes tutorials, samples, quick starts, and labs that can be used in classes. Some of the more commonly found specific vendor sites include:

- AWS [66]
- Azure [52]
- Google Cloud Platform [31]
- IBM [38]
- Oracle [17]

3.6.2 Specific Academic Resources. There are many offerings in this space to choose from. We highlight a few to get the reader started in this area.

Microsoft provides a portfolio of lesson plans and lab exercises to introduce students and educators to cloud computing concepts from the perspective of their Azure platform. Educators interested in exploring Microsoft Azure can get a good solid introduction on the following Github resources [56]. This repository provides technical resources to help students and faculty learn about Azure and teach others. The content covers cross-platform scenarios in artificial intelligence and machine learning, data science, web development, mobile application development, Internet of Things, and DevOps.

For those interested in learning more about Google Cloud Platform (GCP) and how to get started, Google has a site dedicated to educational resources at the Higher Ed Learning Center [30]. For those interested in jumping right into GCP, one can take advantage of "quick starts" and sample projects at the Google getting started guides [33]. IBM Cloud Education offers courses and demonstrations at IBM Developer Community [39]. The Global Environment for Network Innovations (GENI) [28] offers test beds and tutorials. Amazon Web Services (AWS) Educate [5] provides an eco-system which they brand as "Teach Tomorrow's Cloud Workforce Today".

3.6.3 Specialized labs. In addition to labs contained in documentation, many of the cloud providers have sets of labs that cover materials in their platforms. Qwiklabs [63] includes labs for AWS and GCP. GCP also has additional labs available at Google Codelabs [32]. Microsoft offers a number of online training resources including the Microsoft Professional Program [58] and Microsoft Virtual Academy [55].

3.6.4 Online Courses. Many of the online course providers such as Coursera, EdX, and Udacity have courses on cloud computing including vendor specific training [51]. There are also some sites such as Cognitive Class [16], IoT Schools [50], and AI Schools [49] that provide courses specific to cloud topics.

3.6.5 Non-vendor sites. Sites such as YouTube have a wide variety of videos focused on many of the cloud providers. In addition, videos from many of the conferences such as AWS Re:Invent, Microsoft Ignite, and Google Cloud Next are available. Cloud topics are often asked about on sites such as Stack Overflow, but care should be taken with these since the high rate of change in cloud technologies means that many answers may be out of date.

3.6.6 User Communities. Some of the cloud providers have communities of users so faculty can discuss best practices with their peers. These include the GCP Edu Grants Google+ community and Microsoft Faculty programs.

3.6.7 Workshops and Conferences. Some cloud providers offer conferences and workshops about their products. These may be in-person or on-line and may be for all audiences or for academic audiences only. There are also many opportunities for professional training. While some of these opportunities are free, others may have academic discounts. Interested faculty should look for more details with the particular providers. Some of the events that may be useful include:

- AWS Events and Seminars [66]
- GCP offerings include major general audience conferences (Google I/O and Google Cloud Next), Cloud OnAir, a group of general online events [74], and the Google Cloud Faculty Institute.
- Microsoft has a number of fixed conferences which take place throughout the year; these include large conferences such as Build, Ignite, Faculty Summit, and online events [53].

3.6.8 Case Studies. Numerous case studies have been written about experiences using the cloud in classes, such as those in [21, 51, 67] and resources made available to utilise [57].

3.6.9 Certifications. Professional certifications provide a parallel path to classroom learning. By achieving a certification from one of the major cloud technology organizations, students will obtain a transferable credential to compete in the job market. Even if faculty do not want to have their students ultimately take a certification exam, there are typically many useful materials and clear pathways provided as part of the certification. A number of case studies have been generated around higher education using certification to support students, with examples of Microsoft and Cisco certifications, some of which cover cloud fundamentals [15, 61].

3.6.10 Student Ambassador Programs. Some cloud providers have programs that will pay students to help other students and faculty with adoption of their platform. These students can often help faculty with their classes. These programs include:

- Google Cloud Platform Student Innovators [70]
- Microsoft Student Partners [54]

3.7 Cloud Textbooks

As Cloud Computing is a fast moving area with platforms continously evolving, it is challenging for educators to be able to deliver courses from textbooks alone. However, textbooks can play a role in supporting the delivery of concepts and underlying theory, though for practical application it is preferred to source the latest material from official vendor documentation. Academics frequently have to update their cloud learning materials each academic year to deal with the expected cloud vendor platform revisions. The cloud computing textbooks presented in this section may be of use to educators as supporting materials.

- Cloud Computing,*Concepts, Technology & Architecture* [25]: This is a platform-agnostic textbook that approaches cloud-related concepts from a theoretical perspective, and provides basic, generalized use-cases for each.
- Distributed and Cloud Computing, *From Parallel Processing to the Internet of Things* [37]: Presented as a comprehensive guide to cover convergence of distributed computing to cloud

computing, virtualization, and grid computing, the textbook provides some early case studies from Amazon, Google, and Microsoft, and explains how to use virtualization to facilitate core cloud tasks. The textbook includes chapter by chapter exercises and further reading, following a classical textbook approach.

- Cloud Computing, *Theory and Practice* [47]: As a general reference source, this book provides an overview of cloud computing with delivery models and ethical issues, and also in select chapters it provides in-depth examples of use-cases.
- Mastering Cloud Computing, *Foundations and Applications Programming* [13]: Focused on programming aspects of cloud computing, this book provides fundamentals of application development for the cloud. It provides a categorization of concepts related to cloud computing and then focuses on several hands-on examples on how to implement basic programming interfaces for cloud-based services.
- Cloud Computing for Science and Engineering [26]: This is one of the most recent textbooks by two leading cloud researchers, and aims to make cloud computing options comprehensible for hands-on scientists and students. It covers introductory concepts but takes it to the next level and provides examples with Jupyter notebooks, with practical guide(s) to some of the services provided by popular cloud vendors, including Amazon, Google, and Microsoft.

4 CONSIDERATIONS FOR ADOPTING CLOUD CURRICULA

In addition to pedagogical issues of how to incorporate cloud into the curriculum, there are numerous other items to be considered for adopting cloud computing. The most obvious consideration is which cloud provider(s) to use. In addition, there are other important factors to consider such as faculty expertise, university policies on requiring students to have credit cards or accounts with external service, university restrictions on changing curriculum, and university IT restrictions on Internet access. Perhaps most importantly are data privacy issues, such as meeting the General Data Protection Regulation (GDPR) if based in the EU [23] and additional security concerns [41]. This section begins by examining issues to consider in selecting a cloud provider. It then covers security, privacy and ethical concerns.

4.1 Cloud Platform Access

One main consideration in adopting cloud curricula is access to vendor-specific platforms. For a cloud course to move beyond the theoretical and into practical application for real-world deployments, access to a cloud vendor platform is a core requirement [44]. Technology is constantly changing in the cloud paradigm [72] and the need to use available cloud platforms is an important aspect of enhancing a course from a theoretical position to a practical position providing significant learning experience to students. This section discusses the issues that should be considered in selecting a cloud provider.

All of the major cloud vendors as well as most publicly-funded cloud testbeds have educational programs for students and classes. Details of these programs change frequently, so readers should check the most current details at the URLs below:

- AWS: https://aws.amazon.com/education/awseducate
- Azure: https://azure.microsoft.com/en-us/education
- GCP: http://cloud.google.com/edu
- IBM: https://developer.ibm.com/academic/docs/cloud-offer
- Oracle: https://cloud.oracle.com/home
- Openstack: https://www.openstack.org
- VMware: https://www.vmware.com
- Heroku: https://www.heroku.com/students
- ChameleonCloud: https://www.chameleoncloud.org
- CloudLab: https://cloudlab.us
- Geni: http://www.geni.net
- Federation for Fire: https://www.fed4fire.eu
- PlanetLab: https://www.planet-lab.org
- Alibaba Cloud https://www.alibabacloud.com/
- DigitalOcean https://www.digitalocean.com/

As faculty become more familiar with cloud computing, they may decide to use multiple cloud providers in their classes to increase focus on concepts instead of just mechanics, much in the same way as most programs use more than one programming language.

4.1.1 Industrial vs. Academic Cloud. In considering cloud resource providers there are industrial cloud providers and academic cloud solutions that can be used to meet the needs of cloud classes. Academic solutions are more limited than commercial solutions but are often easier to access and have fewer limitations than industrial solutions. For example, doing many cyber-security exercises may be considered abuse and a breach of vendor Terms of Service (ToS) on industrial solutions, but may be permitted on academic ones in sandboxed environments.

4.1.2 Limitations on Student Usage. All cloud providers limit student access to the cloud in some way. This may be as simple as limiting the amount of credit provided or may be as restrictive as permitting very limited access to particular tools or resources. Questions to consider about limits to student usage include:

- How is the student usage limited?
- Some programs only provide time-limited access to labs such as Qwiklabs [63]. In this case, students can get experience using the tool, but cannot do any classwork since the accounts are deleted soon after students complete the lab.
- Some programs provide a credit value to use their cloud platform. This may be allocated per class or per student.
- Some programs provide credits to individual students whereas others provide them directly to the faculty to share with their students.
- Is student access to tools limited to a "free" or "student" tier or are all tools available?
- In some cases, students are limited to a subset of tools (or a free tier). Faculty should ensure the tools available to students will be sufficient for their classes.
- What happens when the student exceeds the limit?

4.1.3 Billing and Monitoring. Billing, monitoring, and the need to provide financial information are significant concerns for educators and students. These areas are important to fully understand, as well as the potential implications which can impact on the student experience. Some questions to consider include:

- Does a student or educator need to provide the cloud provider with credit card information to get access?
- Does credit get issued to the student individually or the institution?
- How can faculty and students see the current amount of credit available and the usage details?

4.1.4 Accounts. Account creation is a concern for both faculty and students. Managing multiple accounts is sometimes troubling and can lead to confusion. Some typical questions might include:

- What account will students use to access the cloud platform?
- Are they forced to sign up for another account or can they use an existing institutional account?
- What happens if an account is suspended or closed?
- Are there warnings and notification of credit usage to educators and students?

4.1.5 Longevity. Instructional courses are built and typically updated yearly or even at longer intervals. If a course is built around vendor cloud resources there is significant concern on how long the vendor cloud program will last. Additionally, credits provided to students often come with an expiration date. Some questions might include:

- Is there any information available about the continuation of the cloud provider's academic program?
- How can students backup and migrate their work after the course or graduation?
- For how long will credits be usable?

4.1.6 Support. Technical support is a significant concern with academic organizations. Institutions have limited resources in many cases. Some questions might include:

- Who provides technical support for issues a student might encounter?
- Is there access to training resources, support forums, or documentation?

4.1.7 Location and Connectivity. Location may be an important factor in whether faculty can use vendor cloud resources. Some programs are not available in every country. In some cases Internet access may be a concern. Some questions might include:

- Are cloud credits available for the program's geographic location?
- Will limited bandwidth connection impact services?
- Are the cloud services you require available within your region?
- Does your campus need a direct connection to a cloud provider such as Azure Express Route?
- Does the cloud provider have a way to remove or reduce ingress and egress cloud costs for large data transfers?

4.2 Security, Privacy, and Ethics

Security, Privacy, and Ethics are significant concerns in the cloud computing paradigm today. When considering the selection of cloud computing resources it is imperative to identify and understand security risks, privacy concerns, and the ethics of utilizing cloud resources [3, 4]. There are two aspects faculty should consider while looking at this section. First, faculty using cloud resources should instil security concepts into cloud course curricula to ensure students are aware of risks and issues that are contained within the cloud computing paradigm. Security is an essential aspect of cloud computing [36]. Second, faculty should consider all necessary security issues when selecting and using cloud resources in the application of cloud computing concepts. Some issues to consider include the type and storage of data used in application exercises, access to personal data (faculty and student), and inter/intra network configuration and connections (as necessary). Security of information is a necessary consideration when selecting a cloud resource provider [14]. From a privacy and ethics perspective, faculty should consider access to data, abuse of the cloud resource system (from either faculty or students) or abuse from third-party vendors. Some questions and important points that might need to be considered will now be discussed.

4.2.1 Privacy and Ethics. Privacy and ethics are a serious concern in cloud computing. Many academic institutions must comply with numerous laws and regulations regarding privacy protection of student generated and owned data, the latest and most important being the EU's GDPR [23]. Some relevant considerations might include:

- Can students use single sign-on for accessing cloud resources using institutional credentials?
- Some faculty might use specific protected data for research or as part of a project; who has access to that data being used in the cloud resources?
- Who has overall access to student content/projects?
- Who owns the content?
- Academics need to see students data and utilisation.
- Legal rights to be forgotten/ anonymity at national and international levels.
- Monitoring of student cloud resource use.
- Students breaching spending/credit limits.
- Instill best practices for shutting down VMs etc.
- GDPR and student account access and provisioning issues.
- Are students or faculty required to provide personal information to use cloud resources?

Additionally, both faculty and students should consider ethics implications in what can be accepted in value or usage of resources outside the original scope of the assessment work or research to be undertaken, and the processes involved in seeking appropriate approval.

4.2.2 Security. Security is a high priority in cloud computing. Security of both faculty and student information is of most importance for compliance in laws and regulations at regional, national and international levels. Some typical questions or aspects might include:

- What happens if a student account is compromised?
- How are account settings handled to meet security needs and requirements?
- How is the students data protected?
- Identify appropriate network and resource configurations and settings.

- Appropriate authentication and non repudiation requirements or needs to mitigate threats.
- Identify appropriate student account and provisioning needs.
- Will the mandatory security, privacy, and ethical legal requirements be met for all relevant stakeholders?

4.3 Adoption Summary

In summary, there are many cloud vendors that offer educational programs that facilitate access to cloud resources for faculty and students. A list of vendors is presented earlier in this section. It should be noted that the level of access to cloud resources will vary between vendors, as such it is important that a suitable platform is chosen that will meet the needs of the course to be supported.

Additionally, data privacy and security cannot be secondary when selecting a cloud vendor, and should be considered from the outset when any faculty or student data will be used on cloud platforms. The consequences of a security breach with the integrity of user data compromised could have GDPR implications, with the institution potentially being banned from processing user data if mandatory, regulatory policies are not adhered to.

5 PROPOSED KNOWLEDGE AREAS AND LEARNING OBJECTIVES

When the working group began its in-person work, there was extensive discussion about what aspects of cloud computing needed to be covered. A list of topics was created and the group realized that depending on the class being taught, there were vastly different subjects that should be covered. These topics were converted to the format of Learning Objectives (LOs) and grouped into Knowledge Areas (KAs) following the format of ACM Computer Science Curricula 2013 [60]. The complete list of KAs is presented below:

- Fundamental Cloud Concepts (FCC)
- Computing Abstractions on the Cloud (CAC)
- Storage Resources on the Cloud (SRC)
- Networking Resources on the Cloud (NRC)
- Cloud Elasticity and Scalability (CES)
- Fault Tolerance, Resilience and Reliability (FTRR)
- Cloud Deployment, Monitoring and Maintenance (CDMM)
- Cloud Orchestration (CO)
- Software Development using Cloud APIs (SDCA)
- Cloud Programming Models and Frameworks (CPMF)
- Service Oriented Architecture (SOA)
- Cloud Security, Privacy, Policy and Ethics (CSPPE)
- IoT, Mobile, Edge and the Cloud (IoTMEC)
- Cloud-based Artificial Intelligence and Machine Learning (CAIML)

Because the generated LOs come from so many different globally situated schools and represent so many different classes, it is not intended that a single program must include all KAs. Instead, they should serve as advice for faculty who teach courses covering these areas about how cloud topics can be included in existing classes. Of course, a cloud-specific class can be built out of a combination of these KAs, based on the ultimate goals of the course.

5.1 Fundamental Cloud Concepts - FCC

Cloud Computing has gained significant momentum in the last five years and is regarded as a paradigm shift away from traditional 'silo' based computing. Students have already had significant exposure to using the cloud through products like social media, email, remote storage, and online games even though they may not recognize that these items use cloud resources.

This KA introduces the fundamental concepts and gives a general overview of the cloud. Students will learn the specific advantages and disadvantages of the cloud over on-premises resources. Students will be exposed to the business model of the cloud, including examination of the true cost of on-premises resources. Students will also be introduced to the different layers in the cloud stack and examples of different cloud stacks. Students will analyze several case studies of companies that use the different layers of cloud stacks to meet their business requirements.

5.1.1 *Learning Objectives.*

- Define the cloud computing concept, its history and motivation.
- Computing Abstractions on the Cloud - CAC.
- Name widely-used cloud-based systems and explain the advantages of having the system on the cloud.
- Define virtualization of computing, storage, and networking resources.
- Explain the differences between leasing versus ownership of compute resources and compare the total cost of ownership.
- Discuss some of the advantages and disadvantages of the cloud paradigm when compared to on-premises resources.
- Discuss the implications of utilizing on-premises versus off-premises compute resources.
- Articulate the economic benefits as well as issues/risks of the cloud paradigm for both cloud providers and users.
- Compare and contrast the types of cloud service models.
- Define service level objectives, agreements and their implications on migrating a solution to a cloud service provider.
- Enumerate and explain various threats in cloud security.
- Analyze a case study about a cloud-based system.
- Demonstrate creating a VM, and provisioning it with compute, memory and storage options. Demonstrate starting, stopping and deleting a VM instance.
- Recognize existing VM templates provided on a particular cloud infrastructure.
- Explain alternative methods of interacting with provisioned resources (e.g., CLI, GUI, API). Browse, identify, and access resources through a GUI and the CLI.
- Create and format virtual storage units.
- Demonstrate attaching virtual storage units to VM instances.
- Copy data from local storage to the cloud.

5.2 Computing Abstractions on the Cloud - CAC

In this KA students will explore different encapsulation mechanisms to abstract computing resources on the cloud. They will compare the capabilities, limitations and overhead of utilizing virtual machines, containers and container clusters, as well as serverless offerings.

Further, students will experiment with and understand the potential advantages and cost of utilizing specialized hardware offerings on the cloud such as GPUs, FPGAs and TPUs.

5.2.1 Learning Objectives.

Virtualization.

- Discuss compute, network and storage virtualization and outline their role in enabling the cloud computing system model. Identify reasons why virtualization is useful, especially on the cloud.
- Utilize virtualization to deploy virtual machines on cloud resources

Containers.

- Describe how containers achieve lightweight virtualization.
- Describe the advantages and disadvantages of containers compared to virtual machines.
- Build, deploy, manage, and administer containers and container clusters and architect containerized applications using container registries.

FaaS.

- Describe the rationale behind serverless computing and how it enables the running and scaling of applications without the need to manage servers.
- Develop and deploy a service utilizing FaaS using APIs that are provided as an auto-scaling service.
- Given a scenario with a set of requirements, determine the best computation type and give the reasons for this decision.

Specialized Computer Resources.

- Describe the advantages of specialized hardware such as GPUs, TPUs, and FPGAs.
- Evaluate application requirements to decide on a suitable specialized hardware resource.
- Deploy an application or service which utilizes specialized hardware resources.

5.3 Storage Resources on the Cloud - SRC

In this KA, students will understand, appreciate and gain insight into the differences between different types and schema of data. Students will compare and utilize different cloud storage types, whether block or object storage, and determine their suitability for a given scenario. Students will understand and compare the functionality and affordances of file systems and distributed file systems. Students will collect, store, extract, query and analyze data in files, relational databases (SQL), NoSQL databases, as well as Data Warehouses.

5.3.1 Learning Objectives.

Data.

- Describe data types (as in text, audio, images, video, etc.). List the differences between structured and unstructured data. Give examples of each type of data.
- Given a scenario using storage, determine whether the storage abstraction should be structured or unstructured and give reasons for this decision. Decide on an appropriate cloud based storage solution.
- Describe the difference between static and dynamic/streaming data and the implications this has on cloud data storage selection.
- Create, populate, access, and manipulate cloud data storage suitable for storing structured data.
- Create, populate, access, and manipulate cloud data storage suitable for storing unstructured data.
- Manipulate the sharing and privacy settings for an existing data stored on the cloud.
- Discuss the techniques and costs to migrate data from and to the cloud. Practice moving a large data set to and from the cloud or across different cloud service providers.
- Consolidate heterogeneous data types and schema into a single schema.

Storage.

- Enumerate and define the characteristics of different storage types and describe the differences between them. For a given scenario, determine the best storage type and give the reasons for this decision.
- Illustrate the abstractions offered by file systems and distributed file systems. Compare and contrast different types of file systems.
- Compare and contrast different types of databases and discuss their design trade-offs.
- Discuss the concepts of cloud object storage as well as their programming interfaces.
- Explain and compare the advantages and disadvantages of flat files, SQL databases, and NoSQL database solutions.
- Practice the basics of SQL language to gather insights from relational databases.
- Implement a prototype of a key-value store supporting different data structures.
- Configure, deploy and utilize a NoSQL database solution in a web service.
- Build and execute analytics queries against a large data set in a data warehouse.
- Describe the motivation, advantages and disadvantages of adopting software defined storage (SDS).
- Recognize the issues in storing state outside of a database in a cache.

5.4 Networking Resources on the Cloud (NRC)

In this KA, students will gain an overview of general cloud-related concepts for networking. Students will define and then utilize virtual networks in the cloud networking paradigm. Students will design network models, and then deploy a developed virtual and software-defined network (SDN) as part of utilizing cloud resources. Students will identify how elasticity, federation, and interoperability play a role in networking resources on the cloud. Students will also identify security concerns related to cloud networking and access management in the cloud computing paradigm.

5.4.1 Learning Objectives.

- Discuss cloud networking as part of cloud utilization.

- Critique connectivity, and application interactions with the network and novel techniques in each of these areas that are pushing cloud computing capabilities farther.
- Define virtual networks as part of provisioning cloud resources on the cloud.
- Explain congestion control, to include TCP congestion control and how it impacts data flow in data centers.
- Design network architecture as part of utilizing cloud resources.
- Configure and provision network resources utilizing cloud networking resources.
- Evaluate physical network structures, considering how the increasing demand for bandwidth within data centers influences the network design.
- Discuss and explain the use of SDNs as part of cloud implementation to address virtual networking requirements and challenges.
- Identify elasticity, federation and interoperability in cloud utilization.
- Explain the importance of interoperability in utilizing multiple cloud networking resources.
- Identify security issues and apply learned threat mitigation techniques at the multiple layers of the network.

5.5 Cloud Elasticity and Scalability - CES

Students should be able to demonstrate knowledge and understanding of cloud PaaS and IaaS vertical and horizontal scaling configurations, with associated cost/performance trade-offs. Additionally, students should be able to implement a cloud service with scaling and load balancing configured for a given application deployment scenario. Consideration should also be given to geographical/regional scaling attributes of the deployed cloud service, with a rationale presented on configuration choices.

5.5.1 *Learning Objectives.*

- Discuss and critique the cost/performance characteristics and trade-offs of using scalable cloud services.
- Describe the vertical and horizontal scaling approaches that can be deployed to enhance the performance of a cloud service.
- Configure and deploy a cloud service solution that addresses the requirements of horizontal or vertical performance scaling and internal or external load balancing.

5.6 Fault Tolerance, Resilience and Reliability (FTRR)

Reliability is one desired property of any cloud-based solution, and can be summarized as providing resources, bandwidth, and relevant interfaces that perform consistently well, to maintain a high-level of service availability, under dynamic conditions of the cloud. To provide reliability, many cloud systems take advantage of an eclectic resource-base and relevant tools that (i) can take resilient actions autonomously to adapt to changing conditions on the cloud, and (ii) can provide advanced fault tolerant mechanisms that can handle failures.

Students should be able to understand the concepts of resource dynamism and autonomy, and how the cloud is designed to take advantage of eclectic resource state to achieve high availability. They should also acquire a basic understanding of how fault tolerance can be ensured based on high availability. Additional topics include: high availability, points of failures, service uptime and impact of cloud-imposed delays, and disaster recovery.

5.6.1 *Learning Objective.*

- Identify and list cloud tools to provide high availability.
- Understand load balancing mechanisms on the middleware.
- Define the concept of service availability, and classify different levels of availability.
- Explain the difference between availability and high availability.
- Describe and critique cloud-based fault tolerance technologies.
- Understand the concept of service-level agreements (SLAs), and related requirements.
- Configure and deploy a fault tolerant cloud service solution that meets the minimum SLA requirements.

5.7 Cloud Deployment, Monitoring and Maintenance - CDMM

This KA focuses on how the cloud changes the way software applications are developed, run and managed. Using a "service oriented" approach, software developed to be run in a cloud environment leverages new tools and methods for monitoring application performance and making changes or upgrades throughout the application lifecycle. This includes application and service deployment, service and resource monitoring, and service and resource maintenance.

5.7.1 *Learning Objectives.*

- Deploy a software application as a cloud service.
- Enroll a monitoring tool to evaluate application performance and resource utilization.
- Establish automated rules to scale the application based on performance and utilization.
- Revise zone, region, or locations of the application based on performance and use case.
- Create a Cloud Integration and Cloud Development (CICD) "pipeline" process for maintenance upgrades, patches and changes to the application.

5.8 Cloud Orchestration - CO

This area covers how the cloud impacts deployment methods and frameworks, for how software applications are developed and deployed. This includes the ability for students to build any application, on any cloud, using popular application frameworks, and CICD pipeline and monitoring. Students should be able to demonstrate an understanding in the automation of workflow processes and the creation, monitoring and deployment of resources supporting the applications. Examples of specific techniques and tools in this area are: Software Delivery, DevOps, CICD, and platform-agnostic 'Infrastructure-as-code'.

5.8.1 *Learning Objectives.*

- Recognize and discuss the concepts responsible for the emergence of DevOps.
- Critique the business benefits of DevOps and continuous delivery.
- Appraise continuous Integration Fundamentals.
- Describe the Service Delivery process.
- Recognize the concepts of test automation, infrastructure automation, and build and deployment automation.
- Describe how DevOps relates to Lean and Agile methodologies.
- Summarize case studies of IT organizations that are making the transformation to Adaptive IT and DevOps models.
- Critique the capabilities of some of the common and popular DevOps tools.
- Critique DevOps in relation to IT Service Management (ITSM).
- Demonstrate Infrastructure Setup and DevOps Installation of CICD, version control, and orchestration tools.
- Critique automating Testing practices and processes.
- Demonstrate configuring, managing and distributing jobs.
- Demonstrate using build automation tools. Demonstrate implementing automated and continuous deployment. Deploying an application to an application server and deployment of a simple web application.

5.9 Software Development using Cloud APIs - SDCA

Implementation of a cloud-enabled system requires the ability to integrate third-party application programming interfaces (APIs) offered by the providers of cloud computing services. Common implementation practices include cloud service integration at different levels. Service-level (Platform-as-a-Service) APIs provide access to, and functionality of, a cloud environment allowing the application to integrate with such systems as messaging, database, and data storage. Application-level (Software-as-a-Service) APIs connect the application with the cloud-enabled IT infrastructure that could provide access to such applications as email and collaboration, customer relationship management, etc. Infrastructure-level (Infrastructure-as-a-Service) APIs help control cloud resources, as well as their distribution.

5.9.1 *Learning Objectives.*

- Define common implementation practices for cloud-based software development.
- Explain the impact of using cloud computing solutions on an application/service.
- Demonstrate the ability to apply commonly-accepted implementation practices.
- Analyze the impact on the application/service performance and dependability resulting from migrating it to the cloud.
- Build a cloud-based application/service and experiment with it under different conditions affecting its performance, reliability, and availability.
- Assess the factors influencing the performance, reliability, and availability of the implemented cloud-based application/service.

5.10 Cloud Programming Models and Frameworks - CPMF

In this KA, students will explore the various capabilities of cloud-based programming models and frameworks. Students will understand the benefits and limitations of each so that they can assess applicability based on the problem domain. Students will gain working experience in one or more of these programming models.

5.10.1 *Learning Objectives.*

- Explain how to describe data in motion, data flow definitions, regular expression, message formats and canonical data models.
- Describe the aspects of and the differences between different programming models.
- Discuss the execution flow, scheduling and fault tolerance concepts in various programming models.
- Recall and contrast different popular cloud programming models.
- Discuss the features and advantages of various parallel and distributed programming models.
- Differentiate between interactive (non-batch), batch, and stream processing models and their applicability to different problem domains.
- Illustrate and explain the execution workflow, overhead, fault tolerance and logical flow of a cloud-based programming framework.
- Design and implement a solution to pre-process a large text-based dataset for data cleaning purposes using a cloud-based programming framework.
- Implement an application using a cloud-based programming framework.
- Investigate the possible sources of different bug types in cloud-based programming framework programs using log files.
- Explore optimization topics in the cloud-based programming framework.

5.11 Service oriented architecture - SOA

This area recognized how the cloud impacts the traditional framework of SOA. Micro-services are replacing monolithic deployments. This is changing performance metrics of SLAs, as well as Service Level Objectives (SLOs).

Students should be able to outline an infrastructure in sufficient detail for technical/infrastructure architecture using SOA principles and practices, as well as demonstrate an understanding of SMART goals and business requirements. Students should also demonstrate the ability to identity risks relating to functional and non-functional requirements. Additionally, students should be able to develop a suitable business architecture, building blocks, models and views clearly demonstrating the ability to be able to design or redesign a solution to meet necessary services level requirements.

5.11.1 *Learning Objectives.*

- Demonstrate the basic units of cloud computer networks: computer, processor, operating system, networking and storage.

- Design a cloud service solution that is fault tolerant and meets the minimum SLA requirements.
- Using the architectural process framework, identify the various inputs, stakeholders, statements of requirements and constraints that guide an architect as to the nature and shape of solutions to be built.
- Recognize the difference between functional and non-functional requirements.
- Demonstrate ways to describe the structure and behaviour of a business system (not necessarily related to computers), covering business functions or capabilities, business processes and the roles of the actors involved.
- Demonstrate business process decomposition and automation, including how to map business functions, processes, goals and services to the applications they support.
- Recognize ways to describe the data structures used by a business and/or its applications, including metadata: that is, descriptions of data in storage, data in motion, data structures and data items.
- Demonstrate how to describe data in storage using data models.
- Recognize how the three primary data qualities (CIA) may be measured at three or more levels.
- Explain ways to modularize the internal structure of an application, and ways to connect components, ranging from tightly coupled to loosely-coupled.
- Critique common OO design patterns.
- Demonstrate the concepts of an Application Programming Interface (API) and Interface Description Language (IDL).
- Explain the goals and concepts of application portfolio management.

5.12 Cloud Security, Privacy, Policy and Ethics - CSPPE

Students will be able to define security governance policies, and principles / risk management compliance related needs and issues. Students will describe how the human component and access management is an important part of cloud security management. Students should demonstrate understanding by implementing best practices in security operations, security engineering, use of confidentiality, integrity, and availability (CIA) triad, and assessment and testing in threat evaluation and mitigation.

5.12.1 *Learning Objectives.*

- Define security related concepts in cloud computing.
- Explain security related implications of the cloud computing paradigm.
- Demonstrate the use of security controls in the cloud computing environment.
- Describe security policies and strategies for achieving compliance in cloud computing.
- Describe security related governing laws and regulations in cloud computing.
- Design a secure architecture model for a cloud-enabled computing system using security design principles.
- Implement security policies and plans in the cloud security environment.
- Summarize best practices of cloud computing security and describe their rationale.
- Understand security threats in cloud computing.
- Apply forensics techniques for investigation and analysis in cloud computing.
- Explain the nature of cloud computing threat mitigation.
- Practice the process of cloud computing threat mitigation.
- Analyze different strategies and develop a plan for cloud computing threat mitigation.
- Use commonly accepted secure software development practices in cloud computing.
- Test for threat vulnerabilities in a cloud computing application/system (penetration testing, ethical hacking).
- Discuss ethical principles of obtaining and use of cloud platform resources and the need to guard against bias.
- Discuss ethical and accountability issues of data and services among cloud platforms.
- Discuss transparency in services and application of using data in cloud platforms.
- Analyze abnormal system behaviors.
- Demonstrate intelligence analysis skills.
- Knowledge of critical business processes.

5.13 IoT, Mobile, Edge and the Cloud (IoTMEC)

The downward pressure on price for compute has pushed a significant amount of processing down to the device level. Whereas Mobile computing leverages the resources of smart phones, IoT and Edge computing refer to the advent of smart devices and "meshes" to monitor and coordinate these devices. These three delivery methods enable applications and services to run on independent and decentralized environments.

Edge moves cloud analytics and custom business logic to devices so organizations can focus on business insights instead of data management. This enables IoT solutions to scale by configuring software, deploying it to devices via standard containers, and monitoring it all from the cloud.

Students should be able to demonstrate knowledge and understanding of IoT communication, security, and data formats, with emphasis on interoperability and lightweight communication. In particular, students should be able to implement a cloud-connected IoT solution using suitable cloud API services to support lightweight, scalable data storage and communication.

5.13.1 *Learning Objectives.*

- Critically assess the separate and composite impact of cloud and mobile computing technologies upon the social behavior of the individual and society.
- Critically evaluate the methods of open data specification, interoperability, formats and delivery mechanisms in the Internet of Things.
- Critique the fundamental tradeoffs related to compute, power limitations and communication needs in these systems.
- Specify, design, and develop cloud-connected IoT applications capable of sending and receiving sensor data.

- Demonstrate IoT Edge within the context of current applications of mobile and sensor systems.

5.14 Cloud-based Artificial Intelligence and Machine Learning (CAIML)

Simply stated, a cloud-based artificial intelligence (AI) solution is about providing relevant infrastructure and machines that can perform tasks that are characteristic of human intelligence. The massive data storage and compute ability provided by the cloud has increased the ability to perform machine learning (ML) and deep learning (DL). While AI encompasses a wide range of approaches and solutions about mimicking human intelligence, ML is a way of achieving AI, by relying on (cloud-based) machines, and related data sources. DL is one of the many approaches to ML, that mimics the biological structure of the brain, and involves using novel techniques, such as artificial neural networks in combination with utilizing large data sets.

In this KA, students should be able to observe, identify, and explain core cloud mechanisms that help build relevant AI solutions. They should also explain the difference between using cloud-hosted AI/ML solutions that many cloud providers offer, and working on a do-it-yourself solution that utilizes existing core resources (compute, storage, network, etc.) on the cloud infrastructure. Students - based on their understanding level and focus on the subject matter - should be able to outline a plethora of relevant ML/AI tools and methodologies, and narrow it down to pick a relevant experimental methodology necessary to perform statistical analysis of large-scale data sources.

5.14.1 Learning Objectives.

- Appreciate the distinction between the popular view of the field and the actual research results, and the fact that the computational complexity of most AI problems requires us to deal with approximation techniques regularly.
- Explore the processing hardware technology (CPU, GPU, TPU, and so on) used by popular ML/DL solutions.
- Demonstrate the ability to identify and critique a subset of use cases for learning and inference, such as classification and regression.
- Demonstrate implementation of underlying algorithms in statistically valid experiments, including the design of baselines, evaluation metrics, statistical testing of results, and provision against over training.
- Use cloud-based scientific computational environments (e.g., Jupyter Notebook) to produce interactive code that interacts with large data sets along with results of running the code and human-readable descriptions.
- Appreciate resource discovery and self-organization methods used in utilizing unstructured networks.
- Identify the ethical implications of how an AI application or service assists humanity, and whether it is designed for intelligent privacy and not for deceiving humans.

5.15 Knowledge Area Summary

In summary, the KAs presented allow educators to choose from a range of topical and specialist cloud areas to build out specific parts of their curriculum. Educators can choose to implement one or more KA as befits their curricula needs, as each KA can be deployed on its own, or in combination with others. KAs can form the basis of program/course level objectives, with the LOs under each suitable for inclusion at module/class level. In particular, there are multiple KAs presented in this paper that directly support the nine identified ID 4.0 technology pillars. Adoption of these KAs provides an opportunity for students to equip themselves with the necessary cloud skills that global industry currently needs, as well the foreseeable future, as the ID 4.0 pillars grow and become more dominant factors in industry.

The next and final part of this WG paper will briefly discuss and outline future work, as the intention is to iteratively build on the work presented here over the next few years. This intention will ensure the KAs and LOs will remain valid and up to date, with the inclusion of further KAs where appropriate, as the cloud continuously evolves.

6 FUTURE WORK AND CONCLUSIONS

This paper presents current identified needs and gaps in adopting cloud curriculum for a cloud-first future. Current findings identify the need for establishing knowledge areas and learning objectives as part of the curriculum framework. Future work should involve establishing a living document (website) to update and address the following: i) Knowledge area and learning objective updates as they evolve, ii) Recent academic publications and contributing knowledge, iii) Links to existing classes, courses, and materials, and iv) To identify best practices. Each of these four items is an essential part of a key set of resources and assets which present a great starting point for academics wishing to utilize cloud within teaching and learning.

Finally, this working group has identified there is limited current literature on cloud adoption in education curriculum as part of using cloud platform resources. The group intends on continuing to work on this project together, because we all passionately feel that cloud skills will be crucial to students going forward, with future work supporting the development of curriculum to keep up with the rapidly evolving state of the cloud computing paradigm.

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