

CvLabs: A Container Based Interactive Virtual Lab for IT Education

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ABSTRACT

With the ongoing trend of digital transformation, the need for more well-trained IT professionals is keep raising, as well as the need for quality IT education. Experiential learning is a key component for learners to practice problem solving and develop skills in many IT courses. Virtual lab is an effective solution to meet the increasing demand on experiential learning environment. However, delivering and managing satisfying virtual labs are technically and economically challenging for instructors, lab designers and educational institutions. This paper presents the design and implementation for CvLabs, a container based interactive virtual lab system. The system can provide learners with ready-to-use virtual learning environments. It also enables learners to share lab sessions to improve collaboration, which is missing in many implementations of virtual lab. CvLabs is built with industrial standard open source container technologies. Container provides a foundation for the delivery of consistent virtual lab environments and improves learning experience. It also simplifies the creation of reusable lab contents, which can significantly reduce the workload of lab instructors and lab designers. The introduction of container ensures CvLabs can be deployed on various infrastructures and scaled to support a large number of learners. By leveraging cloud infrastructure, CvLabs can lower the cost of delivering and managing virtual labs for educators and educational institutions. CvLabs was deployed for a test run with a small group of test users. The system received positive feedback on the learning experience improvement. The preliminary results from this work shows containers is a promising technology for experiential learning in IT education.

CCS CONCEPTS

Applied computing Education → Interactive learning environments → Distributed architectures → Cloud computing; Social and professional topics → Professional topics → Computing education → Computing education programs.

KEYWORDS

cloud computing, virtual lab, container, information technology education, virtual learning environment,

ACM Reference format:

Geng Chen. 2020. CvLabs: A Container Based Interactive Virtual Lab for IT Education.

1 INTRODUCTION

Information technology (IT) is ubiquitous in our modern society nowadays. With the evolution of technology, e.g. cloud computing, machine learning, IoT and virtual reality, the world is becoming more digitalized (Solis & Littleton., 2017). With this ongoing trend, in the foreseeing future, more IT talents will be needed to support the digital transformation for every aspect of the world. As a result, governments, educational institutions and professional training service providers are increasingly investing into IT education (Chea et al., 2019; Joyner & Isbell, 2019).

Experiential learning is an indispensable component in IT education. Learners develop skills and gain practical experience through hands-on problem solving (Rai & Chunrao, 2016). Physical laboratory is a traditional form of learning environment for experiential learning. With the increasing popularity of online IT education, the demand of experiential learning environment is raising. However, the capacity of a physical laboratory is highly limited by its physical space and facilities, which means it's difficult for physical labs to support learners at scale. Also, the construction and maintenance cost for physical laboratory are high, it's challenging for educational institutions which with limited funding to provide quality laboratory services in a sustainable manner (Alkhaldi et al., 2016).

To meet the increasing demand on quality experiential learning experience, Virtual Learning Environment (VLE) was introduced as a solution. A virtual learning environment is a system which provides learning materials and facilities to learners by using information and communication technologies (Mhouthi et al., 2016). A Virtual Lab (VL) is a specific type of virtual learning environment to help learners practice problem solving and develop practical skills (Alkhaldi et al., 2016). Comparing to physical labs, virtual labs provide several advantages (Alharbie & Athauda, 2012; Xu et al., 2014): (1) With the support state-of-art infrastructure, virtual labs can support massive learners. (Geigle et al., 2017) (2) Majority of the virtual labs are accessible over intranet or internet. Learners can access the services regardless of their geographic locations. (3) Virtual labs can deliver a more personalized learning experience. Learners can learn at their own pace and time schedule. (4) The construction and maintenance cost are lower for a virtual laboratory, comparing to a physical laboratory. (5) With new technologies virtual labs can bring novel learning experience to learners and support new learning scenarios.

Whilst virtual lab is an promising solution for the delivery of experiential learning to learners, there are also concerns and challenges on the adoption of virtual labs: (1) Due to its remote nature, it's difficult to achieve high level of peer interactions for group work. (Alharbie & Athauda, 2012; Hu, 2018). (2) Many existing virtual labs are implemented with Infrastructure as a Service (IaaS), which leads to low portability and increases the risk of cloud vendor lock-in (Xu et al., 2014, Cardoso et al. 2017; Rădulescu, 2014). (3) Lack of an efficient manner to develop reusable lab environments. Developing different systems for different subjects is not the most optimized solution.

To address the existing challenges in virtual labs and better support IT education to deliver an experiential learning experience to learners at scale with less management and economic cost, The CvLabs project aims at designing and developing a virtual lab that satisfies six criteria: (1) it must provide learners with ready-to-use virtual learning environments. Learners can maximize their focus on learning; (2) it allows learners to access the lab regardless of learners' geographic locations and time zones. Learners can learn at their own pace with the system; (3) it provides learners an interactive and collaborative learning experience, supporting learners with different learning styles; (4) it can be applied to a wide range of subjects in IT education; (5) it reduces the complexity for lab designers to development reusable virtual lab environments; (6) it can scale to support learners at scale with affordable cost. In this paper, the design and implementation plan and application of a container based interactive virtual lab system, CvLabs, is presented.

2 RELATED WORK

With the increased adaption of online education, especially the success of Massive Open Online Course (MOOC), virtual labs has been widely adopted in education, e.g. in pneumatics (Chea et al., 2019), computational science (Cruz & Mendoza, 2018), computer networking (Dukhanov et al, 2014), software programing (Xu et al., 2014). Virtual labs are considered a supplement or sometimes a replacement for physical labs (Alharbie & Athauda, 2012).

The implementation of virtual labs can be based on various technologies (Berger, 2018). Cloud computing is a popular IT resource delivery and service model. Cloud has been widely applied in education (Jose, 2015; Qasem et al., 2019). The application of cloud computing can also be beneficial to the implementation of virtual labs. Cloud computing can provide a scalable and flexible infrastructure to virtual labs, which can enable virtual labs to support massive learners in an affordable manner. Geigle et al (2017), implemented CLaDS, a public cloud base virtual lab for practical data science education, which can deliver a wide range of hands-on data science assignments to a large number of learners at very low cost. The adoption of cloud can also simplify the implementation of virtual labs. By leveraging private cloud infrastructure, Xu et al. (2014) deployed a hands-on lab solution for computer networking and cybersecurity courses. The introduction of cloud significantly

simplifies lab environment setup. Cardoso et al. (2017) introduced cloud based virtual labs to college students in a programming course and received positive feedback from students. The system also helped reduce teachers' workload. With managed cloud services, cloud can lower the management effort for virtual lab systems, educators can focus more on teaching. Cloud is applied in professional IT education as well. Training service provider Kata Coda provides interactive hands-on labs for cloud technologies and becomes commercially successful (O'Reilly, 2019).

Cloud based virtual labs which introduced before 2017 are mostly based on Virtual Machine (VM) and IaaS (Xu et al., 2014, Cardoso et al. 2017; Rădulescu, 2014). Since 2015, container has been widely adopted by cloud users and cloud service providers, e.g. AWS, Azure, GCP etc., as a light-weight virtualization technology for application deployment and delivery (Burns, 2018; Geng, 2017, CNCF, 2018). With containers, users can create isolated application environments with less computational resource consumption and faster provisioning time (Berger, 2018). Users can efficiently deploy and run applications on top of different infrastructures and clouds (Turnbull, 2014). Berger (2018) reviewed the implementation technologies for virtual labs and concluded containers can be a promising option for the implementation of virtual labs. Containers can be used as a standard for lab delivery and environment setup. This can reduce educators' burden on lab environment management and provide learners a consistent learning environment (Chea et al., 2019). Irvine et al., (2017) reports the use of containers for a cybersecurity labs framework, Labainers. Multiple containers can be deployed to provide a virtual network environment. Containers also enable personalizing lab environments, which helps the faculty to assure the originality of students' work.

As a state-of-art cloud technology, containers can provide many benefits to virtual labs to assist teaching and provide a more engaging experiential learning experience to learners. However, the number of reports on the applications of containers in virtual labs are still relatively low. That indicates the potential of the application of containers in virtual labs hasn't been fully studied.

3 CvLabs: A Container Based Virtual Lab

The CvLabs system is an online virtual labs platform which can provide learners with ready-to-use virtual learning environments to practice problem solving and to improve skill proficiency in IT education. The system aims at (1) providing learners a more interactive and collaborative experiential learning experience; (2) simplifies reusable lab content creation and delivery for lab designers and lab instructors; (3) lower management complexity and cost for virtual lab delivery.

3.1 Roles and user experience

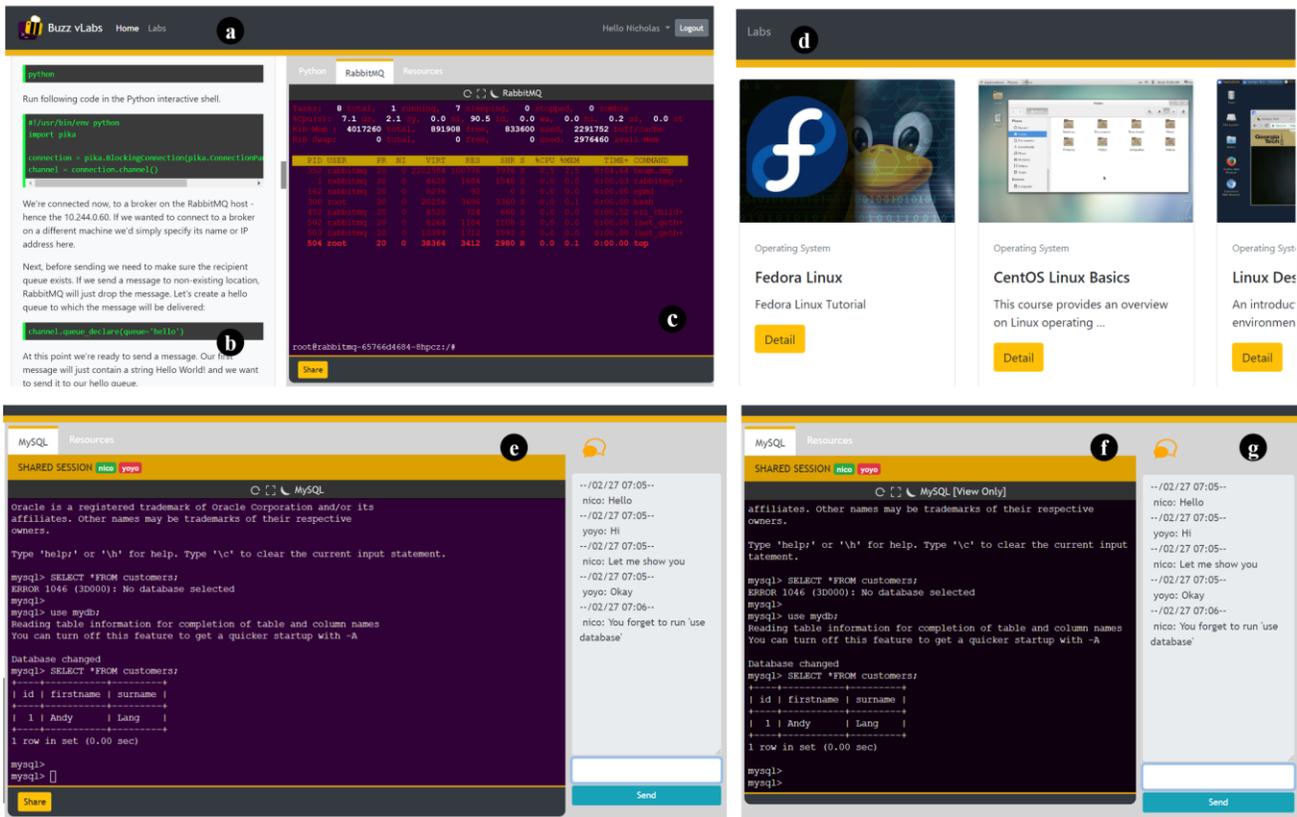


Figure 1 CvLabs user interface for virtual labs. (a) User interface for virtual labs; (b) lab guide with lab instruction and interactive lab steps; (c) web-based terminal interface which is connecting to remote container lab environment; (d) lab catalog with labs in a wide range of subjects. (e) A shared lab session, the owner view; (f) terminal input and output are replicated to the participant view of a shared lab session; (g) chat window in shared lab session for group interaction.

An effective learning with virtual labs involves people of various roles, e.g. learner, lab designer, lab instructor and system administrator. Learner is the major targeting end user role in this context, whilst other roles are supporting to deliver a satisfying learning experience and enhance learning outcomes for learner. CvLabs provides support for these four roles to achieve their goals in an efficient and productive manner.

Learner can interact with the system through a web based graphical user interface (GUI). From the lab catalog, learner can sign up for labs which satisfy his or her learning needs. The lab environment will be created as per learner's request in remote container orchestration clusters. Lab environment will be deleted, and resources will be reclaimed after the lab is finished. Each lab environment will consist one or multiple Linux or Windows containers. Containers within a lab unit will be connected to the same computer network space and can communicate with each other. After the lab environment is deployed, learner will be presented with a web-based terminal user interface, with which learner can execute lab tasks in remote containerized lab environment, as shown in Figure 1. CvLabs allows Learner to expose web-based services which running inside the lab container environments, this enables the access to the remote desktop, thus learners can run labs in a GUI environment.

Lab guide with tasks and detail steps will be provided for learner in the virtual lab user interface. A commonly accepted fact is people learn with their own learning styles and learning habits. According to Kolb's experiential learning theory, some learners prefer learning with "doing", some are learning better with a "watching" approach. CvLabs offers two approaches for executing lab tasks. Learner can either execute all lab tasks on his or her own with the live terminal session. Learner can also choose to execute lab tasks in a click-and-run style. By clicking on a task, the task will be automatically executed in the terminal. Learner can get instant feedback on command execution and easily walk through the lab tasks. This click-and-run style lab execution mimics the process of in-class instructor demonstration.

One challenge of virtual labs is the difficulty to achieve quality peer-interaction and learner-instructor interaction. CvLabs provides a lab session sharing feature for learner to share his or her session to others. As shown in Figure 1 (e), (f) and (g), terminal input and output will be replicated to multiple learners at the same time. Group chat will be enabled for group communication. Multiple learners can be working on the same terminal session. This will encourage collaboration and interaction among learners for trouble shooting and group learning.

Lab designer. In CvLabs, a virtual lab includes two major parts, the lab guide and the lab environment. Lab designers can define the lab guide in a simple Markdown format, which significantly simplifies the formatting and improved content readability. By adding pre-defined tokens, lab designer can embed interactive contents in lab guides. The lab environment is defined with the use of container images. Lab designer reuse existing container images or define custom container images to meet specific lab requirements. The immutable nature of containers can ensure the consistency of lab environments across lab development and production. This will significantly reduce troubleshooting which caused by environment inconsistency. Lab designer can publish container images to private or public container registry for future reuse. The lab guide and lab environment reference can be defined in a structured lab definition format. The lab definition can be versioned by Version Control System (VCS), e.g. git and GitHub¹ etc. CvLabs can be integrated with 3rd party VCS, e.g. GitHub, via webhook. When lab designer commits a new version of lab definition, the change can be automatically updated to CvLabs. This is based on the Continuous Integration (CI) concept which is widely used in software industry nowadays. One outstanding benefit of adopting a container approach is containers can provide an OS-like isolated environment, which makes it possible to support lab scenarios in a wide range of subjects in IT education, including programming, data science, system administration and networking etc. Lab designer can have a unified tool for lab content development across subjects, instead of switching tools and approaches for different subjects.

Lab Instructors. With CvLabs, lab instructors can group lab sessions and assign automatic grading. The results of lab groups can be reviewed in the system to help instructor to gain insights of learners' performance. The lab sharing feature also enables instructor to help learners when it's needed, this also contributes to a more intimate mentorship.

System Administrator. CvLabs is based on container technology, both the virtual lab environments and components of CvLabs are running as container instances on container orchestration platform Kubernetes². The deployment of the system can be streamlined with DevOps CICD pipeline. With the support of public cloud managed container orchestration service, e.g. Azure Kubernetes Service, the infrastructure management overhead can be significantly minimized. Scaling of the system according to actual workload can be done in a push-button manner.

3.2 System Architecture

The CvLabs system includes two key subsystems, the Learning & Lab Management Subsystem (LLMS) and the Container Infrastructure Subsystem (CIS), as shown in Figure 2. The LLMS of the CvLabs system is a web application, which provides user

interface and it's the control plane of the whole system. Both the LLMS and individual lab environment are run on a Kubernetes based CIS.

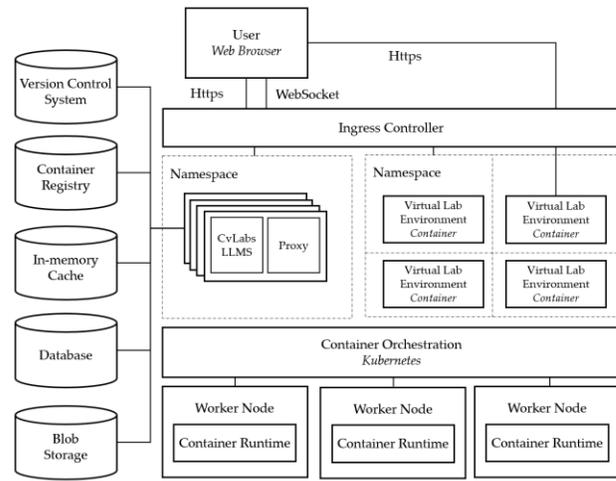


Figure 2 System architecture of CvLabs

- The LLMS is running on the container infrastructure as container instances.
- The container infrastructure is based on a scalable container orchestration platform Kubernetes with multiple worker nodes. Container engine Moby³ is running on each worker node. To minimize the management overhead, public cloud managed Kubernetes service is recommended.
- The system leverages the multi-tenant capabilities (e.g. Namespace, Resource Quota, Network Policy etc.) of container orchestration platform to provide managed isolated environments for each virtual lab environment session.
- Lab definitions will be versioned by VCS GitHub.
- Lab environment container images are stored in external container registry.
- Learning data is persisted in external database.
- Unstructured data is persisted in external blob storage.
- In-memory cache is used for application cache and inter-process communication.
- Learners can access the lab environment through a web-based terminal console.
- Learners can access the services which running inside the virtual lab environments via the ingress controller of the container orchestration platform.

Multi-tenancy & Security. To ensure the security of the system, following configurations and features are in place for CvLabs. (1) With built-in Role Base Access Control (RBAC) subsystem, user's personal information and learning data will be kept private, data will not be accessible to other users without permission. (2) Lab environments are running in containerized sandboxes. Process level isolation (Linux namespaces and cgroups, and equivalents features on Windows) is enforced by

¹ <http://github.com/>

² <https://kubernetes.io/>

³ <https://github.com/moby>

container engine. (3) Container orchestration level resources are isolated by Kubernetes namespaces on a per lab session basis. (4) Resource quota is set for each namespace to ensure resource allocation. (5) Default network policy is set for namespace-based network isolation to lower network security risk.

Scalability. CvLabs is based on container infrastructure, this ensures the system can be easily scaled in and out according to the actual workload.

The LLMS is running as container instances. With container orchestration, system administrator can manually scale up or down the number of running service instances, or setup auto-scaling to scale according to system metrics.

When learner starts a virtual lab session, a set of virtual lab environment will be dynamically created on the container infrastructure. Container orchestration platform will automatically schedule the virtual lab environment container into one of the worker nodes in the cluster. By scaling up or down the number of worker nodes, system administrator can dynamically adjust the system capacity to support the actual workload. Based on managed container orchestration service on public cloud, the scale of container infrastructure can be efficient. Cluster auto-scaling can be enabled to further simplify the system management and lower the total cost.

High availability. To provide continuous service to learners, CvLabs supports deployment model which can ensure high availability of the service. (1) The LLMS can be running with multiple instances to avoid single point of failure, with the support of container orchestration to achieve auto-healing; (2) The database and in-memory cache which used by the LLMS can be deployed in high availability mode to ensure higher level of service availability; (3) CIS is based on a cluster architecture, both the control plane and worker nodes have built-in support for high availability support. (4) The entire system can be deployed into multiple public cloud regions in active-active, active-passive or active stand by mode.

Deployment models. Based on the industrial standard open source container technology, e.g. Docker and Kubernetes, CvLabs will be portable and can be deployed onto different types of infrastructure, including physical machine, virtualization platform, private cloud and public cloud. To increase the accessibility and scalability of the system, CvLabs will be deployed on public cloud platform Azure.

To minimize the management cost of the system, CvLabs will leverage managed container orchestration service, e.g. Azure Kubernetes Service, and application development related PaaS services, e.g. in-memory cache and databases service.

4 CONCLUSION

In this paper the design and implementation of an interactive virtual lab system which built with open source container technology are presented. The system provides a solution to the challenges which are existing in current virtual learning environment implementations. By leveraging containers, CvLabs can deliver better experiential learning environments for learners

in IT education, with enhancements in peer interaction and collaboration. It also simplifies the development of reusable lab contents for lab designers. Lab contents can be delivered with high consistency to avoid additional troubleshooting work. CvLabs currently provides courses covering subjects, including programming, cloud computing, data science and operating system (OS). Lab designer can leverage CvLabs to support a wide range of subjects in IT education. CvLabs supports multiple deployment options, on private cloud or public cloud. When deployed on a public cloud managed Kubernetes service, the underlying container infrastructure can be scaled easily. Virtual lab service provider can scale up the cluster to support a larger number of learners and scale down the cluster at low time for cost saving.

During the project, challenges and concerns over the adoption of containers and virtual labs also surfaced. (1) Containers is based on the process isolation capabilities of OS kernel. Containers on the same host machine are sharing the underlying kernel. This sharing model is beneficial from resource consumption perspective. However, this model also increases security risk. If attacker break the jail which set by the container engine, which means containerized lab environments on the same host machine will be in risk. For this sake, we strongly discourage learners to store or process confidential information in virtual lab environments. For a scenario which requires high security settings, a hypervisor-based virtualization will be a more optimized solution, such as hypervisor-based container runtime Kata Containers⁴ and Kubernetes-based virtual machine management solution, KubeVirt⁵. (2) To achieve a satisfying user experience, a stable, high speed and low latency network connection is required for accessing the virtual learning environment. The distance between learner's geographic location and the system deployment location is an affecting factor. Deliver lab contents with Content Delivery Network (CDN) and deploy multiple instances of the system into different regions of the world can provide a better service quality to learners across the world, at the cost of higher infrastructure expense. (3) Using public cloud is not always true. Misuse of cloud resources can lead to serious financial consequence. Virtual lab service providers need to appropriately estimate and control the resource usage. Dynamically scaling up or down resources according to the actual service usage can more effectively achieve cost saving.

CvLabs received positive feedback from learners which from a wide range of different background. This shows container technology is a promising solution to state-of-art virtual labs. It can be used effectively to deliver a better learning experience and enhance learning outcomes for learners in IT education.

5 FUTURE WORK

⁴ <https://katacontainers.io/>

⁵ <https://kubevirt.io/>

The design and implementation of CvLabs lays an architectural foundation to support a massive number of learners. However, because of the time and budget limit, this phase of the CvLabs project carried out with an economic deployment option to support a relatively small group of learners. The support for larger group of learners for online program like Georgia Institute of Technology OMSCS program will require additional performance optimization, high availability deployment configuration and infrastructure investment. The next step for the project will be on (a) Obtaining feedback from a larger group of users from various background. (b)CvLabs provides an efficient way for creating new labs based on existing lab contents, by enabling students to create lab contents, might bring positive impact for lab content innovation. (c) Evaluating the use of gamification and social networking to encourage learning.

6 ACKNOWLEDGMENTS

Appreciate for all the volunteers for participating in the evaluation of CvLabs. Special thanks to Robert Schmidt's support and mentorship on this work.

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