Virtual Laboratories
Use of public testbeds in Education

Niky Riga[1], Vicraj Thomas[1], Vasilis Maglaris[2], Mary Grammatikou[2] and Evangelos Anifantis[2]

[1]*BBN Technologies, Cambridge, Massachusetts, USA*

[2]*School of Electrical and Computer Enginnering, National Technical University of Athens, Athens, Greece*

{*nriga, vthomas*}*@bbn.com*, {*maglaris, mary, vangelis*} *@netmode.ntua.gr*

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Abstract: Experimentation is an invaluable part of learning in all sciences. However, building and maintaining laboratories is expensive, time and space consuming. Moreover, in computer science advances in technology can quickly make the infrastructure obsolete. In this paper we advocate the use of recently deployed public testbeds as remote labs for computer science education. As an example we describe the successful use of the GENI testbed in graduate and undergraduate courses and present a specific case study of GENI being used in an undergraduate class on Network Management and Intelligent Networks.

1 INTRODUCTION

Experimentation is an invaluable part of learning (Bruner, 1961) in all sciences. Research has shown that lab courses significantly enhance learning (Freedman, 1997; Magin et al., 1986) and help students develop problem-solving and critical-thinking skills (American Chemical Society, 2014). However, building and maintaining laboratories is often expensive, time and space consuming. In computer science in particular that is a fast-evolving field, equipment gets outdated very quickly and requires frequent costly upgrades.

At the same time there have been several efforts around the globe to build and maintain publicly available testbeds (Berman et al., 2014; Peterson et al., 2003; White et al., 2002; Mirkovic et al., 2010; Fdida et al., 2011) to support scientific exploration that scale beyond the capabilities of individual institutions. These testbeds, over the past few years, have matured and transitioned from small prototype deployments to large production virtual labs.

Although the primary purpose of these testbeds is experimentation for research, their accessibility, scale and ease of use makes them well suited for lab experiments in computer science courses. While it is true that remote labs cannot replace all computer science labs (e.g. hardware labs), experience has shown these testbeds work very well for a number of other computer science classes.

Researchers have identified three different types of laboratories for education and research: *hands-on labs, simulation labs and remote labs* (Ma and Nickerson, 2006; Müller and Erbe, 2007). Hand-on labs are co-located with its users and are intended for use by users from the institution that owns the lab. Simulation labs (also called *virtual labs*) simulate the laboratory infrastructure on computers. Remote labs are geographically separated from its users and are intended to be a shared resource for users from different institutions. Multiple studies have examined the effectiveness of the different types of labs in student understanding (Ma and Nickerson, 2006; Corter et al., 2007). Although there is a component of the hands-on labs that can not be easily substituted by simulated or remote labs, studies indicate that in many cases remote and hands-on labs are equivalent in terms of enhancing student conceptual understanding.

In this paper we advocate that the publicly accessible research testbeds should be used as remote labs for computer science education. We describe advantages beyond the benefits described in the above studies and urge educators around the world to take advantage of these valuable community resources and incorporate them in their courses. As an example we present how GENI (Berman et al., 2014), an infrastructure for computer networking and distributed systems research, is used as a remote lab for undergraduate and graduate courses. Although GENI resources are distributed across the United States, it is used by instructors from around the world and it supports multiple concurrent courses. We also include a case study based on the use of GENI by the "Network Management and Intelligent Networks" class at the National Technical University of Athens.

2 RESEARCH TESTBEDS AS REMOTE LABS FOR EDUCATION

In this section we expand on our position that educators will reap great benefits if they take advantage of public testbeds being built for research, in their classes. We advocate the use of these testbeds over institution-specific hands-on labs and present a list of benefits for instructors and students.

We also describe a specific research testbed for networking and distributed systems research, GENI, and present why it has gained traction among educators as a remote lab in the past few years.

2.1 Educational Benefits of Research Testbeds

In most cases educators are better off using remote labs over setting up their own hands-on labs. Hands-on labs put a high demand on space, instructor time and experimental infrastructure (Ma and Nickerson, 2006). The experimental infrastructure can be expensive to acquire, set up and administer. Additionally, advances in technology can quickly make the infrastructure obsolete.

An alternative to building local hands-on labs is to use remote labs. While a few remote labs such as (IBM News Release, 2007; Obstfeld et al., 2014) have been built primarily for education many large testbeds with substantial community support are being built for research. Benefits of leveraging these testbeds as remote labs include:

- *Accessibility.* Research testbeds are designed for use by researchers from around the globe. They are available around the clock and accessible by students from anywhere they have Internet connectivity. Global accessibility also enables innovative teaching methodologies such as cross-institutional student project teams.
- *Access to unique or expensive resources.* Research testbeds often include resources and equipment that would ordinarily not be affordable for educational purposes. Students however can have access to these resources if the testbed is used as a remote lab.
- *State-of-the-art resources.* To facilitate cutting-edge research, these testbeds are frequently updated with state-of-the-art resources. This allows students to be exposed to latest technology, without the burden to the institution to maintain up-to-date local labs.
- *Number of resources.* Many of the research testbeds have orders of magnitude more resources than is realistically possible in a typical hands-on lab. This make it possible for instructors to assign lab exercises that require more resources than were previously practicable. This is particularly beneficial for classes in cloud computing and data sciences.
- *Community support and ease of use.* Shared public testbeds build a community of users that develops an maintain a variety of tools to enable easy experimentation, and researchers spend more time addressing research related problems than making the testbed do what they want. Moreover educators using a research testbed as a remote lab, form their own community that creates a pool of common and up-to-date resources (e.g. lab assignments).
- *Preparing students for research.* Students who are exposed to research testbeds during their coursework are better prepared to use them for their research.

2.2 GENI: A Laboratory for Research and Education

GENI (Global Environment for Network Innovations) is a laboratory for networking and distributed systems research (Berman et al., 2014). It consists of compute and networking resources distributed across the United States. Researchers can reserve compute resources and connect them in Layer 2 topologies that are best suited to their experiments.

Although GENI is a research infrastructure, it has been used extensively in graduate and undergraduate classes as a remote lab by institutions around the world (Figure 1).

GENI is a *sliced* testbed i.e. multiple researchers can run concurrent experiments in isolated slices of the testbed, without functionally interfering with one another (Figure 2). The sliceability of GENI makes it an ideal platform for running classes since multiple students can create virtual topologies on the same infrastructure and multiple labs can run concurrently without interfering with one another or with users running experiments for their research.

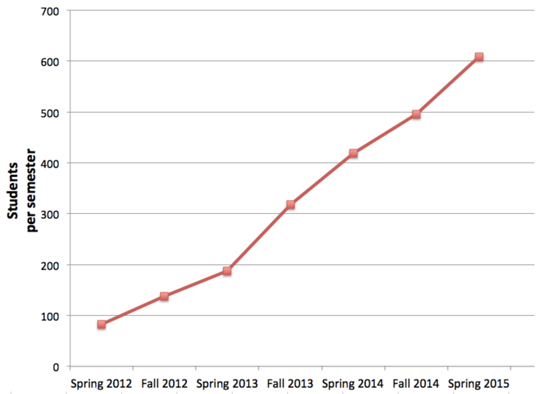

Figure 1: Number of students trained each semster using GENI.

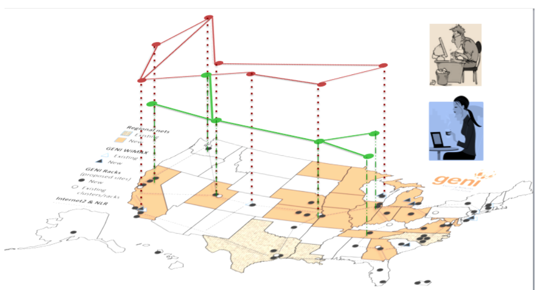

Figure 2: Multiple users can concurrently use GENI in isolated virtual topologies.

Other than its multi-user properties, GENI is a great example of a research testbed that is suitable for education because:

- It is deeply programmable and allows its users to setup, modify, and study network protocols. GENI is suitable for teaching a wide range of networking concepts. It has been used to teach the basics of IP routing and TCP congestion management as well as supported deployment of custom routing algorithms.
- GENI includes unique resources that allows its users to setup interesting experiments. For example:
  - **Software Defined Networking resources**. GENI achieves deep network programmability by deploying programmable network devices (e.g. OpenFlow switches) in the core of the network.
  - **WiMAX base stations**. GENI has deployed and virtualized several WiMAX base stations that can be used remotely for wireless experimentation.
- There is a community of instructors that have developed and shared GENI-based course ware (Marasevic et al., 2013; Griffioen et al., 2013; GENI Project Office, 2014).
- GENI supports collaborative experimentation. In the context of education this enables collaboration between instructor and students and collaborative team projects.
- GENI is designed to support cutting-edge networking research and thus has safe-guards in place to protect the infrastructure from faulty experiments. Additionally, since experimentation is often a process of trial and error, GENI makes it easy for a researcher to terminate an experiment and start over. GENI is therefore a safe environment for students to experiment and start over when necessary, without the need for instructor or administrator intervention.
- GENI employs a single sign-on mechanism that provides easy access to students by simply using their institution login information. This is achieved through InCommon (InCommon, 2014), a US federation based on Shibboleth (Morgan et al., 2004) authentication mechanism. Shibboleth is very popular among educational institution around the world, making it straightforward to provide access to international institutions not members of InCommon.

GENI is not the only publicly available research testbed. Over the past decade several testbeds have been created to facilitate experimentation. Examples of such testbeds include Emulab (White et al., 2002) for networking research, Deter (Mirkovic et al., 2010) for security research, ORBIT (Raychaudhuri et al., 2005) for wireless experimentation, PlanetLab (Peterson et al., 2003) for distributed, peer-to-peer research, OFELIA (Su et al., 2014) for programmable network research, okeanos (Koukis and Louridas, 2013) and, FIRE (Vandenberghe et al., 2013). Although these testbeds are primarily intended to be used for scientific exploration, they have been successfully used as remote laboratories (Wong, 2012; PlanetLab, 2009). Most of these testbeds are either federated or share common APIs with GENI, forming a large ecosystem at the disposal of educators.

3 CASE STUDY

The GENI infrastructure was used for two consecutive years within the laboratory exercises that supplement our 5th year undergraduate course on Network Management Intelligent Networks at the Electrical & Computer Engineering School of the National Technical University of Athens (NTUA), Greece (NET-

MODE, 2015) The main objectives of the lab exercises were to provide students with hands-on experience regarding the reservation, interconnection and usability of dispersed and heterogeneous virtualized resources.

The students in the role of experimenters were asked to create slices, design network topologies and reserve GENI resources at several locations such as Stanford University and the Georgia Institute of Technology. Moreover, students were called to explore the networking capabilities provided by GENI infrastructure. For that, they deployed (i) GRE tunnels to achieve connectivity among resources at different locations and (ii) virtual machines running Open vSwitch acting as Layer 2 software switches connecting the hosts (VMs) in each island.

Overall, 72 users joined the GENI project which was created for the networking class. Amongst them, 68 undergraduate students in 49 groups (comprised of one or two students) were asked to create one slice per group and run their own experiment following the exercise instructions (Figure 3). For the completion of the exercise assignment, 343 VMs were spawned, 98 local networks were created at different sites hosting GENI resources and 49 multi-domain networks were formed. As a result, a significant number of simultaneous users deployed virtual slices across the Atlantic, pushing GENI capabilities to higher levels and indicating feasibility of sharing educational labs across the globe.

Experimenters (students) were provided with the GENI Experimenter's guide along with step-by-step instructions for slice creation via GENI-provided GUI tools. Subsequently, they were called to document their experience by filling in a questionnaire on the following items:

1. *Overall GENI service experience:* 87% of the students noted a good understanding the GENI service functionality and 92% declared that they were satisfied by it.

2. *Resource creation/deletion:* Approximately 74% were satisfied with the reservation procedure. This was highly dependent on students choice of site where the resources were created. Also although 83% of the students encountered difficulties the first time they tried to setup their experiment, 70% of them where able to overcome their problem without help from the instructors and start over.

3. *Resources availability and accessibility:* 35% had difficulties in the process of resource reservation. This might be partially attributed to students oversubscribing for popular GENI resources.

It is worth noting that a staggeringly high percentage of students, 97.5%, declared that the integration of remote labs (not just GENI) in education could advance significantly the quality of their studies.

Moreover the instructors of the class found the role-based membership of GENI projects very valuable. By assigning administrative privileges to the lab instructors, it enabled remote assistance and debugging from anywhere and anytime in response to students inquiries.

4 Benefits in a nutshell

Leveraging public research testbeds, such as GENI, in education yields multifold advantages for both students and educators. Students have the opportunity to work in a collaborative environment and join an active worldwide community engaged in shaping the Future Internet era. Besides the exercise assignments, students experience in practice how dispersed and heterogeneous compute resources can be remotely reserved, controlled and orchestrated through open source tools towards establishing on-demand networking experiments. In fact, in our study at NTUA, 92% of the students declared their eagerness for continuing using GENI for research purposes in the future.

Educators using large scale research infrastructure with unique, otherwise unaffordable, resources and user-friendly tools are able to provide students in advanced networking courses with experiences they would not otherwise have. The geographically dispersed remote labs provide also the opportunity to surpass the geographical barriers by reproducing experiments in different locations and offering to the students a better understanding of how Internet works in reality. For instance, students at NTUA used testbeds to learn how an inter-autonomous system routing policy can enforce global internet traffic.

5 CONCLUSIONS

Technological advances in information technology have radically changed not only our everyday lives but have also transformed education and learning possibilities. They have enhanced the old-school hands-on laboratories where students and infrastructure need to be collocated, with simulated and remote labs (Ma and Nickerson, 2006; Müller and Erbe, 2007).

Recently several publicly availbale testbeds for computer science research have been built and made available to the research community. In this paper we

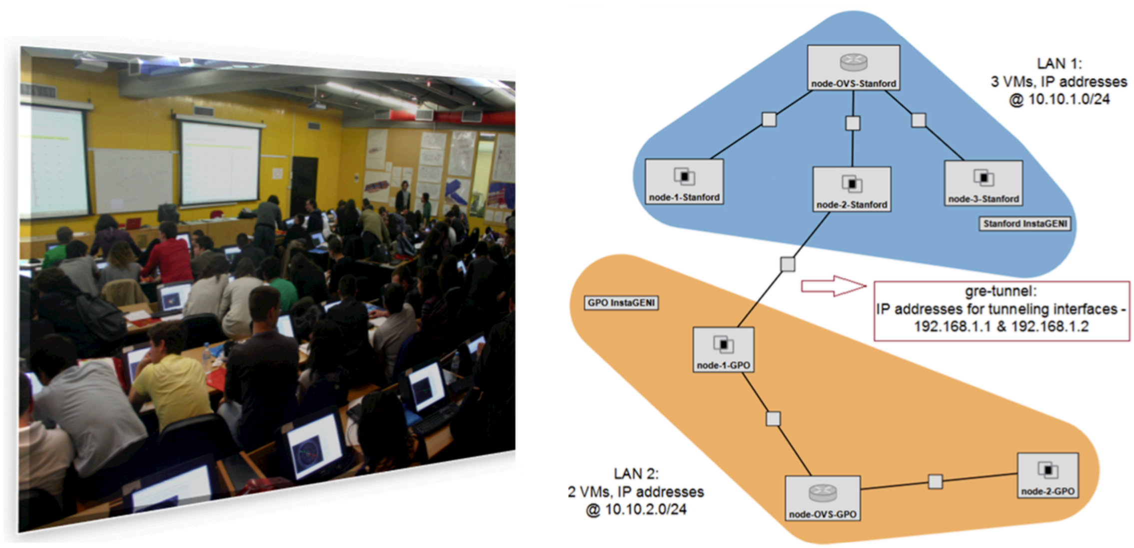

Figure 3: Lab Experiment using GENI Infrastructure at NTUA

argue that these testbeds should be adopted by educators as the platform of choice for developing course modules for computer science cources. There are great benefits to the educators and the students not the least of which are: no need to buy, build and maintain infrastructure, access to unique resources, being part of a community that actively develops and enhances new modules.

Education is moving towards a model of continuous, online learning where the norm will be for students to be remote. We believe that we are going to see an increase in use of remote and virtualized labs. These large scale public testbeds are not only suitable as remote labs for traditional classes but are also ideal for online courses and as a platform for Massive Open Online Courses (MOOC).

REFERENCES

American Chemical Society (2014). Importance of hands-on laboratory science. http://www.acs.org/content/acs/en/policy/publicpolicies/invest/computersimulations.html. Public Policy Statement 2014-2017.

Berman, M., Chase, J. S., Landweber, L., Nakao, A., Ott, M., Raychaudhuri, D., Ricci, R., and Seskar, I. (2014). GENI: A federated testbed for innovative network experiments. *Computer Networks*, 61(0):5 – 23. Special issue on Future Internet Testbeds Part I.

Bruner, J. S. (1961). The act of discovery. *Harvard Educational Review*, 31(1):21–32.

Corter, J. E., Nickerson, J. V., Esche, S. K., Chassapis, C., Im, S., and Ma, J. (2007). Constructing reality: A study of remote, hands-on, and simulated laboratories. *ACM Trans. Comput.-Hum. Interact.*, 14(2).

Fdida, S., Wilander, J., Friedman, T., Gavras, A., Navarro, L., Boniface, M., MacKeith, S., Avéssta, S., and Potts, M. (2011). FIRE Roadmap Report 1 Part II, Future Internet Research and Experimentation (FIRE).

Freedman, M. P. (1997). Relationship among laboratory instruction, attitude toward science, and achievement in science knowledge. *Journal of Research in Science Teaching*, 34(4):343–357.

GENI Project Office (2014). Resources for instructors using GENI. http://groups.geni.net/geni/wiki/GENIEducation.

Griffioen, J., Fei, Z., Nasir, H., Wu, X., Reed, J., and Carpenter, C. (2013). GENI-enabled programming experiments for networking classes. In *Proceedings of the 2013 Second GENI Research and Educational Experiment Workshop*, GREE '13, pages 111–118, Washington, DC, USA. IEEE Computer Society.

IBM News Release (2007). Google and IBM announce university initiative. http://www-03.ibm.com/press/us/en/pressrelease/22414.wss.

InCommon (2014). Incommon. http://www.incommon.org.

Koukis, E. and Louridas, P. (2013). okeanos iaas. In *EGI Community Forum 2012 / EMI Second Technical Conference, Proceedings of Science*, Munich, Germany.

Ma, J. and Nickerson, J. V. (2006). Hands-on, simulated, and remote laboratories: A comparative literature review. *ACM Computing Surveys*, 38(3).

Magin, D. J., Churches, A. E., and Reizes, J. A. (1986). Design and experimentation in undergraduate mechanical engineering. In *Proceedings of a Conference on Teaching Engineering Designers*.

Marasevic, J., Janak, J., Schulzrinne, H., and Zussman, G. (2013). Wimax in the classroom: Designing a cellular networking hands-on lab. In *Proceedings of the 2013 Second GENI Research and Educational Experiment Workshop*, GREE '13, pages 104–110, Washington, DC, USA. IEEE Computer Society.

Mirkovic, J., Benzel, T., Faber, T., Braden, R., Wroclawski, J., and Schwab, S. (2010). The deter project: Advancing the science of cyber security experimentation and test. In *Technologies for Homeland Security (HST), 2010 IEEE International Conference on*, pages 1–7.

Morgan, R. L., Cantor, S., Carmody, S., Hoehn, W., and Klingenstein, K. (2004). Federated Security: The Shibboleth Approach. *EDUCAUSE Quarterly*, 27(4):12–17.

Müller, D. and Erbe, H. (2007). *Advances on Remote Laboratories and E-Learning Experiences*, chapter 2, pages 35–59. Number 6 in Engineering. Deusto Publicaciones.

NETMODE (2015). Courses offered by the netmode ntua lab. http://www.netmode.ntua.gr/main/index.php?option=com_content\&view=article\&id=22\&Itemid=36.

Obstfeld, J., Knight, S., Kern, E., Wang, Q. S., Bryan, T., and Bourque, D. (2014). VIRL: The virtual internet routing lab. In *Proceedings of the SIGCOMM 2014 Conference*.

Peterson, L., Anderson, T., Culler, D., and Roscoe, T. (2003). A blueprint for introducing disruptive technology into the internet. *SIGCOMM Comput. Commun. Rev.*, 33(1):59–64.

PlanetLab (2009). Planetlab courseware. https://www.planet-lab.org/courseware.

Raychaudhuri, D., Seskar, I., Ott, M., Ganu, S., Ramachandran, K., Kremo, H., Siracusa, R., Liu, H., and Singh, M. (2005). Overview of the ORBIT radio grid testbed for evaluation of next-generation wireless network protocols. In *Wireless Communications and Networking Conference, 2005 IEEE*, volume 3, pages 1664–1669 Vol. 3.

Su, M., Bergesio, L., Woesner, H., Rothe, T., Kpsel, A., Colle, D., Puype, B., Simeonidou, D., Nejabati, R., Channegowda, M., Kind, M., Dietz, T., Autenrieth, A., Kotronis, V., Salvadori, E., Salsano, S., Krner, M., and Sharma, S. (2014). Design and implementation of the OFELIA FP7 facility: The European OpenFlow testbed. *Computer Networks*, 61(0):132 – 150. Special issue on Future Internet Testbeds Part I.

Vandenberghe, W., Vermeulen, B., Demeester, P., Willner, A., Papavassiliou, S., Gavras, A., Sioutis, M., Quereilhac, A., Al-Hazmi, Y., Lobillo, F., Schreiner, F., Velayos, C., Vico-Oton, A., Androulidakis, G., Papagianni, C., Ntofon, O., and Boniface, M. (2013). Architecture for the heterogeneous federation of future internet experimentation facilities. In *Future Network and Mobile Summit (FutureNetworkSummit)*, pages 1–11. IEEE.

White, B., Lepreau, J., Stoller, L., Ricci, R., Guruprasad, S., Newbold, M., Hibler, M., Barb, C., and Joglekar, A. (2002). An integrated experimental environment for distributed systems and networks. *SIGOPS Oper. Syst. Rev.*, 36(SI):255–270.

Wong, G. (2012). ProtoGENI and undergraduate courses. http://dept.cs.williams.edu/~jeannie/nsf-workshop/slides/gary.pdf.