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**Allison, Jordan ORCID logoORCID: <https://orcid.org/0000-0001-8513-4646> (2022) Simulation-Based Learning via Cisco Packet Tracer to Enhance the Teaching of Computer Networks. In: ITiCSE 2022, 11-13 July 2022, Dublin, Ireland. ISBN 9781450392013**

Official URL: <https://iticse.acm.org/2022/>

EPrint URI: <https://eprints.glos.ac.uk/id/eprint/11214>

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# Simulation-Based Learning via Cisco Packet Tracer to Enhance the Teaching of Computer Networks

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## ABSTRACT

Teaching and learning computer networks is a crucial part of a computing undergraduates' education. However, it is an abstract topic with theory that can be challenging for students to comprehend. Simulation-based learning can be used as a teaching tool to enhance networking-based lecture topics and help students more easily understand and visualise how it really works in a safe, user-friendly environment. One such simulation tool, Cisco Packet Tracer, can be used to good effect, and this paper reports on the practical implementation of the tool as identified in existing literature. Additionally, this paper discusses how Packet Tracer was utilised as part of a UK based first year undergraduate module 'Computers and Security', and details the content of nine practical sessions, whilst also identifying the main benefits and challenges of their implementation from a practitioner's perspective. It was found that while Packet Tracer can be an additional benefit to augment the teaching of networking concepts, there are limitations and challenges which educators must be aware of if implementing the tool. The paper therefore concludes with providing recommendations which should help educators and curriculum designers in creating and delivering more effective and interactive networking sessions.

## CCS CONCEPTS

• Social and professional topics → Computing education programs; • Networks → *Network simulations*.

## KEYWORDS

Simulation-Based Learning, Packet Tracer, Networking Education, Computing Education, Computer Networks

## 1 INTRODUCTION

Due to the growth and increasing demand for inter-connectivity worldwide, ICT, and associated services [1], specialists in the field of computer networks are required so that effective infrastructure can be designed, built and maintained [4, 15]. This requires a supply of suitably qualified professionals, and therefore this places an importance on suitable education and training in computer networks. A fundamental knowledge of networking has become crucial within computer science, cyber-security, and engineering education [11, 17, 25], with the joint task force of ACM and IEEE indicating how networking is a key knowledge area in the curriculum guidelines for undergraduate degrees in Computer Science [10].

Learning about computer networks is a complex task [7], as there are many different features and functions, so a lot of time and energy is required by students in their studies [9]. Therefore, teaching computer networks can be a challenge for both students and teachers, most notably as some of the more theoretical concepts are difficult to explain and understand [17, 22]. This makes practical sessions extremely important so students can more effectively link theory to practice. Besides, only focusing on theory can make it difficult for undergraduate students to have a deeper learning experience which would have long-lasting effects [1]. Unlike practical sessions in topics such as programming which can often only require a computer [17], there are extra resources required in teaching computer networks such as networking equipment which can both be costly and take up a lot of space [4, 18]. In situations such as this, simulation tools are beneficial to overcome these issues.

## 2 SIMULATION TOOLS FOR TEACHING COMPUTER NETWORKS

Networking as a subject often requires students to spend time in a lab, and with larger groups of students, it may be challenging regarding timetabling to give each student enough access to equipment [9]. Furthermore, when setting complex networking assignments and projects in educational settings, implementing this effectively can be challenging [18, 22], while in practice, real-life situations without proper guidance may be overtaxing for students [5]. However, it has been described that computer animations can help students more quickly comprehend the functionality of networking protocols [9], while the most frequently used visualisation object is network simulation [17]. For teaching computer networks, there are a variety of simulation tools available for educators to choose from. Two of the most common are Cisco Packet Tracer and GNS3 (Graphical Network Simulator 3) due to minimal costs and being student friendly [20]. Other choices include OPNET (Optimized Network Engineering Tool) Network Simulator, Network Simulator (NS-2/NS-3), and NETSIM.

For any simulation tool used, consideration must be given to the purpose of the tool and how it is used for teaching and learning [7]. For example, there is the danger that the mere completion of tasks, such as completing the steps in an exercise to configure a networking device will not necessarily allow for a deep understanding of the topic [7]. This very much brings up the debate of deep versus surface learning as illustrated by [3]. If using a simulation tool for educational purposes, the practical lab or session should be scaffolded in such a way to allow students the opportunity to apply their learning. If students are instead given full guidance on how to do something, this may lead to students simply completing the lab, as opposed to understanding the 'how' and 'why' of what the lab contains. This is more akin to surface learning [3], and does not help the student should a similar networking situation arises again. For instance, [7] found that even when students had completed a set of exercises, when they were given other exercises that built upon these completed sessions, they had difficulties in completing the work. Hence, it is likely that only surface learning was achieved through those initial sessions. However, it has been reported that designing practical lab exercises that enable deep learning and understanding of theory is a significant challenge [17], and this gives precedence to the importance of what educational initiatives have taken place to teach computer networks through the utilisation of simulation tools.

Simulations are a very effective way to design learning environments within higher education [4, 5], and this paper will explore simulation-based learning in the context of computer networks. While earlier literature has claimed there are few studies which investigate how simulation-based learning is used in assisting the learning of computer networking [14], as time has progressed, the abundance of papers reporting on such studies has increased. Therefore, this paper will consider one main network simulation tool, Cisco Packet Tracer, and aim to answer this research question: *What are the benefits and challenges of utilising Cisco Packet Tracer in the teaching of computer networking concepts?*

To help answer this research question, first, an overview of the tool will be provided, followed by examples from literature of how the tool has been used for educational purposes. Next, this paper will explore the background context to the authors own implementation of teaching and learning where Cisco Packet Tracer was utilised for first year undergraduate students on a 'Computers and Security' module of study. Following this, details of nine created practical labs will be provided, with reflections of what worked well (or not). Finally, through the combination of literature and practitioner experience, recommendations on implementing the Cisco Packet Tracer tool for use in teaching computer networks will be provided.

## 3 OVERVIEW AND USAGE OF CISCO PACKET TRACER

A literature review of methods of teaching computer networks found that 39% of the papers included in the study utilised Cisco Packet Tracer [17]. Cisco Packet Tracer is a longstanding simulation environment that provides a wide

variety of features and functions which allows both students and educators to create and test complex and wide-ranging networking scenarios [18–20]. It allows the opportunity for educators to promote independent active learning, while not being overly onerous for students [7]. Packet Tracer has an interactive graphic user interface where users can simply ‘drag and drop’ networking devices (e.g. routers, switches, workstations, servers, IOT devices), connect devices via networking cables (e.g. coaxial, copper straight-through, serial DTE/DCE), while also providing a command line interface for configuring the network devices where users can enter IOS commands [12]. Therefore, Packet Tracer has commonly been used in educational initiatives to enhance student learning of computer networks.

One experience of using Packet Tracer had the aim enhancing the learning of network concepts by students through the creation and implementation of four practical laboratories (labs). These labs included the demonstration of network commands and the Packet Tracer tool itself, interpreting ping and traceroute output, troubleshooting and resolving network issues, and examining the functionality of TCP, UDP protocols and demonstration of application layer protocols [25]. Through conducting a quiz before and after the activities, the authors found that student understanding of networking concepts improved significantly [25]. This has been shown to be the case by other authors too. For instance, one early study details the content and process of seventeen learning modules which were for students to perform in groups [27]. Ranging from setting up a peer-to-peer network to building an intrusion prevention system (IPS), the authors explain how each class consisted of a regular lecture and then a hands-on practical lab, but overall, each class was designed with four components in mind: each linking to different learning phases. These included a background and reflection phase, the introduction of a new topic, a hands-on lab, and then applying the newly found knowledge in a real-world situation [27]. The authors described how using the simulation labs improved student learning of networks. More recently, a study based in the UAE analysed student opinions over a four-year period regarding the delivery and implementation of practical networking simulation activities [1]. Through using five-point Likert scale questions, the authors found that students perceive that the lab courses enhanced their learning experience [1].

Other authors have gone further in their analysis of student surveys. For instance, an introductory course to IT conducted at a university in Taiwan for students (n=43) used Packet Tracer to augment their networking lectures [14]. The authors proposed thirteen hypotheses regarding the association between factors such as the interactivity of Packet Tracer (information representation, and responsiveness), student’s perception towards Packet Tracer (usefulness, enjoyment, and education value), self-evaluation, and intention of use. They found that interactivity is influential on a student’s perception towards Packet Tracer, while perceived enjoyment is significantly associated with intention of use [14]. Similarly, [12] explored the relationship between six variables (interactive user interface, perceived ease of use, confirmation, satisfaction, perceived usefulness, and intention of Packet Tracer use) through conducting an online questionnaire with students (n=37) enrolled onto a Computer Networks and Security course at a university in Thailand. While only a small sample, they found that through simple linear correlation, that perceived ease of use, perceived usefulness, satisfaction, and an interactive user interface equally had a strong impact on intention of use [12].

	Citation
Provides multiple functionalities to replicate the real world	[4, 8, 9, 13, 14, 17, 19]
Safe environment for security education	[20, 23]
Can save money for institutions (e.g. it can negate the need to upgrade lab equipment as often)	[4, 17, 20, 23, 27]
Negates the need to have as much lab equipment and facilities, thus saving space	[4, 9, 14, 17, 23, 24]
Packet Tracer is upgraded periodically with latest hardware for students to simulate	[23]
Students can practice lab assignments at home without the need for networking equipment	[4, 6, 9, 13, 17, 23, 24]
Allows students to tackle large complex topologies	[6, 9, 17, 24]
Suitable for distance learning students	[8, 9, 17, 19, 24]
Student/User friendly	[13, 17, 20, 27]
Useful for testing and evaluating student learning	[9, 13, 15, 17, 24, 25]
Helps students and teachers to collaborate	[6, 8, 9, 15]
Students can have no fear in damaging networking equipment	[17]
Extends/enhances the learning experience	[6, 9, 13, 14, 17, 22, 25, 27]
Develop problem solving, creative and critical thinking skills	[6, 8]

Table 1: Benefits of Using Packet Tracer

While the studies so far indicate factors relating to student learning, others compare student perspectives between Packet Tracer and real devices. A Slovakian based study conducted a survey of students studying computer networks in 2009 [9], and found that 90% of students felt that Packet Tracer was sufficient enough to meet their needs when asked about the functionality between Packet Tracer and real devices [9]. Similarly, a Romanian based study evaluated the use of Packet Tracer for teaching computer networks and embedded systems to students (n=56) in 2018 [6], and found that most students (n=50), preferred Packet Tracer activities to learn, with just a small minority (n=6) stating that access to hardware equipment helped them prepare for their final exam [6]. However, using real-world devices is essential for teaching and learning computer networks [17], with some authors explaining how students may only clearly understand what is happening when faced with actual networking equipment [9, 24]. Nevertheless, simulation tools do allow educators to overcome some issues which can be present in using real devices, such as when teaching about cyber security.

When teaching aspects of network security, simulation tools such as Packet Tracer are particularly important, as they provide a safe environment to do so without the chance of serious problems occurring [23]. For example, [20] and [23] discuss how they used Packet Tracer to create four practical labs regarding firewalls which included filtering inbound ping traffic, filtering inbound traffic based on an IP address, filtering inbound web traffic, and implementing host filtering based on a devices Media Access Control (MAC) address. Feedback from students (n=52) indicated that these four practical labs had a positive influence on their understanding, with classroom instructors also indicating this too [23]. However, instructors also mentioned how Packet Tracer does not allow

students to efficiently learn how to defend against attacks, nor in setting up the firewalls physically [23]. Equally, some authors have described how Packet Tracer has the limitation that some commands, protocols and functions do not work on real devices [24]. However, Packet Tracer can provide many benefits from both a student and teachers perspective, as indicated in Table 1.

While many benefits exist when using Packet Tracer as evidenced by the literature, this paper will now explore the implementation of using Packet Tracer and provide details surrounding both the benefits and the challenges from a teaching perspective. However, first the context in which the teaching took place must be explained.

## 2 CONTEXT OF PRACTICE

This paper reports on the experience of utilising Packet Tracer within a first-year undergraduate module 'Computers and Security' delivered in the first semester of the academic year 2021-2022. This module introduces students to a variety of topics such as cyber security principles, number systems, computer architecture, operating systems, and an introduction to networking and security measures. Just over one-hundred students are enrolled onto this module, and consist of computer science students, cyber security students and cyber forensic students. Furthermore, the students come from a variety of backgrounds, with some having studied networking concepts before, including using Packet Tracer, while others had extremely limited knowledge on the subject. Therefore, the teaching and learning approaches needed to be flexible enough to accommodate the needs of such a broad cohort of students.

The module delivery consisted of the overall cohort being split into two groups, where each group had a three-hour session once a week for a period of twelve weeks. Generally, the teaching and learning of computer networks is separated into two parts, a theory part and a practice part [12], and this was no different in this module. Furthermore, as suggested by [17], teaching computer networks should be oriented towards more practical experimentation than theory, and should include active participation by students. Therefore, each three-hour session was divided into two. The first 75-90 minutes consisted of theory through standard lecture delivery, although within this time, student research tasks were included, such as exploring theoretical concepts, identifying academic literature related to the topic, or linking theory to real life attacks or security breaches. The other 90-105 minutes were devoted to practical sessions where students could put the theory into practice.

A constructivist ethos was taken to guide the teaching approach, which is based on the view that students construct their own systems of knowing unique to them [16], based on their own experience [26]. Hence, this view influences the teaching and learning approach, and guides educators to focus on how to ensure students can construct their knowledge in an effective way. One aspect of doing this was to ensure that there was 'constructive alignment' [2] between learning outcomes, the theory and practical sessions, and the assessment method. Packet Tracer as a simulation environment has been described as being synonymous with a constructivist approach [19], and with design-based projects being identified as a way to integrate learning in many computing and engineering courses [18], utilising tools such as Packet Tracer was included as part of the student assessment. However, unlike some educational initiatives that have tested student's ability at using Packet Tracer through means such as exams [1], the assessment for this module was a piece of coursework.

Students were given a brief and needed to act as a cyber security consultant for a school who had decided to update its computers and network. Students would need to write a fully referenced 2000word report (weighted at 60%), where they would need to make assumptions and provide recommendations for security measures to be implemented, and what operating system they would recommend. In addition to this, students needed to submit a Packet Tracer file of their network design and configuration in regards to the given brief (weighted at 40%). The provided brief also included the following details:

- There is a general open-plan teaching staff office, and this must contain three hot desk computers, and a printer. Teaching staff are allowed to bring their own devices such as laptops to work, so this office should have wireless connectivity available.
- There is a student computer lab containing 15 PCs.
- The IT department consists of a small team of two, they should have their own desktop PC and they maintain two servers, the file server, and the email server (which has the IP address 192.168.100.22).
- One router (border router) should have the connection to the ISP for the Internet (web server).
- The three areas (departments) should each be a separate network. However, the following should apply: Students (i.e., the computing lab) should not be able to communicate and access the teaching staff or IT departments. However, they should be able to access the file server only. Teaching staff should be able to communicate with everyone else and have access to the mail server and web server, but not the file server. The IT department should be able to access and communicate with all three servers and the other departments.

Having both elements to the assessment (report and packet tracer configuration) ensured that students developed the skills of evaluating a brief, applying their knowledge towards the creation of a technical implementation, but it also meant students could develop their report writing skills, and ability to conduct academic research and referencing. Furthermore, as suggested by [8, 18], hands-on

4

projects allow students the opportunity to integrate critical thinking, communication skills, and to demonstrate their cumulative knowledge in order to solve a problem. All these skills are important skills for students to develop in their first year of undergraduate study, so the aim was for the created assessment to allow for these skills to be developed effectively. In order to prepare students effectively for this, a variety of nine practical lab sessions using Cisco Packet Tracer were created.

### 3 PACKET TRACER PRACTICAL LABS

Lab 1 (My First Ping): This lab served as an introduction to Packet Tracer, including its installation, and then configuring two workstations via a hub, and then pinging one workstation from another. Finally this lab involved adding another workstation, and using the simulation mode to 'visualise' the ping.

Lab 2 (My First Network): This lab introduced routers, and included configuring two sets of three workstations connected to a switch, where the two switches are connected to the router. This lab also served as an introduction to the router command line interface.

Lab 3 (Direct and Static Router Configuration): This lab served as an introduction to static routing, connecting two routers via a serial connection, and pinging workstations either side of each router.

Lab 4 (Static Router Configuration 2): Again two routers connected via static routing, where one router is connected to a server, with the other connected to a laptop. This lab also introduced using a web page on a workstation, and visualising the difference in connectivity before and after adding the static routes.

Lab 5 (Static Router Configuration 3): This lab built upon the skills learnt from the previous labs, and involved the addition of a log server, with the goal to simulate the transfer of unknown packets to the log server (Figure 1).

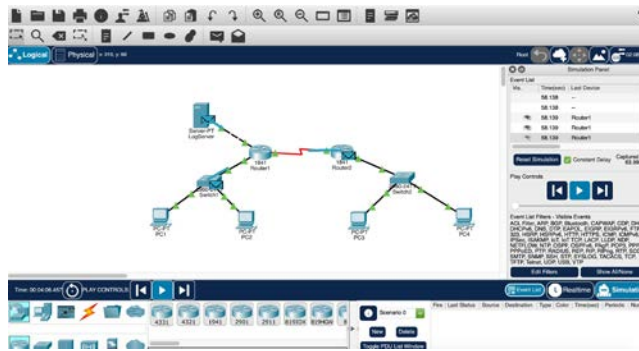


Figure 1: Lab 5 Configuration: Static Router Configuration 3 (in simulation mode)

Lab 6 (Access List Configuration): This lab involved setting up a network and configuring standard access lists to remove access to a server from a workstation. This lab also involved using extended access lists to prevent an entire subnet having access to a different server.

Lab 7 (Basic Firewall Implementation): Building on the works of [20, 23], this lab introduced some basic levels of firewall implementation in Packet Tracer. This included allowing/denying certain ICMP traffic, and filtering in bound web traffic (see Figure 2).

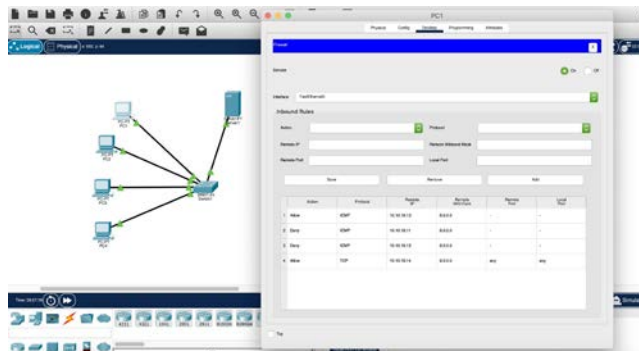


Figure 2: Lab 7 Basic Firewall Implementation (via traffic filtering)

Lab 8 (Wireless Network Configuration with WEP): This lab introduced wireless devices, and an introduction to using a wireless router GUI, and changing modules on devices. This lab also involved disabling DHCP by default, changing wireless router settings such as default passwords, disabling SSID broadcast, and setting up WEP encryption.

Lab 9 (Wireless Network Configuration 2): This lab involved adding wireless LAN security, and configuring the internet interface on the router to connect the LAN to the internet. This involved setting up the internet interface to act as a DHCP client, with the DHCP server configured on the ISP router (see Figure 3). This lab also included configuring MAC address filtering on wireless laptops.



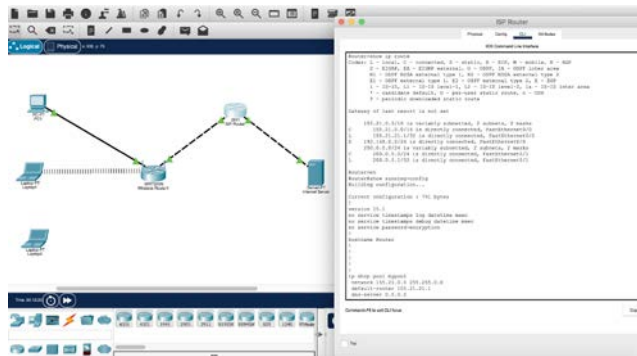


Figure 3: Lab 9 Configuration (with Router Command Line Interface)

### 3.1 Practical Lab Implementation

Much like earlier work that reports on how some students have difficulty with subsequent exercises that build on future work [7], the same thing happened with the student cohort in regards to the nine practical Packet Tracer labs. For instance, the earlier labs provided guidelines on how to set IP addresses, subnet mask and default gateways on devices, but as the labs progressed, these guidelines were removed on the assumption students would have gained the knowledge on how to do these types of tasks. In later labs, students were merely given an address table and a screenshot of the intended network design and had to configure the devices and routing themselves. However, they would then be provided with guidelines on how to configure network security measures such as access control lists or MAC address filtering. While this approach would hopefully address the problem of students merely following instructions and demonstrating superficial learning [17], issues did occur with some students complaining and being frustrated that the lab tutorials did not provide sufficient guidance. This occurrence was not a surprise as prior experience, in addition to academic literature has highlighted how users can get frustrated or even upset with Packet Tracer [24]. However, in occasions like this, students were reminded that for their assessment, they would not be provided with any guidelines so learning how to configure networks themselves was extremely important. In these situations, students were also guided to refer to previous labs, as opposed to simply being told how to do something.

Another issue faced was students thinking that an implementation in one lab was applicable in all situations, most notably due to the lack of experience they had so far with network design and configuration. Equally, the most common issues throughout the module regarding student Packet Tracer problems included not setting default gateways, not saving configurations, using the wrong cabling, having incorrect IP addresses set, and configuring devices across the wrong interfaces. Unfortunately, a weakness of Packet Tracer is that when something is not configured correctly, it does not tell you what the issue is, and while it can be argued that feedback from a simulation tool should be clear [17], this does mimic real life. That said, when something is configured correctly, you can relatively easily identify whether that is the case, for instance, through pinging a device from another. This served as great satisfaction for many students when completing a lab exercise and helped in gauging student progress.

When students had issues, a common theme was a student's lack of intention to troubleshoot problems themselves, often asking for help, and simply saying 'it does not work'. When teaching networking through using simulation tools such as Packet Tracer, it is important to consider the possible challenges students could face so a plan or mitigation's can be put in place [17], with appropriate scaffolding to maximise the opportunities for learning [5]. Therefore, when presented with situations like this, learners were instead provided with some

guidelines of how they could find out the information and where from, to encourage students to become more independent and research conscious. A similar approach was used when students sent questions via email, although they were also guided to ask their questions on a shared forum, so the whole student cohort could see the questions and answers and minimise the number of emails received.

The implementation of practical Packet Tracer labs appeared to help improve student understanding overall, and while this is synonymous with other authors [7, 15, 24], it should be recognised that there was a wide disparity of learners, with some students having zero knowledge of networking, so it is difficult to quantify how much they would have improved if Packet Tracer was not utilised as a tool. Equally, some of those students who had used Packet Tracer before brought misconceptions on how to use it. Therefore, it was important from the very start to not assume student knowledge [17] and ensure the tutorial labs contained sufficient guidance for students starting from this point. However, this was a time-consuming endeavour, an already cited issue [17], which practitioners should consider if looking to implement Packet Tracer themselves.

#### 4 CONCLUSIONS AND RECOMMENDATIONS

Within higher education, opportunities for students to apply knowledge in simulation environments is crucial [5]. Therefore, this paper has instead culminated findings from existing literature, before presenting the context of how Cisco Packet Tracer was utilised as part of a teaching and learning strategy for first year undergraduate students for the module 'Computers and Security'. In addition to providing details regarding the module, student assessment, and practical labs, this paper has provided practitioner perspectives on what worked well (or not). This is significant considering the importance of bridging the gap between learning outcomes, teaching content and assessment [2], especially for computing lecturers [21].

Formative feedback was given to students regarding their ability to configure each practical lab, in addition to providing feedback when students conducted research tasks in class. However, a single synoptic assessment was used to assess students regarding their knowledge of networking and using Packet Tracer, their ability to conduct research, and how students can effectively contextualise security requirements for a specific case. From a teaching perspective, it was evident how initially, student learning was more akin to surface learning, where students may have had a greater focus on completing the labs, as opposed to learning the networking concepts effectively [3]. However, as the module progressed, the assessment deadline drew closer, and the practical labs provided less initial guidance, it was clear how deeper learning was being achieved by some students, as they could apply their learning to networking configurations more comprehensively, for instance, by also including aspects not taught on the course. Overall, this implementation of Cisco Packet Tracer resulted in some key lessons being learnt during the module, which can serve as guidelines or recommendations for educators willing to adopt a similar approach.

##### 4.1 Recommendations

The following recommendations have been suggested based on the teaching experience reported and from existing literature:

- Set clear expectations for the module delivery from the very start of each module and keep clarifying expectations as sessions progress.
- In each session, highlight to students the learning goals or objectives at the very start so students understand the plan.
- Highlight to students how the overall module delivery fits together, and why each session is important for their course.
- Ensure there is a clear link between the lecture topics (theory) and the practical Packet Tracer sessions.

- Ensure there is a clear link between lecture/practical sessions and the learning outcomes and assessment (i.e. constructive alignment).
- Do not tell students how to solve every problem, for instance troubleshooting a network for them. Instead provide some guidance of what the issue may be, or how they could find out how to solve the issue or minimise its likelihood of occurring.
- In the creation of practical Packet Tracer labs, try to ensure each one slowly builds on prior knowledge of the previous lab, as there is so much students could potentially explore on the simulation tool.
- Once any common student issues or misconceptions are identified, address these to the class more widely or in the subsequent session (in the context of what is reported in this paper, this predominantly included not setting default gateways, or not saving configurations correctly).
- Ensure plenty of opportunities to build rapport with students and gauge their understanding, this can be done when setting research tasks or in the practical sessions, by speaking to each student and finding out how they are getting on.
- For larger cohorts of students (e.g. 20+) try to have more than one instructor during the practical session to speak with students and help provide guidance with any issues.
- Encourage students to engage in collaborative discussion and helping each other out.
- Consistently ask for feedback from students about what is working well (or not).
- Recognise the disparity in student ability and that while some student questions may seem basic, help them effectively so they will not be deterred from engaging in the course.
- Some students may be less willing to engage in the course. In these situations, still check in with how they are doing and offer support as and when needed.

Simulation based tools such as Packet Tracer have been used successfully internationally, whether that is for classes taught face-to-face [1, 24], for distance learning students [19], or as part of an incorporation with virtual learning environments [15]. While Packet Tracer has also been implemented successfully in the context reported in this paper, educators need to be aware of the limitations that can be faced when utilising these types of simulation tools. Some authors highlight how simulation-based learning allows reality to be brought closer to the teaching environment [5, 22], but simulation tools are not reality. Packet Tracer does not contain all functions and features that can occur in the real world, and teaching networking needs to keep pace with the rapid developments that are taking place [24]. Furthermore, there can be the assumption that using simulation tools will encourage deep learning, but this assumption is incorrect [7]. Utilising simulation tools are just one part of an overall pedagogical approach, so educators cannot simply let students loose on using simulation tools and assume learning will take place effectively. Following some of the recommendations provided in this paper should help educators and curriculum designers mitigate against this possibility if simulation tools are to be adopted in other educational contexts.

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