System For Pratical Evaluations of Network Administration Course
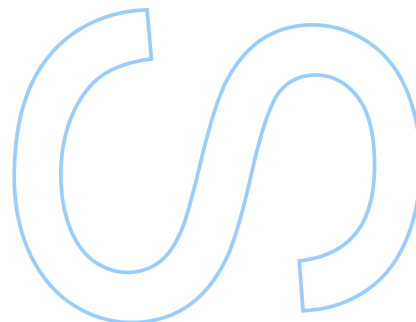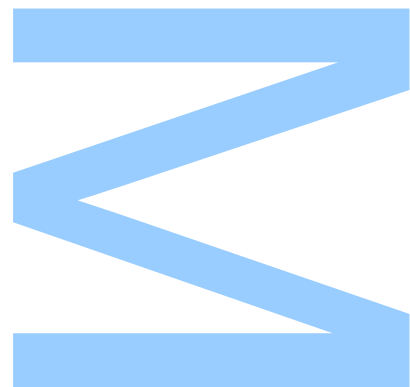
Diogo Nunes

Mestrado em Engenharia de Redes e Sistemas Informáticos
Departamento de Ciência de Computadores
2025

Orientador
Prof. Rui Prior, Faculdade de Ciências
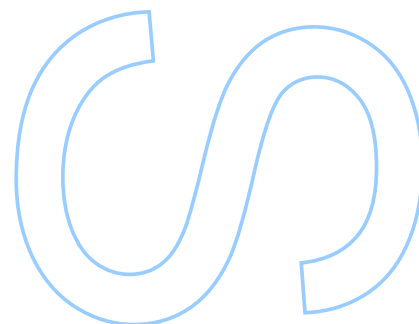
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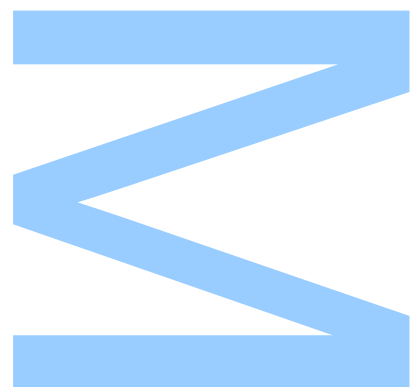UNIVERSIDADE DO PORTO

Todas as correções determinadas
pelo júri, e só essas, foram efetuadas.

O Presidente do Júri,

Porto, _____/_____/_____

Acknowledgements

Acknowledge ALL the people!

Resumo

Este tese é sobre alguma coisa

Palavras-chave: física (keywords em português)

Abstract

This thesis is about something, I guess.

Keywords: Computer Science

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ANN Artificial Neural Network. 6

CS Computer Science. 1

1. Introduction

In today's digital age the need for qualified Computer Science (CS) professionals is growing. The CS field is vast and has many areas of expertise, one of which is network administration. It is a crucial part of any organization, as it is responsible for the maintenance and management of the organization's network infrastructure. Proper training for network administrators is crucial for preparing them for real-world situations. One way to provide this training is through practical evaluations, allowing students to apply the knowledge they have acquired in a real-world scenario, helping them to develop the skills they will need in their future careers.

Creating a physical network environment for practical evaluations may be costly and challenging to scale for large student populations. Emulation and virtualization technologies can help to simplify and cost-effectively create practice environments for students. These technologies alone do not address the issue of manually reviewing a network topology's setup. Manually reviewing each student's network configuration can be time-consuming and prone to human error, rendering it challenging for their instructors. Automating the evaluation process may substantially alleviate the burden on educators and guarantee uniform and fair assessments.

1.1. Aims and Objectives

This dissertation continues the work of a previous student, who carried out research and first steps of development of a system for automated evaluation system for network topologies[1]. The main goal is to design and implement a scalable system capable of automatically evaluating evaluating network topologies that make use of different vendors and device types. The support for different vendors and device types is crucial, as it allows students to practice with a variety of networking equipment, preparing them for the real-world scenarios they will face in their future careers. Automating the evaluation process will help educators dedicate more time to other tasks such as supporting students, and would also provide a more consistent and fair evaluation, eliminating the possibility of human error.

Talk about the end goal

The main steps of this project are as follows:

- Study the bases for the system already developed

- Requirements gathering

- Identification of the main problems that need to be solved

- Proposal of solutions for these problems

- System design

- Implementation of a prototype

- Testing with volunteers to validate the system and identify possible limitations.

2. Background

This chapters main focus is to provide the reader with the necessary background information to understand the context of this project. The main goal of this project is to provide a system capable of automatically evaluating network topologies by validating configurations and running tests on different devices in the network. Analogue systems exist in the market, primarily focused in programming. These systems receive code from students and subsequently run tests on it against multiples test cases and are already widely deployed in educational environments. Shifting from programming to network topologies appears simple at first glance but comes with a particular set of challenges not present in programming evaluations. Each student will require an individual working environment, which can be addressed by using virtualization platforms. There is also the matter of communicating with the devices in the network, which can be addressed by using network automation tools. Finally there is the matter of combining these technologies to create a system capable of automatically evaluating network topologies.

2.1. Programming Evaluation Systems

While not directly related, they are the main inspiration for this project. Programming evaluation systems are widely deployed in universities and other educational institutions. These systems receive code from students and subsequently run tests on it, outputting a score and even being configurable to provide students the first test case that they failed in, guiding students to the solution without handing it out.

These tools typically provide a structured approach to test coding and problem solving skills. They begin by offering a problem statement coupled with an optional image and an example test case, normally in the form of input and expected output. Users can interact with the system by use of an online code editor, where they can write their solution and submit it for evaluation, or by uploading a file with their solution. The system then evaluates the provided solution against multiple pre-defined test cases, and validating the output against the know-good output, outputting a score based on the number of test cases passed. The system may also be configured to have time and/or memory constraints, to ensure that temporal and spatial complexity are also taken into account.

All of these, serve to provide a thorough evaluation of the student's solution, which can help guide a student to better their coding and problem solving skills.

In the context of the Department of Computer Science (DCC), Mooshak and Codex are commonly deployed to be used in the context of classes and even exams and programming contests.

The main differentiator between these systems and the one proposed in this project is the ability to solve a network exercise using multiple configurations across multiple devices, while programming evaluation systems will expect the same output every time, given the same input. Another key difference is the fact that programming evaluation systems dont always provide a working environment for the students to test their code, owing to the fact that students might prefer to user their own development environment for initial development and testing. This project aims to provide a working environment for students to work on for a few reasons that will be discussed later on

DISCUSS REASONS WHY LATER

2.1.1 Mooshak

Mooshak is a web-based system for managing programming contests and also to act as an automatic judge of programming contests [2]. It supports a variety of programming languages like Java, C, etc. Under each contest students will find one more problem definitions each containing varying sets of test cases in input-output pairs. After submiting their solution, the system will compile and run the code against the test cases giving a score based on the the amount of test cases passed. The system can also differentiate between differing types of errors, such as not giving the expected output, poorly formatted output, failure to compile or even exceeding the time limits. Mooshak also includes some features designed to drive competition between students, like a real time leaderboard and the ability to have more than 100% of the score for a given contest.

The system however is not without its limitations as it uses plain text files for its test cases and validates the output of student's code character by character, which can lead to false negatives if the output is not formatted exactly as expected.

2.2. Virtualization

Virtualization is the process of creating a virtual version of physical resources, such as routers, switches, or even entire computers. In the context of this project, it is used to create virtual machines to provide students with a work environment and virtual networks, comprised of various types of virtualized devices. This approach enhances scalability and reduces costs, as it allows multiple virtual machines to be run on a single physical machine.

Virtualization can be categorized into **emulation** and **simulation**.

- Emulation is the process of creating a virtual version of a physical device in software, replicating its behavior exactly—including any bugs and limitations. This is useful for various things like testing software on different platforms, running legacy software on modern hardware and even running potentially harmful software in a safe isolated environment. Emulation will be used to provide students with a work environment to test their network configurations, as well as to emulate certain network devices.

- Simulation models the behaviour of a device, without replicating the underlying hardware or software. This results in a simpler less resource intensive model, though it may not fully capture the real device's behavior. Simulation will be used to simulate the behaviour of certain, simpler and generic, network devices.

2.3. GNS3

Graphical Network Simulator-3 (GNS3) is an open-source graphical network emulator software that allows the user to create complex network topologies and interact with the various devices in it. It is widely used for educational purposes and is often used in preparation for professional network certifications like the Cisco Certified Network Associate (CCNA).

GNS3 employs a simple drag and drop interface to allow users to add new devices, make links between them and even add textual annotations. The software allows users to interact with the devices by way of a console or even a GUI if the device supports it. The software also allows users to export their topologies to be shared with others, which can be useful for teachers to provide students with a pre-configured topology to work on.

Additionally, the software supports packet capturing which is essential for students to develop their debugging and troubleshoting skills. Finally it can also be interacted with via a Representational State Transfer (REST) Application Programming Interface (API) which is of particular interest for this project.

2.3.1 Architecture

The software can be employed in a variety of ways due to its architecture [3] that separates the user interfaces that it offers, namely the locally installed gns3-gui as well as the browser accessible gns3-web, from the gns3-server that runs the emulations and the controller who orchestrates everything.

2.3.1.1 Controller

The controller is integrated in the gns3-server project and is responsible for communicating with all the other components of the software. The controller is a singleton, meaning there should only be one instance of it running at any given time, and it does not support concurrent requests. It is able to control multiple compute instances if so desired, each capable of hosting one or more emulator instances, varying depending on their complexity. The controller also exposes the REST API allowing the ability to interact with the software programatically. All communication is done over Hypertext Transfer Protocol (HTTP) in JavaScript Object Notation (JSON) format and there is support for basic HTTP authentication as well as notifications via websockets.

2.3.1.2 Compute

The compute is also integrated in the gns3-server project and controls the various emulators required to run the nodes in the topology. The list of currently supported emulators is:

- **Dynamips** - Used to emulate Cisco routers and basic switching.

- **IOS on Unix (IOU)** - Used to emulate Cisco Internetworking Operating System (IOS) devices.

- **Quick Emulator (QEMU)** - Used to emulate a wide variety of devices.

- **Virtual PC Simulator (VPCS)** - A basic program meant to simulate a basic PC.

- **VMware/VirtualBox** - Used to run virtual machines with nested virtualization support.

- **Docker** - Used to run docker containers.

2.3.1.3 GUI

The GUI is composed of two separate but with mostly identical functionality, namely the gns3-gui and the gns3-web projects. The gns3-gui project is a desktop application that is used to to interact with a local or remote gns3-server instance. It is written in Python and uses the Qt framework for the graphical interface. The gns3-web is a web application that is accessed via a web browser it is still in a beta stage but is already capable enough to be used as a substitute for the gns3-gui.
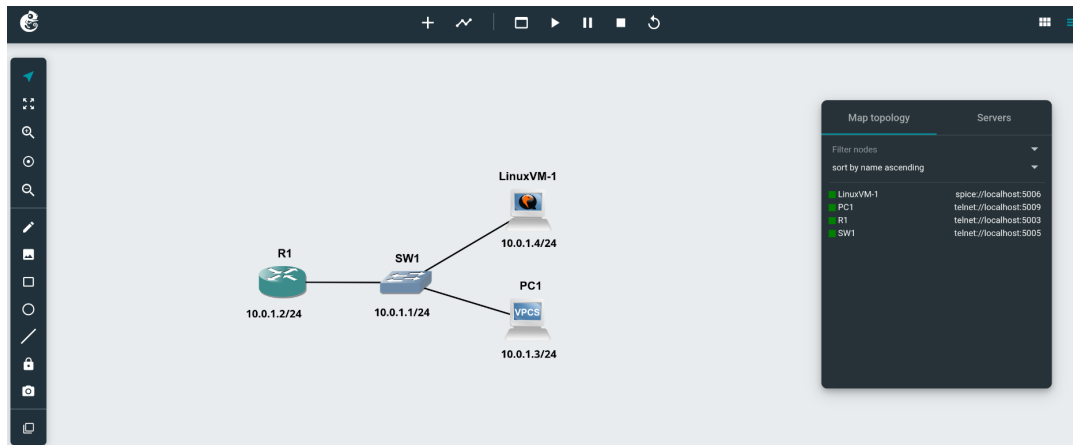
Figure 2.1: A simple network topology example in the GNS3 Web UI

2.4. Linux

Linux is a core component of this project, as it is the operating system used to host all the services provided.

- **Containerized Flask Application** - The Flask web application runs inside an LXC container on Proxmox. Since LXC containers share the host kernel, the containerized Flask app benefits from efficient resource usage while maintaining isolation from the host system.

  "Flask" subject to change

- **Virtual Machines hosting GNS3** Proxmox also hosts virtual machines running Linux-based Ubuntu GNS3 servers. These VMs provide students with isolated environments to configure and test network topologies, benefiting from the flexibility of full virtualization through KVM, giving them the ability to virtualize any type of network device. Students only interact with these Virtual Machine (VM)s via the GNS3 web Interface.

- **Proxmox Virtual Environment (Proxmox VE)** - Proxmox is a Linux-based open-source platform for enterprise-level virtualization. It is based on the Debian Linux distribution.

2.5. Proxmox Virtual Environment

 Proxmox VE is an open-source platform designed for enterprise-level virtualization [4]. It is based on the Debian distribution of Linux and provides a web-based interface for managing virtual machines and containers. It is widely used in data centers and cloud environments, as it provides a scalable and reliable solution for virtualization.

Proxmox VE bundles several core services that can be interacted with via shell commands, a web interface or even by using the Proxmox VE REST API. These allow the user to interact with every service provided by Proxmox VE, in a plethora of ways, depending on the user's needs, skills and preferences. The web interface is the most user-friendly way to interact with the platform, as it provides a graphical interface for managing the cluster. The shell commands provide a more direct way to interact with the platform, allowing for more complex operations to be performed and opening the doors to scripting and automation. Finally, the Proxmox VE REST API allows for programmatic interaction with the platform, enabling users to create custom applications that can interact with the platform.

2.5.1 Virtualization Technologies

Proxmox VE supports the the deployment and management of two distinct types of virtualization, namely, Kernel-based Virtual Machine (KVM)- based VMs and Linux Containers (LXC)-based containers.

Users can interact with these virtualized environments via NoVNC, a simple web-based VNC client or SPICE which is a more feature-rich protocol that provides better performance and more features than VNC. Both of these protocols support the use of a console-based interface, aswell as a full desktop graphical interface.

2.5.1.1 KVM

KVM is a virtualization solution provided by the Linux kernel. It leverages the hardware virtualization extensions of modern processors to provide a full virtualization experience at near-native speeds. Supports a wide range of guest operating systems making it a good choice for general purpose virtualization.

In Proxmox VE, KVM is used as the core component for running virtual machines and is used alongside QEMU.

2.5.1.2 LXC

Containerization is an operating system-level virtualization method that packages an application and its dependencies together into an isolated environment. Contrary to tradional

VMs, containers dont emulate hardware or require a guest operating system relying instead on the host's kernel. This approach leads to a faster and more lightweight virtualization solution, as they consume less memory and cpu resources.

LXC creates full system containers, capable of simulating a complete Linux distribution providing users with an environment that behaves like a traditional VM but with the speed and efficiency of a container. LXC start much faster than VMs making them ideal for scenarios requiring rapid deployment and/or scaling.

However, it's important to note that while containers offer a degree of isolation, they do not provide the same level of security as VMs. This means that while they may not always be a suitable replacement for VMs.

2.6. Python

Python is a high-level, interpreted programming language renowned for its readability and versatility. It supports multiple programming paradigms, including procedural, object-oriented, and functional programming, making it suitable for a wide array of applications. In the context of this project, Python serves as the primary programming language as its extensive standard library and supportive community contribute to efficient development and maintenance of the project's codebase.

2.7. WSGI

The Web Server Gateway Interface (WSGI) is a pivotal standard for Python web application deployment, defining a consistent interface between web servers and Python applications or frameworks.

Prior to WSGI's introduction, Python web frameworks were typically written against various server-specific APIs such as CGI, FastCGI, or mod_python. This diversity led to compatibility issues, limiting developers' choices of web servers and frameworks, as not all frameworks supported all web servers and vice-versa. To address this fragmentation, WSGI was created as a standardized interface, promoting portability and flexibility in deploying Python web applications.

WSGI serves as a bridge, enabling web servers to communicate with Python applications. It specifies a simple and universal interface for web servers to forward requests to Python applications and for those applications to return responses. This standardization

allows developers to choose from a variety of web servers and Python frameworks without compatibility concerns[5].

Introduced in 2003 as PEP 333, WSGI was later updated to PEP 3333 in 2010 to accommodate Python 3. These specifications outline how web servers and Python applications should interact, ensuring a consistent and reliable deployment environment across different platforms.

The WSGI standard consists of two main components:

- **Server/Gateway Side** - Responsible for receiving HTTP requests from clients and passing them to the Python application. Then receives the response from the application and forwards it to the client.

- **Application** - The Python application that processes requests and returns responses.

Additionally WSGI has support for middleware components. WSGI middleware is a Python callable that wraps another WSGI application to observe or modify its behavior. Middleware can perform various functions, including request preprocessing, response postprocessing, session management, and security checks. This modularity allows developers to add functionality to their applications in a reusable and maintainable manner.

The separation defined by WSGI allows for flexibility and scalability in deploying Python web applications.

During development, Python web applications often use built-in servers provided by frameworks like Flask. However, these servers are not suitable for production environments. In production, WSGI servers act as intermediaries between web servers (e.g., NGINX or Apache) and Python applications, handling incoming requests and serving responses efficiently.

2.7.1 Flask

Flask is a web application micro framework written in Python, adhering to the WSGI standard, designed to facilitate the development of web applications by providing essential tools and features. Classified as a microframework, Flask does not require particular tools or libraries, instead choosing to focus on simplicity and extensibility[6].

Here, Flask serves as the backbone for the entire project, providing the necessary infrastructure to handle HTTP requests, render templates, and manage application routing.

Its flexibility and minimalistic approach allow for the integration of various extensions and libraries as needed, ensuring the application remains lightweight yet functional. Flask's comprehensive documentation and supportive community further enhance its suitability by the creation and support of community-driven extensions speeding up development and reducing the need to reinvent the wheel.

flask might be changed to Quart of FastAPI

An example of how easy it is to develop a basic web application with flask is provided in the following small piece of code.

Algorithm 1 Flask Hello World

```
1: from flask import Flask
2: app = Flask(__name__)
3:
4: @app.route('/')
5: def hello_world():
6:     return 'Hello, World!'
7:
8: if __name__ == '__main__':
9:     app.run()
```

2.7.1.1 Asynchronicity

2.7.2 Nornir

Nornir is an open-source automation framework written in Python, designed to provide a flexible and efficient approach to network automation tasks[7]. Unlike other automation tools that utilize customized pseudo-languages, Nornir leverages pure Python code, offering developers the full power and versatility of the Python ecosystem.

Nornir supports multi-threaded task execution, allowing operations to run parallel across multiple devices. This capability enhances efficiency and reduces the time required enabling easy scaling to a large number of devices.

The framework provides a robust inventory management system, enabling the organization of devices into groups and the assignment of specific tasks to these groups. This structure facilitates targeted automation and simplifies complex network operations.

Finally, thanks to nornir's architecture, it is highly extensible through its plugin system, allowing users to create custom plugins for inventory management, task execution, and result processing. This modularity ensures that Nornir can adapt to a wide range of network automation scenarios.

Nornir is particularly well-suited for tasks such as configuration management and state validation which makes it highly desirable in the context of this project. Its ability to handle concurrent operations will also ensure it can scale alongside the rest of the project.

2.7.3 Requests

The requests[8] library is a popular and user-friendly HTTP library for Python, used to send HTTP requests to web services. It simplifies interactions with APIs by simple to use methods for the various HTTP verbs, as well as providing support for cookies, sessions, authentication, JSON and exception handling for network failures and invalid responses.

Main technologies used to talk about Python Nornir GNS3 ProxmoxVE Flask -> quart/fastapi Requests -> celery -> HTTPX WSGI -> ASGI Linux NGINX? Gunicorn?

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Appendix Title Here

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