Designing Infrastructure for an Online Teaching Assistant

Bachelor project

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Contents

Chapter 1

Introduction

In this report, we will describe the design and implementation of an infrastructure for a system facilitating submission and automated correction of student assignments.

A Master's project carried out in the spring of 2014 has laid the foundation for this work by discussing the intricate aspects of performing automated assessment of assignments[1]. This work builds upon the previous project by describing an infrastructure for a complete system supporting the submission and automated assessment of assignments

FiXme Note: Rewrite last part

1.1 Background and motivation

As a result of the study progress reform recently passed by the Danish parliament, students are required to finish their university studies faster than previously. A consequence of this, is that many students can no longer find the time to act as TA's alongside their studies.

This has sparked a general interest at DIKU[1] to investigate implementing an automated assignment assessment system in order to reduce the workload of student TA's.

Since the assignments of many Computer Science courses require students to complete programming homework, Computer Science finds itself in a unique position with regard to take advantage of automated assignment assessment systems.

The system that we here will describe does not intend to replace TA's entirely, but rather automating the tedious of compiling an executing student programs. Human involvement is still needed to asses submissions as a whole.

An additional goal of this system is to act as pedagogical support for students while they are solving their assignments.

[1]Department of Computer Science, University of Copenhagen

1.2 Terminology

We shall describe some of the terminology that we will use henceforth in the report. This section is intended to clarify the contexts-specific interpretation of terms from which ambiguities could otherwise arise.

FiXme Note: Is this section even needed?

Assignment Is given to students by course responsibles and contains what you would exect.

Evaluator An evaluator is

1.3 Related works

Chapter 2

Analysis

We will describe some of the aspects of handling student submissions in this analysis chapter of the report

2.1 Data overview

The system are required to handle several sensitive data items which must be protected from adversaries before the online assessment system can be put into production. The types of data are listed here in order of decreasing sensitivity.

1. The submissions of other students
2. The code for assessing an assignment
3. The completed assessments of assignments.

The first two items on the list are close in terms of sensitivity. We regard the submissions of other students as being the most sensitive data since they have a larger potential to enable plagiarism.

Since it would have less impact if an adversary gained unintended access to the code for assessing an assignment we don't assign it the same sensitivity. Getting access to the assessment code would only tell you what kind of output that your assignment should produce in order to pass. It would not tell you how to make the actual assignment. Thus, an assignment that is "'tuned"' to produce the output or contain the phrases that is checked for would not pass subsequent human inspection. A possible exception to this occurs should this system ever be used to correct assignments with a single correct answer. In this case, getting hold of the assessment code equates acquiring the answers for the assignment. However, we don't expect the system to be commonly used in this way.

Assessments generated by the system is the least sensitive data being handled since the, a) do not identify students by name and b) TODO

Because of the data that we handle, securing assignments from unauthorized access is our primary priority.

FiXme Note: Is it always the case that they do not identify students by name?

2.2 Assignment lifecycle

In this section we describe the life cycle phases which an assignment goes through from submission to the assessment being returned to the student. The life cycle of a specific assignment depends on several factors. Particularly if we are dealing with an identified or anonymous assignment.

2.3 Submission constituents

2.4 Executing untrusted code

If the OnlienTA system are to fulfill its intended role, it is a necessity that it executes arbitrary code submitted by students. . For obvious reasons, we cannot trust student submitted code not to perform inappropriate actions, may these be unintended site-effects of programming errors or deliberate malicious attempts to escalate privileges.

FiXme Note: rewrite

2.4.1 Sandboxing

We will handle this challenge by executing the student-submitted code in sandboxes where they have no chance of inducing side-effects on other parts of the system, gaining access to privileged data or affecting the assessment of other students assignments.

Sandboxing technologies range from fully-flgedged virtual machines to rule-based execution environments for programs. We will here focus on containers which is a type of OS-level virtualization which isolates the sandboxes by enforcing separate namespaces for e.g. networking, filesystems and system permissions. The Linux kernel provide support or this kind of sandboxing through a set of features called `namespaces`[**namespaces**].

There are several well-known "'packaged"' implementations OS-level virtualization for Linux which is implemented using the namespaces features. In this section we will comparatively evaluate some of these and their suitability for our purpose.

Docker

Docker is a relatively recent addition to the family of application containerization tools. Opposed to most other OS-level virtualization technologies it focuses on application isolation rather virtualization of an entire operating system. It has popularized a new way of deploying and executing applications where, instead of applications being installed on a shared system, applications are deployed by starting a container which includes the application, its dependencies and its configuration. [2]

Docker comes with a complete set of tools for building and managing containers. These could be useful in supporting the TA's job of developing and testing assessment units for assignments.

On the other hand, the codebase of Docker is very large and contains a lot of features that are superfluous for our use case. A large codebase also has a higher chance of containing security critical bugs. The widespread adoption of docker for security critical applications, however, mitigates this concern somewhat.

Priviledge escalation vulerabilities has historically been more likely to arise from peripheral feature sets (as seen in the recent QEmu floppy driver vulnerability [**CVE-2015-3456**]), rather than the core containment functionality itself.

Sandstone

As part of a related student project, a minimalist and modular interface to the Linux container APIs were developed. The philosophy behind this system, named sandstone, is to provide access to the sandboxing features of Linux as small individual building blocks which can be composed, providing the program executed with the desired level of isolation.

The building blocks of Sandstone is implemented as small programs written in the C language, each of which implements a part of the Linux container system. The programs are composed through command chaining. Exemplifiedied, the composition works as follows: Let a, b, and c be programs in Sandstone and let p be the program that we wish to execute in a sandboxed environment. We execute the process with the command line `a b c p`. Then b will be constrained by the isolation provided by a, c will be constrained by a and b and p will be constrained by a, b and c and will thus be executed with the level of isolation that we desired. [1]

There are good reasons to be wary of custom built security critical utilities. Security is hard to get right and custom built utilities that never see widespread use will never go through the public scrutiny offered to more publicly visible tools. A mitigating feature of Sandstone in this regard is its relative simplicity and the limited amount of code used in its implementation.

Conclusions

The design that we propose later in this report will provide an

2.5 Design principles

We have devised a number of principles that our system design will be based on. These principles aims to simplify the design of our s

Modularity We want the components of our system to be modular and loosely coupled. Large monolithic components tends to foster unmanageable complexity

which makes them harder to maintain and review for security problems. Modularity also adds flexibility to our system by enabling certain components to be swapped.

Clearly defined minimal interfaces

Minimum permssions A common "'best practice"' related to the security aspects of software development is to assign a minimalized set of permission to a component required by the work that it needs to perform. Traditional Unix environments only makes the distinction between a superuser (root) and a regular user. It's common for applications to be started with full superuser permissions and then, after performing privileged actions,resume operations as a unprivileged user.

The sharp separation between superusers and regular users no longer exists in model versions of the Linux kernel following the introduction of the *Capabilities* interface [3].

Several operations

Data ownership separation The most basic permission management primitive in Unix operating systems is the concept of a user. We wish to enforce fine grained user separation across the system such that a given user only have access to what is absolutely necessary. A common concern of executing applications inside a container is what happens in the unlikely event that a process successfully manages to escape the container. In this case, the attacker would usually end up having the same permissions as the process executing the container.... TODO

An important advantage of linux capabilities is that they follow a *process* and not the user. This means that an attacker would need to exploit, either So even if an attacker manages to escape our container, he would

2.5.1 Securing special capabilities

Despite our best efforts, we can never completely eliminate the possibility that an adversary will be able to take advantage of the capabilities given to our programs and force them to preform unintended actions. For instance, gaining arbitrary code execution in a process with the `chown` capability would allow one to change permissions of any file in the system. Since our security model to a large extent relies on users having access to a minimalized set of files, we would consider this to be a rather serious security incident.

Secure Computing (seccomp) [**manpage**] is a facility provided by the Linux kernel to provide application sandboxing through the filtering of syscalls. It allows an application to unidirectionally transition into a secure state where all of its syscalls are filtered by specified rules. Building on our example in the previous paragraph, we can use the seccomp to filter the `chown` syscall such that it only allows changing the owner of files to UID within an allowed range, e.g. $(\mathtt{aaa000})_{36} - ((\mathtt{zzz999})_{36})$.

We can use seccomp to build an extra layer of security around our programs which limits the effects of

FiXme Note: discuss problem of go spawning multiple threads per default somewhere

2.6 Handling user identities

We will support assessing submissions from two groups of user: anonymous and authenticated users. Submissions from these groups will be handled in two different ways, both with regard to what services are offered to the user, but also how we represent their submissions internally.

Anonymous submissions are removed after their life cycle has concluded. Only the assessment of the submission persists until it has been read by the submitting user.

FiXme Note: We should hold off describing our implementation of handling usernames through

Identified submissions

For the time being, the scope of OnlineTA is limited to students at DIKU. Thus, we can take advantage of the standardized usernames assigned to everyone who is in some way associated with the University of Copenhagen (KU-usernames), both students and employees. KU-usernames are matched by the regular expression `[a-z]{3}[0-9]{3}`, with the exception that vowels aren't used as letters in generated usernames. We can use this username generation scheme to our advantage since we can interpret the KU-usernames as base 36 numbers and thus achieve a stateless and bidirectional mapping between Linux UIDs and KU-usernames, e.g.:

FiXme Note: example?

$$(\text{gfr534})_{36} = (993919360)_{10}$$

Since UIDs in Linux are represented as a 32-bit signed integer, actual implementations of this scheme needs to take into account that the (numerically) largest valid KU-username $(zzz999)_{36}$ is larger than $(2^{31})_{10}$.

Verifying user identity Another ongoing student project are designing and implementing a purpose-built GPG key server which are intended to be implemented into the OnlineTA system

2.7 Interacting with the system

In this section, we describe modes of interaction with the system for making submissions and receiving assessments.

Since this system is intended to be used even by freshmen submitting their first assignment, providing a simple, familiar, universal and immediately accessible interface for submitting assignments is an important goal. However, a secondary purpose of this system is, not just aiding TAs in their grading work, but also to provide students with continuous feedback while they are solving their assignments. It's

therefore important that we meet students where they are and provide them with (from their perspective) the most seamless interaction possible.

The first goal is best achieved through a well-designed web interface for uploading assignments. The interface should, when possible, provide immediate feedback within the browser. As previously mentioned, we have based our user identification on verifying that an assignment has been signed with the GPG-key belonging to the user claiming to have submitted the assignment. This poses a potential obstacle when implementing authenticated submissions through the web interface. One option, is to require students to GPG sign their assignments prior to submission... Talk about WAYF, browser certificates, etc...

FiXme Note: Talk about when system overload causes long submission times

Many additional submission interfaces has been proposed since the conception of OnlineTA. The prevailing proposal has been to implement a command line interface which would allow a student to submit the current folder or a file for assessment. The Windows equivalent of this would be a Shell Extension adding tantamount functionality to the right click menu of files and folders. We are not qualified to provide equivalents for other platforms such as OSX, but in that particular case, the command line interface would also be feasible. A tangential advantage of this submission method is that it could be implemented to only transmit deltas between repeated submissions and thus significantly reduce upload time and internet bandwidth required for submission.

Another submission interface under consideration is Git. We consider the addition of

2.8 Large Submissions

Some courses may require large submissions which could saturate any feasible internet link through only a limited number of concurrent uploads. We propose that the upload bandwidth requirement can be reduced by applying a delta transfer algorithm on repeated submissions.

The rsync algorithm is an abvious candidate for solving this problem. However, the alogrim assumes that the receiving end has access to all files. Honoring our porperty of minimal user permissions the submission receiving process won't have access to the files of the previous submissions. We therefore propose a variation of the rsync algorithm built for our purpose. Since we cannot rely on being able to retrieve the state of the remote files we must be able to keep the difference between local and remote files locally. TODO

Chapter 3

System Architecture

In this chapter, we propose a design for our system. We will use the principles that we laid down in the previous chapter and present them as a part of an integrated system

3.1 General concepts and overall goal

With security as the, as previously stated, principal goal, we focus our design around several small processes, each with a well defined purpose and interactions. We furthermore enforce a principle of minimum permissions across our entire system. This means that we eill

3.2 Users

There are two levels of users in the OnlineTA system. One is the user owning the daemons responsible for handling the main assessment flow, and the other is the users owning the submissions. In the case of anonymous submissions

3.2.1 Representing systems on users

Name lookup services in GNU/Linux systems are handled by the NSS (Name Service Switch) subsystem which is implemented in the Gnu glibc library. The NSS service is responsible for handling the mapping of several system resources including domain names, user names and password files. The NSS system is extensible through providers which is called in the order specified by the `nssswitch.conf` file. In the OnlineTA system, we add a password mapping module which can be used for looking up user names to UIDs and vice-verca[4].

This allows us to represent our dynamically created users on the Linux system and thus avoid having to fill all of them into an extremely long /etc/passwd file.

We perform user handling in two separate NSS modules for handling named an anonymous submission respectively. The usernames of identified submissions

are assigned by a NSS module which implements the bidirectional UID to KU-username mapping previously described. conversion scheme previously described.

We handle the usernames of anonymous submissions slightly differently through a different NSS module. This module works on lists of preallocated users and is autonomously responsible for maintaining lists of allocated and non-allocated users

FiXme Note: rewrite

3.3 Interactions

The scope of the current implementation is limited to supporting direct interactions via a web browser, however, the additional modes of interaction previously described can be implemented on top of the interface that we will describe in this section.

In the current design, all interactions with the system occurs over a secure HTTP connection. We use the first part of the request URI to determine which action is requested by the user while subsequent URI components are used as parameters for that request. The system supports the following actions:

`/` This URI can be issued as a HTTP GET request and will return the main index page which will contain a list of courses and assignments availiable on that server

`/submit/<course>/<assignment>/` When a HTTP POST request is issued to this URL it will be handled as an anonymous submission. If the submission is accepted, the fronted will repsond with a page showing the assigned submission UUID. This UUID can then be used in order to retrieve assessments once they are completed

`/submit/<course>/<assignment>/<KU-username>` This request type is the same as the previous except that it will perform an authenticated submission.

`/query/<uuid>` Used to query assessment status of assignment identified by given UUID. The status of an assignment can be the following ACCEPTED The assignment has been accepted and is awaiting schediling QUEUED The assignment has been picked up by the scheduler and is awaiting prioirization TODO

`/assessment/<uuid>` Retrieves the assessment of a submission if availible

3.3.1 Relaying assessment to user

TODO: Describe what happens when a user requests an assessment.

3.4 Components

The components that our design is separated into are the following:

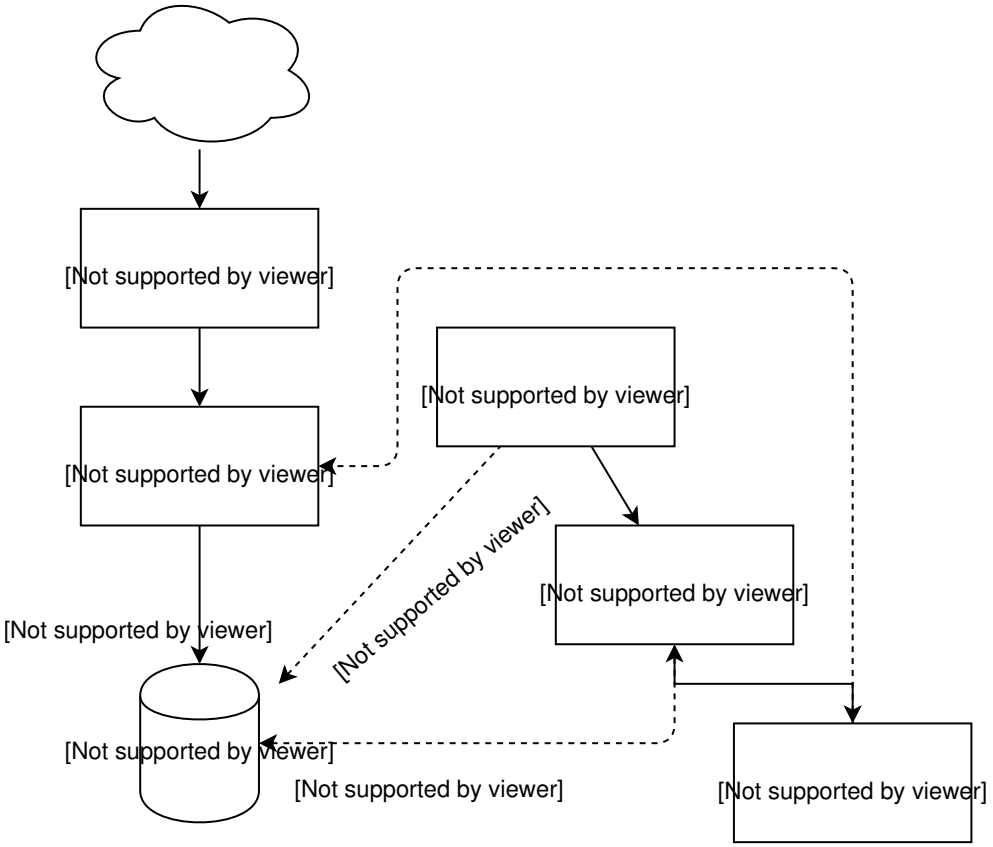


Figure 3.1 – Flowchart showing interactions between the components of the OnlineTA system

Frontend The frontend is responsible for accepting submissions. In case of authenticated submissions it is also responsible for verifying the identity of the user submitting the assignment. It will also perform the initial storage of the submission. Furthermore, the frontend is responsible for returning the assessment to the student.

It will go through the following steps in order to accept an assignment.
The frontend has the following roles

- Accepting submissions from the HTTP proxy
- Verify GPG signature of submission if authenticated
- Generating and assigning a UUID to the submission
- Writing the initial metadata file
- Creating directory for containing the submission and setting ownership of files

This component require the `CAP_CHOWN` capability.

Scheduler The scheduler will pick up the assignment after it has been saved to disk and pair it with a suitable assessment unit. Assignment scheduling is based primarily on a priority assigned to the submission by the frontend. Submissions with equal priorities are scheduled on a FIFO basis. If no priority is provided by the assignment, it could assign a priority based on a number of factors, e.g. time remaining before submission deadline. The scheduler directly spawns processes for executing assessment units.

The scheduler has the following roles:

- Monitoring the incoming directory for new submissions
- Pairing submissions with an appropriate assessment unit
- Scheduling and prioritizing assessment of assignments
- Invoking workers for performing the actual assignment

Worker A worker process is spawned by the scheduler and its overall purpose is to set up and initiate the assessment process. It is initially started as the `onlineta` user but after the assessment environment has been configured and the containers has been created it will `suid` to the user owning the submission and shed its special capabilities.

Specifically, its roles are the following

- Setting up the environment for performing an assessment including mounting filesystems
- Setting up containers for assessment
- Relaying assessment to frontend

The special capabilities required by the Worker process are `CAP_SYSADM`, `CAP_SUID` and `CAP_SETPCAP`

Assessment units An assessment unit handles the actual assessment of an assignment... TODO

3.5 Storage

In our current design, availability of persistent local disk storage is assumed. The directory structure used for storing submission data is as follows:

`submissions` The parent of the directory tree

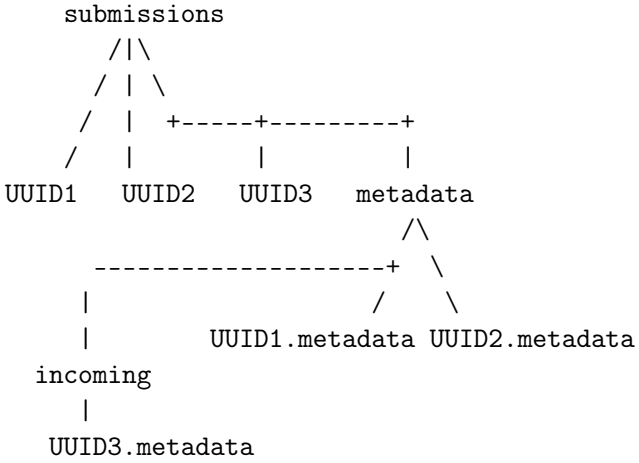
`<UUID>` A directory named after the UUID assigned to a submission is placed as a sub directory of the submissions directory. It holds all the files related to a submission, including it's assessment. he contents of this directory are owned by the user who made the submission and thus it can only be accessed by an assessment unit running as this user.

`incoming` This directory is where the metadata files of all newly created directories are stored. It is monitored by the scheduler using `inotify` which, after a metadata file is scheduled it is moved away from this directory

`accepted` This directory holds metadata files which has been accepted for processing. The separation of incoming and accepted metadata files is needed due to limitations of inotify

FiXme Note: elaborate

FiXme Note: Make actual figure



3.6 Interfaces

3.7 Scaling and distributing

A driving idea behind our design is to enable horizontal scalability. A key element to acheiving this

Chapter 4

Measurements

A goal of this project is to determine the serer capacity required by the OnlineTA system. Since the current implementation is not yet at a state where we can reliably perform such measurements, we will instead focus om describing measurements which can be performed on the final implementation in order to assess the server capacity requirements.

4.1 Metrics of submission assessment

In order to know what benchmarks to conduct we need to establish the performance metrics that we can use to estimate the expected performance of our system.

4.2 Performance thresholds

In order to prevent making overestimated hosting recommendations it's important to establish acceptable thresholds for assignment throughput. A system that is scaled toward delivering assessments "'as fast as possible"' under any circumstance will have significantly different requirements that a system where we accept queuing of assignments, and thus delaying assessments, during peak load.

The perceived usefulness of the system and overall student satisfaction will depend greatly on striking the right balance between acceptable assessment throughput thresholds and cost of hardware deployments.

4.3 System scaling requirements

As our initial scope is limited to performing assessment of the assignments of DIKU coursess, we can develop an idea of how large our assignment throughput needs to be fairly easily. E.g if we have 100 students enrolled in the introductory programming course, we can calculate an upper bound on the amount of resources consumed. This can be done by calculating the expected resource requirements for each assignment in the course. Our required throughput is then

4.4 Estimating static requirements

We define static requirements as resources that scales linearily wuth an assignment, e.g. if we need to estimate the requried

Chapter 5

Discussion and conclusions

We will end this report by presenting our conclusions and discussing the wider implications of our proposed design.

5.1 Practical deployment considerations

In this section, we will devote some space to consider the practical and economical implications of the possible hosting choices that we have for our design.

It may seem that a cloud hosting provider such as Amazon or Digital Ocean would provide the ideal environment for operating OnlinT

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