FBase:

The next evolution of modularised code execution

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by

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Preface

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M.J.G. Olsthoorn
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Abstract

The abstract should contain a brief overview of the research and the most important results

Contents

1 Introduction

For decades software re-use has been seen as the holy grail of software development. Even in the eighties, papers were already written about this topic [36]. Throughout the years, more and more research has been done on the benefit of re-usable software [19]. Studies have also been done on how to re-use software in practice [34]. But up until recently, there was more discussion about software re-use than actual software re-use. Even though most software uses the same blocks of code over and over again, almost all software is built from the ground up [17]. Today, this situation is completely different. Nowadays, almost every application re-uses software in the form of software dependencies. However, this re-use pattern is starting to become unchecked. The shift to re-usable software has happened so quickly, the risks associated with choosing the right dependencies are often overlooked [10].

1.1. Code Evolution

Over the years, the way we use code has evolved with the changing need of the users and society as a whole [33]. This evolution started with specific applications written for each use case and each platform it had to run on. These monolithic applications took a lot of time to develop and could not be re-used. To reduce this time, system libraries were built to make it possible to run these applications on similar platforms. This abstraction layer, however, was still limited to broader types of platforms e.g. Linux, Unix, Windows. These shared system libraries could now be maintained and distributed separately. This led to easier development and applications that could be used on more systems.

The Debian package system is a good example of this evolution. It made it possible for code that was meant to be used as a library to be packaged separately for both system and user code. This allowed applications to indicate which library would be required for the application and the system would make sure it is available to the application. This possibility allowed these applications to be developed faster. [40]

These new shared code libraries provided a lot of benefits and speed to application developers, but to improve the ecosystem further a new step had to be made. At this point when applications were distributed they were static. There was no option to adapt the application to include features that the user would like. Also, users that wanted to add their own functionality had to go through the developers to accomplish this. To solve this, the larger applications began to include plug-in systems. A plug-in system allows specific functionality to be added to an existing computer program. This enabled customization of applications, making it possible to reduce the size of the core application or separating source code because of incompatible licenses. This paradigm allowed the rapid development of extra features by both developers and the users of the application.

A well known example of a program with a plugin system is Winamp. The Winamp developers used a plug-in system to provide users with a customizable package that could serve each user's preference [27]. A large community formed around the application with different plug-ins for every imaginable feature [7]. This community building gave an incentive for other applications to implement similar plug-in systems.

Eventually programming languages were created that allowed the development of cross-platform applications that could be run on all common platforms. This eliminated the need to create separate binaries for each individual platform. These applications were either written in an interpreted language, e.g. Python, or in a pre-compiled portable byte-code format for which interpreters exist on all platforms, e.g. Java. In the last decade, a major part of these cross-platform applications have moved towards the web. These new web applications make use of existing cross-compatibility of web technologies, that were designed when the web became universal, that run on all platforms.

With the development of cross-platform applications, there was also a rise in the availability of code frameworks. A code framework provides particular functionality as part of a larger software platform to facilitate development of software applications. Software with common use-cases could make use of the abstraction provided by these code frameworks to create application-specific software with only limited additional user-written code. These code frameworks can be seen everywhere nowadays. Some examples of code frameworks are: Spring, WordPress, and the Android platform. Spring is a popular code framework for developing applications in Java. WordPress is a web framework that runs more than 25% of the websites on the internet [15]. The Android platform is the underlying framework that allows apps to be created for the Android mobile operating system.

A more recent concept in the development of software applications is the microservice architecture. This architecture breaks an application up into a collection of loosely coupled services. These services are normally small in size and have one use-case that they were specifically designed for [37]. This architecture facilitates code re-use on a big scale with platforms like NPM (Node Package Manager) storing over 750.000 JavaScript packages [4].

1.2. Code Re-use

The constant factor during this code evolution is code re-use. The ability to make development easier and faster by making use of existing solutions already created by a different party.

Re-use is software development's unattainable goal. The ability to put together systems from re-usable elements has long been the ultimate dream. Almost all major software design patterns resolve around extensibility and re-use. Even the majority of architectural trends aim for this concept. Despite many attempts in almost every community, projects using this approach often fail [6]. This is often attributed to one big problem: usability. The more reusable we try to make a software component, the more difficult it becomes to work with said component. This is a critical balance that needs to be worked on.

1.2.1. Re-usability vs Usability

The challenge we face when creating a highly re-usable component is to find this balance between re-usability and usability.

To make a component more re-usable it needs to be broken down in smaller parts, that each handles only one task. Components with multiple tasks are harder to re-use since each application has different use cases and therefore has to modify and maintain there own version of that component. Smaller components that handle only one task can be used as building blocks for bigger components making them easier to re-use, saving developers the need for maintaining their own version. However, to create complex application hundreds of small re-usable components would have to be used creating a problem of itself. How are all these components going to be managed? The largest part of this problem has to do with dependencies [6], an additional piece of code a programmer wants to call. Some aspects to think about are:

- Is the API (Application Programming Interface) going to stay constant?
- How do we deal with breaking changes?
- How do we prevent dependency conflicts?

Some of these aspects are already partly being addressed through Semantic versioning [30], but most of these are still unsolved today.

The context dependability of a component also greatly affects the balance between re-usability and usability. When a component depends on the context it is running in, it makes it impossible to move it to an different environment that does not have this context. For components to be more re-usable, this context has to be moved from code to configuration. However, if each small component has to be configured each time it is used, the application would become less usable.

Both the granularity and the degree of dependability on the context can improve the re-usability at the cost of usability. The key is to find a balance.

1.3. Component Terminology

Two different kinds of reusable components that are often integrated into applications are modules and plug-ins. Since these terms can have a different meaning depending on the application, the interpretation that this work will use is defined below:

- **Modules** are main functionality components that are used to break up the application into smaller subsystems that can more easily be worked on with different/larger teams. Modules can either by re-usable components or tied to the specific application, and should be able to operate independently
- **Plug-ins** are components used to extend the main functionality of the application without having to make changes to it. They are often created by the community of the application. The functionality in these plug-ins are often too small or too unique to integrate into the core application. Plug-ins depend on the services provided by the application, they do not operate independently. They are also tied to a specific application and can not be re-used for other applications.

The function of both kinds of components is, however, not different. They both provide extra functionality to the application. It would therefore also make sense to both make them first-class citizens of the application instead of making plug-ins a secondary operator.

This distinction is often made to differentiate between the code of the original authors and code created by third-parties. Plug-ins are most of the time also not reviewed by the original authors of the project.

1.4. Research Goal

Over the last couple decades, extensive research has been performed into the field of software re-use. In this period, several survey studies have been done to see what different approaches were used in research literature for creating re-usable software [20] [17]. The surveys tried to make generalizations about the methods used to research if there is a common pattern among them. The approaches mostly centered around re-using code for common use-cases like code frameworks.

Other studies have worked on designing metrics and models for measuring progress in software re-use to identify the most effective strategies [16]. Morisio et al looked at success and failure factors in software re-use to identify key factors in its adoption [25]. The main cause of failures that they discovered was a lack of commitment by companies and projects.

A more recent study, attempted to build a framework for highly modular and extendable software systems, called Normalized System theory. This theory is based on a theoretical concept called system theory. This theory, however, takes the abstraction of modules to a level that makes it inefficient beyond usage. It takes this approach to make the system more agile. However, without simplicity all agility is lost. [11]

Lehman's laws of software evolution is a law describing the evolution of software. The law describe a balance between forces driving new developments on one hand, and forces that slow down progress on the other hand [21] [22] [18]. One of the forces that slows down the progress of new developments is the ability of developers using the development to understand and easily use the functionality of the development.

In the current research there exits a gap in balance between re-usability and usability. This works tries to fill that gap. Many people have tried solving the problem of software re-use, but it has proven to be a hard problem. There needs to be a trade-off between re-usability and usability.

This thesis focuses its work on developing a framework that continues the progression in the development of re-usable code. It tries to find a balance between the software practices of Today and the impractical concepts of the future.

There have already been many attempts to solve the goal of practical code re-usability. However, these attempts still left some problems open, that this thesis tries to solve. These problems include:

- How to find a trade-off between re-usability and usability?
- Can we use social trust and crowdsourcing to improve security of libraries
- How to ensure dependency availability efficiently and securely?

The rest of this document is outlined as follows: Chapter 2 will go further into the problems that this thesis tries to solve. Chapter 3 will discuss the solution proposed to solve the problems mentioned in Chapter 2. Chapter 4 will discuss the proof-of-concept implementation. Chapter 5 will evaluate the proposed framework against existing solutions. We use a concrete use-case driven methodology to advance the cause of software re-usability.

2 Problem description

This work sets out to create a framework for the next evolution of modularized code execution to find a balance between software re-usability and usability. The key property is permission-less code execution at near-zero cost.

There should be no difference between modules and plug-ins. Each user can also choose which functionality and therefore module they want to run on their instance of the application. This allows users to compose their own desired version of the application. The user can compose larger modules out of smaller ones or fork modules to represent their view on how it should be done. This should create a community around each module that could spark an ecosystem.

This framework attempts to solve the problems that exist in the software practices of today. One of these software practices is the microservice architecture. This architecture like explained in the introduction breaks an application up into a collection of loosely coupled services. However, this pattern was specifically designed for maximizing re-usability without taking into account usability [26] . Studies have been done into the practical issues that the microservice architecture creates when used in a software application [14]. Examples of these issues are the manageability of packages on NPM, no explicit dependencies, interfaces that are not well defined. The architecture makes use of completely decoupled services that communicate through REST APIs. This interface, however, limits the type of communication that can be send between the nodes.

Smart contracts, in particular, Ethereum is another software practice used today, to solve the problem of code re-usability. However, since Ethereum is based on a proof-of-work principle, it requires payment so execute actions on the system. This will make applications build on top of Ethereum subject to these charges. In many cases these charges will have the consequence that the application would be to expensive to use in practice. The Ethereum model is not long-term sustainable

2.1. Requirements

Requirements for our envisioned runtime engine are as follows

2.1.1. Decentralized

No central entity or central governance should be in control of the network. The network should be owned by everybody and nobody. The system should have no central servers except for bootstrapping.

2.1.2. Self-governing

The system should be able to run on its own without supervision. As there is no parent governing entity. The system should be able to handle all tasks needed for operating the network by itself.

2.1.3. Trustworthy Code

Since this work is proposing a framework that is highly dependent on re-usable code, it is important that the user running the application can trust all its parts. This trust aspects is very important for a code execution ecosystem. There are many examples of application being compromised by running untrusted code [5][2].

Open Ecosystem

For a user to trust the application it wants to run, it also needs to trust the framework running it. That is why it is important that every part of the code execution ecosystem is open for inspection. Making the source code public allows users or external parties to verify the behavior of the system.

Next to opening up the framework for inspection, it is also of vital importance that each re-usable component used within the framework is able to be inspected to increase the trustworthiness of the code.

Crowdsourcing

DevID is a previous work of the authors of this thesis. It evaluates the possibility of using social trust as a way to increase the trustworthiness of code by using crowdsourced peer-review [12].

Cargo Crev is a cryptographically verifiable code review system for the cargo (Rust) package manager [1]. It lets users cryptographically sign packages when they have deemed them to be safe.

Both of these systems make use of crowdsourcing to minimize the risk of users running undesired malicious code. This is a very important property, since manually inspecting all code running in an application can take a lot of time. By crowdsourcing this task to other individuals, the trustworthiness might be lower compared reviewing it yourself. However, because the code review is crowdsourced to many different individuals, the eventual trustworthiness of the code will be higher.

Dependencies

The current dependency trend is risky, developers trust more code with less justification for doing so. Since the recent explosion of code re-use systems, application have started shifting to using more and more existing libraries in the form of dependencies. This rapid shift, however, has caused developers to take along their perspective on code trustworthiness of classical dependencies like OS system libraries. The trust-ability of these new libraries is not as obvious as most developers believe.

H2020 FASTEN is a project that strives to minimize the risk associated with using dependencies [3]. It solution for this problem is performing static analysis of the code and creating a dependency graph. With this dependency graph, changes to the dependency can be detected. This allows inspection of the code that would be affected by this change.

When using dependencies without inspection, applications risk running code that contains bugs or has security exploits. Next to this, when the author of the dependency decides to change the purpose of their dependency or remove it entirely, the depending application becomes broken and useless. A study done by Xavier et al, has looked into the impact of breaking changes in dependencies [39]. They determined it poses a great risk to application, since the frequency of breaking changes and the impact are high in many cases.

Although Semantic Versioning is a system designed to indicate to developers when breaking changes have been made to the dependency, the system is not being used properly according to recent studies [31] [32]. Raemaekers et al, found that backward-incompatible changes are widespread in software libraries.

Trust Function

Trustworthy code is a cornerstone in software development. However, how is trust defined? Trust is a social notion. One person might need more or less information to trust a particular piece of code than another person. This is highly dependent on the social constructs of the user. Therefore, trust shouldn't be a fixed concept. Each user should be able to define a trust function that is used to determine if a dependency should be used or not.

2.1.4. Runtime Support

A key bottleneck for re-usability and usability is the lack of runtime support within the execution environment.

Integrated Autonomous Dissemination

Centralized systems store all code libraries in one or multiple central locations. These locations require a lot of infrastructure which is not free. Besides this, they also have a few downsides. One of these downsides is that these locations are susceptible to influence of governments. They can be blocked or shutdown when the government feels like the platform is not complying with its laws. Decentralized systems do not have this disadvantage. Another disadvantage of centralized library storage is that any library made by revoked at any time.

A system that has integrated autonomous dissemination of code libraries through decentralized methods, can not be controlled from outside the system. It also allows everything to be done from inside the framework making is easier to use.

Dynamic Loading

For the code execution framework to be easy to use, the user should not have to restart the application or load applications into the framework. This should be done automatically on-demand by the framework. Dynamic loading would also make sure that only the application that should be running are loaded into the system, so that unused applications will not waste computer resources.

Seamless Upgrading

Updating of dependencies is very important. Outdated dependencies that contain security exploits can seriously harm the system it is running on. So when a new version of a dependency is available on the network, it should automatically be distributed to all nodes that run applications depending on that dependency. There should be no user action required for the updating to happen. Once the dependency is available on the host computer, it should do an in-place replacement of the dependency in the framework.

A similar system has been proposed by Rellermeyer et al for Java OSGi modules [35]. In this paper, they devise a mechanism to extend the default functionality of OSGi modules to make it possible to upgrade them when used in a distributed method.

Module Interconnect

For applications to be built up out of modules, there has to be a way for modules to find each other and to communicate with each other. The way this connection is constructed is very important, since the code execution architecture defines the maximum complexity of the code that can be produced. JVM, Nodejs, CPAN perl modules and other real-world framework and the connection between modules determine the Maximum Complexity of Applications (MCA) which a single company, an global consortium, or open source community can create. We devised the first architecture to take the MCA as the cardinal design optimisation. Science what defines MCA? What constrains/boosts MCA? The interconnection fabric is the key determinant for the MCA. How data flows between modules, how the future-proofing is arranges, how any piece of code can interconnect with any other code, and how can we devise the universal module interconnector?

To optimize the MCA some properties of the interconnection fabric have to hold:

- Strong encapsulation: hide implementation details inside components, leading to low coupling between different parts. Teams can work in isolation on decoupled parts of the system.
- Well-defined interfaces: you can't hide everything (or else your system won't do anything meaningful), so well-defined and stable APIs between components are a must. A component can be replaced by any implementation that conforms to the interface specification. Rest is not ideal for this, native code is better Interfaces can't be fixed since application could be anything
- Explicit dependencies: having a modular system means distinct components must work together. You'd better have a good way of expressing (and verifying) their relationships.

Currently, there are some attempts at creating a universal module. One of these attempts is UMD. Universal Module Definition (UMD) strives to create a module that can run on all platforms, e.g. browser, nodeJS, that run JavaScript. UMD, however, doesn't have to deal with a lot of complexities since the interface on all platforms are almost identical and JavaScript has a common pattern for interconnection modules. Another platform that is trying to create a universal module is Java's OSGi. This platform allows modules conforming to the standard to be used interchangeably with other modules.

3 FBase Design

This chapter will expand on the design of the proposed framework called FBase. FBase is a framework designed to create a usable ecosystem for the development, distribution, and execution of applications. In this chapter we will elaborate on the high-level structures within the framework. The implementation considerations and details will be discussed in Chapter 4. The evaluation of the framework through an experiment will be done in Chapter 5.

3.1. Overview

An overview of the architecture of FBase can be found in Figure 3.1. It shows the three different layers that make up the framework.

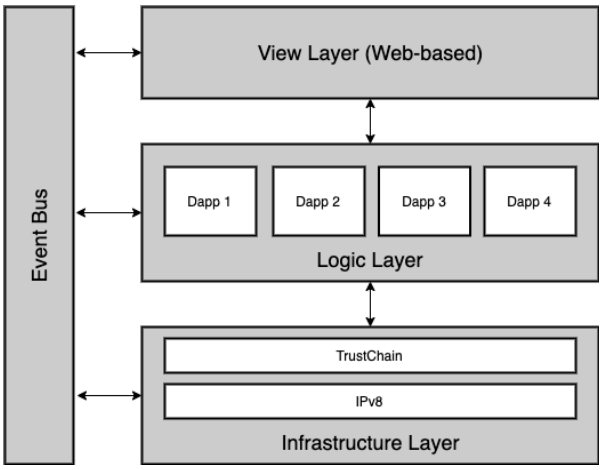


Figure 3.1: The architecture of the FBase framework

- **View Layer:** The view layer is responsible for the interaction between the user and the logic layer. This layer contains the view components for both the FBase framework and the user applications.
- **Logic Layer:** The logic layer is responsible for the execution of the user applications. It provides runtime support through the FBase runtime engine.
- **Infrastructure Layer:** The infrastructure layer is responsible for providing services to the FBase framework. These services include database storage, encryption primitives, and network capability. This layer contains the module distribution and overlay network.

These layers are connected by a system-wide event bus that is used for connecting different parts of the user application to each other. Connecting these components together to form the user application can quickly become a mess. To prevent this from happening, the FBase framework is built according to the event-driven architecture style. In this style of framework, actions are taken according to events happening in the system. Every component in the framework can trigger events. Creating simple and maintainable logic. Input such as human interaction, network packets, creation of components, and system notifications, trigger these events and cause corresponding actions in other parts of the system. An example of this would be the downloading of a module when a new one is discovered. The event bus is the main method for communications between different layers.

These layers together create the components needed to run and distribute modularized code in a decentralized fashion. The next few sections will expand on each of the mentioned layers and their components.

3.2. Generic Modules

The FBase framework aims to support as many different use cases of modules as possible. However, to create a single module type that can support any type of interaction and behavior would be infeasible. That would require an interface between modules so generic and complex that it would not satisfy our requirement of a usable system. If such an interface would even be possible to create, it would have a substantial performance penalty because of the abstractions and complexities needed to support such as system.

The method that FBase uses to find a balance between this flexibility and feasibility is a system of four generic modules:

- **View Module:** The view module type contains the components that deal with human interaction. This module type is not required for a user application to be functional. The module represents a Graphical User Interface (GUI).

  To meet our goal of having a re-usable ecosystem, these GUIs have to be cross-platform compatible. This cross-platform compatibility enables the view module to be used on any major platform in use today e.g. Windows, MacOS, Linux, Android, iOS. To accomplish this, the view modules will be created using web technologies. Web technologies were chosen for the FBase user interfaces, as they are one of the only GUI technologies that allow for uniformly looking cross-platform user interfaces. They are becoming the current standard for these kinds of GUIs.

  Web technologies also allow for easy decoupling between the view layer and the logic behind it. A view module component consists out of a HTML, CSS, and JavaScript website. This website is run as a standalone component and connects to its logic counterpart through an Application Programming Interface (API). This decouples the user interface part of the user application and allows it to be interchanged. Multiple different GUIs could be offered for the same user application. It also allows GUIs to be created with different purposes that could be run simultaneously. An example of this would be a music visualization plugin.

- **Application Module:** The application module type is the main module type in the FBase framework. This module type contains the main logic and it is the entry point into the user application. User applications can be either an isolated application on each users system or a decentralized application that spans across the FBase network overlay.

  The logic in the application module type acts as the controller in the Model-View-Controller (MVC) architectural software pattern. Controllers act as an interface between the View module and the Service Module to process all the incoming requests, manipulate data, and interact with the GUI to render the final output.

- **Service Module:** The service module type provides services to the application module that have common use-cases. These re-usable services should contain the bulk of the code in a user applications. Most applications share a significant portion of their functionality with other applications. The service module encapsulates those functionalities to make them more re-usable. A good example of such a service is authentication. Almost every user application needs a form of authentication.. Writing a secure and well structured authentication service is not simple. When applications can re-use well built services it adds to the usability of the application and ecosystem.

  Service modules should be standalone services. They should provide functionality that is not dependent on other parts of the user application. Service modules also maintain their own state. This makes sure the complexity of the functionality is encapsulated by the service.

Application modules can also be used as service modules. This can be achieved by marking the module with both types. An example of such a module is a zip code lookup system. Such a system can be used as either a standalone application with a GUI or as a service to another application.

Service modules can also be used to emulate plugin behavior where certain functionality is exchanged by a different one. This is done by changing the service module used in the user application. This ability would be similar to the Strategy software pattern. A use case of this would be changing the algorithm used to calculate trust in a network on runtime. It also allows service to be replace when security vulnerabilities have been found that are not being fixed.

- **Package Module:** The package module type is added to make it possible to remove dependencies on existing code repository infrastructure. Many programming languages have a native package manager to house common use code libraries to make it possible to re-use code already used by others. However, these package managers almost all use centralized infrastructure and have many problems of their own e.g. revocability. FBase uses the package module to provide an alternative for these code repositories or act as a back-up.

  The Package module contains downloadable code libraries that are made available to the other modules in the system. Examples of use-cases for the package module are validation libraries and database abstraction libraries.

3.3. Discovery and Distribution

FBase makes use of its own decentralized discovery and distribution network. Current networks for software distribution are most of the time centralized and controlled by a company entity. By making use of our own decentralized network, we can eliminate the possibility of the network being brought down by the company behind it, the government, or the the law. It also allows use to make the FBase network completely self-governing, so the system would be owned by everybody.

3.3.1. Identifier and Versioning

To distinguish different modules from each other, FBase makes use of an identifier. Each module has such an identifier, which is unique in the network. To guarantee this uniqueness a cryptographic asymmetrical keypair is used. An asymmetrical keypair consists out of two keys. One key is the public key to identify the object it represents, in this the module. The other key is the private key which can be used to prove the ownership of represented object. This private key acts as the credential for the author of the module to manage it.

The module identifier consists out of two parts. One part is the previous described public key. The other part is the versioning code. This versioning code is a hash of the entire module code. A hash is a short representation of a piece of data that is calculated in an one-way function. This method is chosen over more conventional versioning code like Semantic Versioning as it makes it significant harder for malicious actors to spoof the module code corresponding to a version number. Since the hash represents the code.

The complete module identifier format is:

```
<public_key>.<module_hash>
```

New versions of the module have a different module hash and would be a separate entity in the network. Each module also has a timestamp of when the module was created. Together with the module identifier, this allows nodes to pick the most recent version of the module.

When a module wants to introduce breaking changes to the API, a different approach has to be used. Using the current approach for updates with breaking changes could cause dependent modules to break and stop functioning. In FBase when a update includes breaking changes a complete new module has to be created. This means it has a different public key than the previous versions. This approach was chosen because breaking changes are often accompanied by a change in functionality of the module. FBase represents this change as a new module.

3.3.2. Discovery

The discovery mechanism of FBase relies heavily on crowd-sourcing. It does this through voting. It is very similar to how code repositories on GitHub gain popularity. The way the discovery mechanism works depends on the state of the network. Below different scenarios will be discussed depending on the state of the network.

Scenario 1: New Module

When a new module is created the network is not aware of this. To make it possible for other nodes to discover this new node, the author will automatically vote on its own module. This vote is stored on a blockchain and includes a module manifest. The module manifest contains the module identifier, module timestamp, and a description. The block representing this vote is sent to all connected neighbors in the FBase overlay network of the current node. At the end of this scenario the author and its connected nodes know about the new module.

Scenario 2: Upvoting

When users discover new modules they can inspect the module and determine if they want to vote on it. When the user determines it does not want to vote on the module, the spreading is terminated at this node. When they do want to vote on the module, the module information is distributed in the same way as in Scenario 1. This is done to promote the spreading of quality modules and hinder the spreading of bad quality modules.

Scenario 3: Random Discovery

The previous scenarios have the downside that they make it hard for modules to get of the ground. To give modules a better chance at discovery, FBase makes use of a mechanism called Random Discovery. In Random Discovery, nodes send out discovery messages through multiple hops in the connected network. The nodes that receive this message discover the new module. This approach creates multiple different starting points from which modules can be discovered. This increases the possibility for a module to be discovered on a larger scale. The rate at which these discovery messages are send is determined by the number of votes a module has.

Scenario 4: Updated Module

When a module is updated a new version has to be discovered by the network. To make sure critical updates are discovered as fast as possible, nodes automatically vote on updated nodes when they have voted on the previous versions. This fast updating is critical to prevent security vulnerabilities from persisting in code bases longer than necessary. In a framework designed around re-usable code, security vulnerabilities are a big problems since many different applications rely on the same pieces of code. One vulnerability can effect many different applications.

Scenario 5: New Node

When a node connects to the network for the first time, it has not discovered any nodes yet. It will only discover nodes recently voted on by its connected neighbors. This is also called the bootstrap problem.

To bootstrap new users, the node crawls the blockchain of its connected neighbors. During this crawling it fetches the modules that have been discovered by these neighbors and stores them in its own blockchain.

Performance

The performance of the discovery mechanism is determined by multiple factors.

One of these factors is the number of connected nodes each node has. This controls the speed at which modules can spread through the network. Making this value too low creates a scenario where modules have a difficult time being discovered when just created. Making this value too big could flood the network with (malicious) modules and create a Distributed Denial Of Service (DDOS) attack.

Another of these factors is the active involvement of the users of the system. When users don't actively participate in the voting process. It makes it much harder for modules to be discovered by the entire network.

A third factor would be how capable users are in determining the quality of modules and voting on them. When users vote on almost every item, it would flood the network. Since each user would send a message to all its connected neighbor for every module it knows about.

By making use of multiple discovery mechanisms, FBase tries to find a balance between the speed at which modules can spread through the network and preventing a flood.

3.3.3. Distribution

When nodes have discovered modules, the module code has to be distributed to them. To satisfy the requirements that where determined in Chapter 2, the distribution mechanism has to be decentralized.

By making the distribution mechanism decentralized it allows network to operate without a central point of failure. Another benefit of this approach is that the load of storing and distributing the module code is spread across the users of the network. When nodes download a module it increases the availability of that module within the network. This means that modules that are more popular and will be downloaded more often, have a higher availability to scale with this. Modules that are less popular will have a lower availability to correspond with the demand.

Each module must have a minimum availability to make sure that every module that is discovered is also available to download. To make sure this happens the author of the module always keeps a local copy of the module. Besides this copy, the Random Discovery mechanism will make sure that a minimum number of other nodes also have a copy to prevent a problem when the original author is offline. When a Random Discovery message is received that node automatically downloads the module to increase the availability of it temporarily.

If a node has a copy of a module that it has not used for a while this module is deleted from that node to keep the network lean and fit.

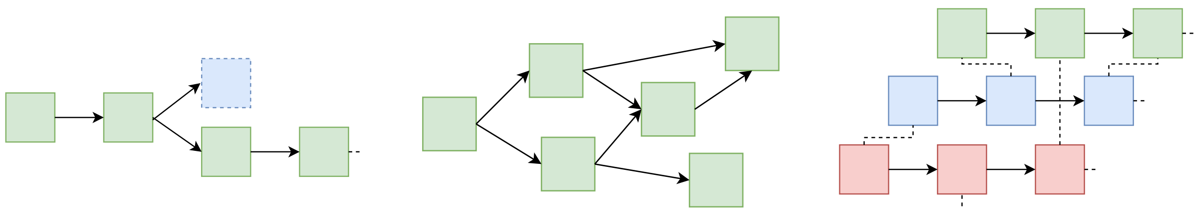
3.4. System Strategies

Since the framework deals with untrusted executable user code, the framework provides several different strategies that the user can select from to protect their system against possible threats from running this code.

3.4.1. Download and Retention Strategy

The framework allows the user to configure and replace the download and retention strategy. This strategy is responsible for choosing which components get downloaded and how long they are kept on the system. For the distribution of components it is necessary to download packages that might not be used by the host system itself, but are solely for the intent of distributing. Some users might want to take a different approach to accomplish this. The framework addresses this by allowing parts of its code to be replaced by other components written by a third-part or by the user itself.

3.5. Blockchain Storage



(a) Linear ledger (Ethereum). (b) DAG ledger (IOTA). (c) Pairwise ledger (Nano).

Figure 3.2: Three different structures of distributed blockchain ledgers. Each arrow points to the subsequent block in the chain.

FBase requires a blockchain that can store tamper-proof and accurate data records. We now explore three common blockchain structures, displayed in Figure 3.2.

Linear ledger:

Figure 3.2a shows the linear blockchain ledger used by Ethereum. The fundamental property of this ledger is that at least a majority of users agree on the exact sequence of transactions. A global consensus mechanism like Proof-of-Work or Proof-of-Stake prevents the double-spend attack where a malicious user intentionally creates a fork of their chain [38]. While providing a high level of consistency, the transaction throughput of these ledgers is often not high enough to facilitate record creation and modification by millions of users. This motivates us to consider different blockchain structures for FBase.

DAG ledger:
Another blockchain structure is the Directed Acyclic Graph (DAG) ledger, where each block can be referenced by multiple other blocks. This ledger structure, shown in Figure 3.2b, is adopted by blockchain platforms like IOTA and Dagcoin [29] [24]. IOTA is optimized for micro-payments within Internet-of-Things, and Dagcoin advertises itself as data storage for arbitrary data (e.g., documents or ownership records). Since these ledgers allow for different consensus mechanisms, transaction throughput is often superior compared to that of linear ledgers. However, they usually do not have the same consistency guarantees. While these ledger structures are more suitable for data storage, we consider current implementations unfit for the storage of votes. The reason is that they either rely on a centralized coordinator (IOTA) or a fixed group of witness nodes (Dagcoin). Instead, our goal is to devise an infrastructure without any authority with leveraged permission.

Pairwise Ledger:
A third blockchain structure we consider is the pairwise distributed ledger. The key property of this ledger, given in Figure 3.2c, is that each user maintains and grows their individual chain with transactions. Each block holds exactly one transaction and optionally contains a (hash) pointer to a transaction in the individual chain of another user. Blockchain fabrics like R3 Corda, Nano, and TrustChain, use pairwise ledgers as their underlying data structure [28] [23] [9]. These platforms address the double-spending attack either by a trusted notary (Corda), a weighted voting system (Nano) or by guaranteed eventual consistency (TrustChain). In general, they provide superior scalability compared to linear ledgers as used by Bitcoin and Ethereum but lack global consensus.

We strongly believe that the pairwise distributed ledger is a suitable data structure to store voting records as transactions. Compared to linear and DAG ledgers, only data that the user is interested in, is stored on that users host. Pairwise distributed ledgers enable selective queries of data stored on the chains of other members, without the need for full data replication across the network. In FBase, each individual ledger stores all data associated with a module, in a tamper-proof manner, and without global agreement.

3.6. Module Interconnect

To combine the different modules into the use application the module interconnect mechanism is used. This mechanism uses a top down search approach. When a module searches for a dependency it defined , it sends a message on the event bus specifying the module type and name.

View modules can load Application modules. Application modules can load Service Modules and Package modules. Service modules can load Package modules. Package modules can load other package modules.

When the lower module receives the event for itself, it registers itself with the higher module.

3.6.1. View Module

When a new view component is added to the system, it needs to know how to connect to the logic component of the application. It does this by triggering an event on the event bus, specific for the type of application it belongs to, indicating it is requesting an endpoint address. The logic component is subscribed to this event. Its registered handler will return the REST API endpoint address back to the view component through the event bus.

To define a view component, a special file has to be created: view-component.json. This definition file stores the attributes and the settings of the view component. Attributes of the file include: name, version, app-tag (Application tag used for hooking on to the logic component). Each view component also needs to have a directory named public which contains the index.html file. An example structure can be found below.

- view-component.json
- public
  - index.html
  - Other HTML/CSS/javascript resources

3.7. Trust

3.7.1. Verifiable modules

module manifest is signed with private key

Code should be viewable
Decide if each version should be a separate module, has downsides to upgrade speed
Each user in the network can inspect the module

3.8. Identity Profiles

In peer-to-peer systems each peer in an overlay has to have an identity. This identity determines the trust and association within and across overlays. This identity can be shared between different overlays or each overlay can use its own identity. If two overlays use the same identity, one overlay can benefit from the built up trust and reputation of another overlay. However, actions performed by one overlay can also have a negative trust impact on the other overlay. To allow applications to choose between the having a shared identity, having its own identity, or having an pseudo-random identity, the framework provides a configuration option in the component.json to select what kind of identity profile is preferred..

3.8.1. Verified Identities

To further improve trustworthiness of modules, users can optionally verify their digital identity. A verified identity is uniquely linked to a real-world entity. Software built on FBase can give preferential treatment to module authors that have verified their identity.

Identity verification can be done with an attestation given by a trusted third party like the government or a notary. Enforcing strong, long-lived identities in FBase is comparable with account validation that many centralized platforms use (e.g., the verification of a phone number). The requirement for verified identities addresses the Sybil Attack, where an adversary assumes multiple fake identities to influence or subvert the network [13].

We propose two solutions to achieve trustworthy importation of data: *challenges* and *TLS auditing*.

The first solution is to pose a challenge where the developer importing the data, proves that they have control over this data. For example, when importing data from GitHub, we can require a public identifier (e.g., a public key) of the developer to be part of the "bio" profile field. This information can then be verified for correctness by other users who query the public GitHub API. We call users who verify data *witnesses*. While this is a basic mechanism to ensure the accuracy of imported data, it heavily depends on the availability of a public API.

The second solution is TLS auditing [8]. The key idea is to proxy a TLS connection through a random witness, which then verifies and signs the data after the TLS connection terminates. When the TLS session finishes, the client gives the witness the private key used to decrypt HTTPS responses from the web service. Note that this way the witness is not able to decrypt the request made to the web service, which likely includes credentials or access tokens. The role of a witness can either be fulfilled by other entities in the network, or by a trusted notary service. Depending on the significance of data being imported, multiple witnesses can be used for this. Compared to challenges, TLS auditing works when access to a public API is absent but is more advanced. Our lab has implemented an advanced TLS auditing mechanism, which is currently under a security audit.

3.8.2. Isolated Execution

Since all distributed components have to be executed on the host system for them to function, it can pose a security risk by running untrusted user code. To minimize the risk that this poses, the framework allows components to be run inside of an isolated execution environment using Docker. When this method is used an execution environment is setup inside of the docker engine and the code will be mounted inside of this container. This container will then be able to run the code in isolation. This method, however, will prevent other applications running on the system from communication to it. It does allow the view layer to communicate with the isolated components since this makes use of network sockets.

4 Implementation

This chapter discusses the design principles and implementation details of the system described in the previous chapter. This work took a prototyping approach to get to a functioning prototype rapidly and improve from there. The sections below we explain the different functionalities that were tackled in chronological order.

4.1. Module Distribution

The first step that was taken to undertake this project was module distribution. Distribution was chosen as the idea hinges on the ability to setup an integrated content distribution network that would work efficiently and scale. Since this is not the first time this is done and there already exist excellent solutions out there that could accomplish this. Below I will list the different protocols considered.

4.1.1. Protocols

TFTP

Trivial File Transfer Protocol (TFTP) is a very simple and old file transfer protocol. It is mostly used in older enterprise equipment and is not really used anymore today. This has to due with the downsizes of the protocol in that it has no security built-in and has no verification that the content has arrived intact.

FTP(S)

File Transfer Protocol is a newer protocol than TFTP, but still older than the other alternatives. This protocol is mostly used for transferring content to web servers. For that purpose this protocol functions well because it is lightweight, provides content verification, and is simple. The downside for our use-case is that it isn't secure by default (gets routed through a HTTPS connection), doesn't support file transfer resumes, and doesn't scale well.

Web protocols

Web protocols like HyperText Transfer Protocol (HTTP) and its secure variant HTTPS are a very common transfer protocol in the current day internet. It is used by all major Linux distribution to distribute the system packages, by websites for downloading content and watching videos. This protocol supports file transfer resumes, encryption. It, However, doesn't scale well when the same content has to be uploaded to multiple users and doesn't natively provide content verification.

BitTorrent

BitTorrent is the protocol used by all bittorrent clients. It provides encryption, content verification, file transfer resumes, and scales very well when large amounts of the same contents has to be distributed thanks to its mesh architecture. That is why this protocol was selected as the basis of the module distribution of this work.

4.1.2. Module transfer protocol

Several small experiments were conducted to test the feasibility of the BitTorrent protocol with the regards to this work its use-case. These were related to choosing a suitable BitTorrent implementation, testing the creation of a torrent and downloading this just created torrent on multiple other nodes. We made use of magnet links to transfer the information required to download the torrent. Ones these experiments were deemed successful, we had to find a way to distribute this magnet link through the network without using the traditional method of content indexing services. The method that we chose is described in the discovery section.

4.2. Discovery and Voting protocol

When a suitable transfer protocol is chosen, the next step was to make it possible for modules to be discoverable by all nodes in the system. Since we were already building our framework on top of the IPv8 peer-to-peer communication library. We decided it would be a good fit to use this to accomplish our goal, since it was very suited for bulk small size data gossiping. So this became out chosen method of module discovery.

Since IPv8 also provides a block-chain storage back-end it was an perfect opportunity to

5 Experimentation and Evaluation

This chapter will propose an experiment and evaluate the framework described in Section 3. The evaluation will be performed based on the result gathered from the experiment.

5.1. Experiment

The experiment consists out of conducting a use-case study, by creating a fully functioning example that demonstrates the composition and construction of an application with interchangeable trust models. This application will consist out of 6 components:

- Test application GUI (view layer)
- Test application (logic layer)
- Trust algorithm 1 (logic layer)
- Trust algorithm 2 (logic layer)
- Execution engine (infrastructure layer)
- Transport engine (infrastructure layer)

Figure 5.1 shows an overview of the example application. The domain of trust was chosen since this is a very interesting use-case that has not been explored yet in other works. It allows users of a system to define their own notion of the concept of trust and apply this to their system without requiring extensive knowledge about each application they are using. For this experiment, this work makes use of two different trust algorithms: Netflow and PimRank. These two algorithms act as an exampl for this experiment.

5.2. Mobile App

To test the robustness and the flexibility of the framework, an experiment was performed to try to create a proof-of-concept prototype of an Android application that could run the same stack of code to extend the ecosystem to mobile platforms. Since the two major mobile platforms (Android, iOS) only run applications custom made for these platforms, different methods had to be explored. Because iOS has a very restricted development environment and strict security policies, this route was not further explored.

The Android platforms allows app developers to run Java, Kotlin (Java based), and C. The desired framework language (Python) does not natively run on this platform. Converting the project code and dependencies is not a simple or maintainable method. This approach, however, also would not work. To improve security, the Android platform makes use of app scanning to verify that the executables haven't been tampered with. This security method severly hinders the working of the framework, since more functionality is added by distribution of application through its peer-to-peer network. These new code inclusions would trigger warnings in the Android security system and would block the app.

To circumvent this, a un-official method was used to package all the necessary code, dependencies, and executables as a single file and execute this as a C service on the Android platform. To accomplish this, a

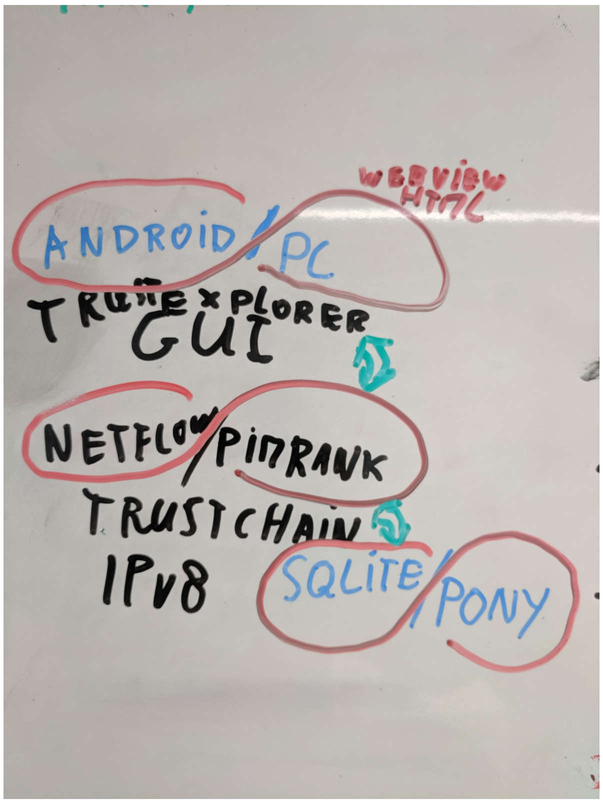


Figure 5.1

project called Python-for-Android was used. Python-for-Android is a build script that compiles the desired Python system version and Python dependencies for the ARM platform and creates a directory structure that can be used to run on Android. In Figure 5.2 and overview of the Android app structure can be seen.

Since the Android app is needed to interact with the C service in the background, a part of the app had to be written in either Java or Kotlin. To keep this amount of code to a minimum, a decision was made to create all GUIs in web technologies, so the view layer can be shared between mobile and desktop platforms. This decision made it possibly to include a web browser as the only component written for the mobile platform. This web browser can then interact with the web server and REST API running on the C service.

To package the executable code in a way that would not trigger the Android security system, the code had to be bundled in a single file, disguised as a MP3. This format does not get checked by the Android security system and therefore can be used for the purpose of this work. Underneath the extenstion, the code is packaged as a GZIP Tar-archive. Upon running the Android application, this MP3 file is unpacked in the application space of the app and the C service is started with the right configuration to run the code.

In Figure 5.3 a screenshot can be seen of the framework running with a test dApp on the Android platform. Development was stopped after reaching the proof-of-concept stage as it is not the main goal of this work and the development cycle is very tedious and slow. Each time a change or addition is made to the Framework the entire app structure has to be rebuild. This process can take up to 20 minutes.

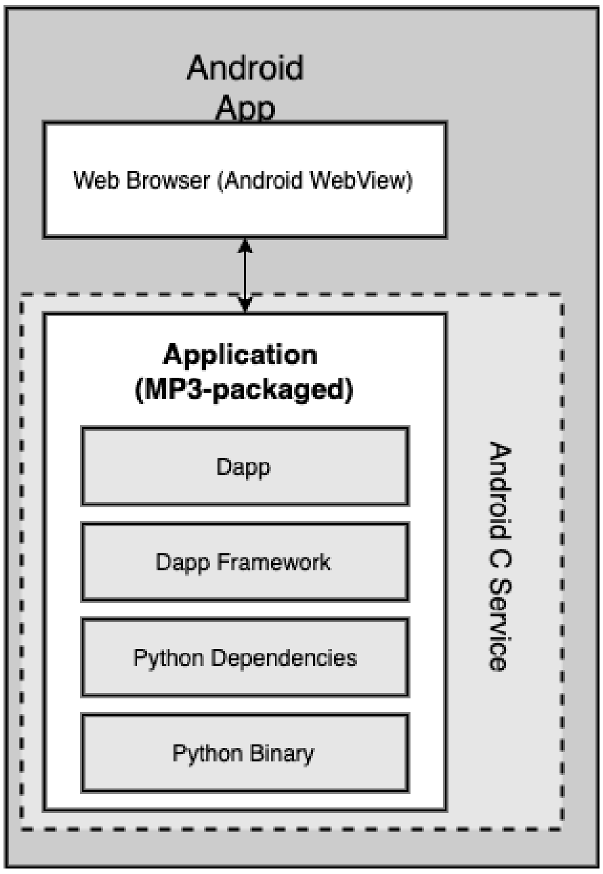

Android App
Web Browser (Android WebView)
Application (MP3-packaged)
Dapp
Dapp Framework
Python Dependencies
Python Binary
Android C Service

Figure 5.2

dApp
dApp
Done
Tap here to fill entire screen

test

4c69624e61434c504b3ae08e57f02b03e90726da888147a4359d7d

2

Figure 5.3

6 Conclusion

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Module tutorial