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Trust in your friends, on the ledger

Safer reproducible builds through decentralized distribution of `.buildinfo` files

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Stockholm, Sweden, 2022

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$$\int_a^b x^2 \, dx$$

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I would like to thank xxxx for having yyyy.

Stockholm, May 2022
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List of acronyms and abbreviations

API	Application Programming Interface
DLT	Distributed Ledger Technology
DNS	Domain Name System
FOSS	Free Open Source Software
IPFS	InterPlanetary File System
RDBMS	Relational Database Management System
TLA	Temporal Logic of Actions

The list of acronyms and abbreviations should be in alphabetical order based on the spelling of the acronym or abbreviation.

Chapter 1

Introduction

This chapter describes the specific problem that this thesis addresses, the context of the problem, the goals of this thesis project, and outlines the structure of the thesis.

1.1 Background

Discussions on how to verify the lack of malicious code in binaries go at least as far back as to Ken Thompson's Turing award lecture [1] where he discusses the issues of trusting code created by others. In recent years, several attacks on popular packages within the Free Open Source Software (FOSS) have been executed [2] where trusted repositories have injected malicious code in their released binaries. These attacks question how much trust in such dependencies is appropriate. In an attempt to raise the level of trust and security in Free Open Source Software (FOSS), the *reproducible builds* project [3] was started within the Debian community. Its goal was to mitigate the risk that a package is tampered with by ensuring that its builds are deterministic and therefore should be bit-by-bit identical over multiple rebuilds. Any user of a reproducible package can verify that it has indeed been built from its source code and was not manipulated after the fact simply by rebuilding it from the package's `.buildinfo` file. These metadata files for reproducible builds include hashes of the produced build artifacts and a description of the build environment to enable user-side verification. The crucial link to ensure reproducibility is by this notion `.buildinfo`, which also means that a great deal of trust is assumed when using them. Current measures for validating `.buildinfo` files and their corresponding packages involve

package repository managers and volunteers running rebuilderd [4] instances that test the reproducibility of every `.buildinfo` file added to the relevant package archive. This setup allows users to audit the separate build logs, thus confirming the validity of a particular package. However, because this would be a manual process and the different instances do not coordinate their work, it relies on the user judging on a case-by-case basis whether to trust a package or not.

Validating the aggregated results from many package builds could potentially be done through Distributed Ledger Technologies (DLTs). DLTs were popularized by Bitcoin [5, 6] for crypto-currencies but has wide ranging applications in trust related domains. A distributed ledger is a log of transaction held by many different nodes on a network. Transactions are validated, ordered and added to the network by a consensus algorithm to ensure that no single or small group of nodes can act maliciously. The log itself is commonly a tree or graph of hashes which allows proving that a particular transaction has happened in an efficient manner. Because of their distributed nature, DLTs are however hard to test and verify. One way to go about this without loosing accuracy **Precision?** is by modeling the system with formal specification tools that can validate the properties of the system design. Even though such a model is not a true representation of the system itself,

This project seeks to reduce some of the above mentioned burden from the user while increasing their trust in the software they use by investigating possible decentralized solutions for distributing and proving the correctness of `.buildinfo` files.

1.2 Problem

Equivalences between human-readable source code and binaries are hard to prove **(cite)**. Likewise, the same holds when comparing the source code and hash of a binary program. A more easily proved variation of this problem is whether multiple binaries have been built from the same, potentially unknown, source. If the binaries are identical and the builder is trusted not to forge their results, the binaries can confidently be assumed to have been built the same way. The proof, though, is only as strong as the trust in the builder; who could potentially be compromised. With multiple builders, the risk is reduced and the trust will likewise increase.

Distributing the workload creates the need for a system where the build results can be aggregated. Because users have different needs, they should be able to choose their own trust models and use the packages they trust based on

the build results from the different builders. With this as background, there is the question of how such a system can be designed and implemented in order to maximize user trust in that the packages they use have been derived from the authentic source code.

1.2.1 Original problem and definition

The *Debian Reproducible Builds* project uses `.buildinfo` files to store checksums of derived artifacts. These files can serve as proof that a package has been built from source by a particular builder. Storing the aggregated `.buildinfo` files from multiple builders in a system could increase user trust in `.buildinfo` files, and therefore in packages. This follows from the fact that even though any particular builder could act maliciously, the probability that all builders are doing so lowers for each added builder. With this in mind we ask the following question:

- To what extent can distributed and decentralized storage secure the integrity of `.buildinfo` files?

1.2.2 Scientific and engineering issues

In the process to answer the research question, the following more technical questions will have to be answered as well:

- Which distributed data storage solutions are applicable for `.buildinfo` files?
- How can we model a relevant system for efficient evaluation of integrity preservation?

1.3 Purpose

As society relies more and more heavily on software and digital infrastructure, threats to those technologies are increasingly more important to mitigate. By supplying additional safeguards to the way we manage software, we can make it harder for malicious actors to take advantage of users.

One current way of managing software in a safe manner is to first download its source code and then building it on our own machines. This way, we can be confident in that we are running the software we intend to run. Such a method, however, is time consuming for the user. The purpose of this project is to

give alternative solutions with a focus on user trust while not relying on users' building packages themselves. Furthermore, this project seek to increase trust and security in Free Open Source Software and reduce the risk of supply-chain attacks on package archives.

1.4 Goals

The main goal of this project is to formulate a plan for how to store `.buildinfo` files in such a way that their integrity is maintained. This involves understanding the purpose `.buildinfo` files and the context they exist within. The storage plan should be formulated based on this context and written as a formal specification.

1.5 Research Methodology

The project is in three phases. The initial phase is a pre-study focusing on reproducible builds, Distributed Ledger Technologies and formal specification. Its purpose is researching possible technologies, solutions and evaluation methods for solving the issues mentioned under section 1.2.2. With this initial phases finished, an appropriate storage strategy for ensuring the integrity of `.buildinfo` files and a methodology for modeling such a storage system is decided. The last phase involves producing and evaluating the model of said system to find an answer to the original research question stated in 1.2.1.

1.6 Delimitations

While this project utilizes `.buildinfo` files and reproducible builds as its core problem domain, no builds or `.buildinfo` files are necessarily produced during it. More specifically, the relevant part of `.buildinfo` files in terms of the project are their meta information and context in the software ecosystem. Their actual content and semantics are mainly irrelevant for the project and is represented in an abstract manner in any implementation or artifact.

Chapter 2

Background

This chapter covers an introduction on reproducible builds as seen within the Debian project. It also describes the core ideas in Distributed Ledger Technologies, examplified most notably with the blockchain *Hyperledger Fabric* and temporal logic and formal specifications written TLA$^+$. Important terminology such as Confidentiality, Integrity, Availability is also presented. The chapter ends with a review of previous work related to this project.

2.1 Confidentiality, Integrity, Availability (CIA)

Within information security, the terms confidentiality, integrity and availability are at the core of how researchers and security auditors describe the security of information systems [7]. They each relate to the respective security risk where an actor can read, write or hinder information when they should not have been able to do so. *Confidentiality* is the ability to stop unauthorized information leakage *i.e.,* you must be authorized to read the information. In a similar vein, *integrity* is the ability to stop unauthorized changes to information. *Availability* is the extent to which a a resource is guaranteed to be present and available to those authorized to manage it.

2.2 Pretty Good Privacy (PGP)

2.3 Reproducible builds

As a response to supply chain attacks on package archives for open source software, several projects have started within the linux community in order

to raise build reproducibility [3]. Traditionally, linux distributions come with package managers (such as apt **(cite)** (apt) or pacman **(cite)** (pacman)) that help users installing and managing programs. While many packages have their source code available online and can be built directly from it by each user, package managers commonly have the functionality to download pre-built programs from an archive. This is convenient for the user but comes with security risks. Using pre-built packages relies on trusting the builder to use the correct source code and that any dependencies needed to build the package are themselves non-malicious.

Building a package reproducibly means it is bit-by-bit identical every time it is built [2]. Verifying its correctness can therefore rely on multiple parties, each building it separately, instead of trusting a single builder. Each builder can supply a hash of the built software which, if everything has been done correctly, should all be the same. Reproducible builds allows a separation between distributing the software artifact and its verification. Different efforts to make builds reproducible have used various strategies, but a core similarity between them is the use of some kind of specification for the build-environment.

TODO: Add note on percentage of packages that are reproducible on Debian

2.4 `.buildinfo`

In order for builds to be reproducible on different computers, the Debian project uses `.buildinfo` files to describe the necessary parts of the environment in which a package was first built. By recreating this environment on a different machine, build artifacts become identical, as long as the package is reproducible. Included in `.buildinfo` files are, among other properties, name and version of the source package, architecture it was built on, checksums for the build artifacts as well as other packages available on the system [2]. See appendix C for an example file. The `.buildinfo` files origin and authenticity is given by the builder signing it with their private PGP key. A user can verify that a package has been built from source by comparing its checksum from **hash example** with the one in a corresponding `.buildinfo` file from a trusted source.

Currently, `.buildinfo` files are distributed in a centralized archive **(cite)**. Because this is a single-point-of-failure, if a malicious actor takes control of this archive, it could be very hard for users to know whether or not a package should be trusted.

2.5 Distributed Ledger Technology (DLT)

Storing and managing data is commonly done in databases such as Relational Database Management Systems (RDBMSs) or key-value stores **(cite)**. Because of these solutions' often centralized nature, they come with both integrity and availability risks **(cite)**. They can become single-point-of-failures. If that data storage is interrupted or manipulated, a system relying on it is at risk. Distributed Ledger Technologies are an alternative solution to data storage, mitigating the shortcomings of traditional, centralized methods. DLT is an umbrella term for several different technologies which rely on decentralized append-only logs [8] . The data stored in such a network cannot be changed by a central node. Instead, there has to be a consensus over the participants on how a change is to be made, followed by that change being propagated to all nodes in the network. Depending on the application, different solutions to how consensus is made and how the ledger itself is represented have been designed, each with its strengths and weaknesses.

The term is sometimes used interchangeably with blockchain, but while the latter uses a specific shape on its ledger, the former is more general. Other examples of DLTs are Certificate Transparency logs **(cite)** and peer-two-peer networks.

2.5.1 Merkle trees

Patent approved in 1982 [9] as a method for managing digital signatures, Merkle trees have since then been used for applications amongst file sharing and peer-to-peer communication [10], auditing certificate authorities [11] and running blockchains [12]. Merkle trees are directed acyclical graphs where each nodes' value is a hash based on the values of its child nodes. The leaves of the graph contain the data (or a hash thereof) relevant for a particular application, while the other nodes enable efficient proof mechanisms for validating the integrity of the data. For example: given a subgraph (*i.e.,* one with less data), verifying that its supergraph contains a certain value relies only on a subset of their differing nodes. This makes Merkle trees applicable to distributed systems where sending entire graphs between clients would be too expensive.

2.5.2 Consensus

When multiple systems or processes cooperate on a shared state, any change to this state needs to be agreed upon between the different entities. If no agreement, or consensus, can be found, the entities' different views of the state can drift away from each other. This can lead to an invalid system from which no meaningful progress can be made. The problem of creating consensus can be further complicated by assuming that entities can crash and be revived at any time, or even be malicious in the messages they send to the network.

A number of consensus algorithms exists, serving various applications. One way to differentiate them is whether they are proof or voting based [13]. In a proof based consensus algorithm, only the party that has provided a certain proof is allowed to change the data. Such algorithms can be found in some public ledger blockchains, such as bitcoin. The proof itself can be, for example, finding a number given certain constraints, which is known as proof-of-work. With proof-of-work, the greater computational investment any one participant makes, the greater is the probability that they will be allowed to change the blockchain. However, the greater the computational power is in the whole network, the more limited is any one participants possibility to control or use it maliciously. Other proof based algorithms exist, but they are all centered on connecting responsibility with some type of resource investment. Voting based consensus algorithms on the other hand relate more to a more intuitive understanding of agreement, *i.e.,* democratic voting. Agreement is made only when a certain fraction of the nodes have voted in acknowledgment to a certain decision. This relies on knowing how many nodes there are on the network in total, making voting based consensus less usable in certain scenarios. While simple in idea, a voting based consensus algorithm can become complicated in practice. The algorithm should not only be able to find consensus in perfect conditions, instead a realistic solution should work even if some nodes on the network crashes and, perhaps, even if some nodes are malicious. A consensus algorithm that can handle both of these kinds of issues is called Byzantine resilient [14] or that it has Byzantine fault tolerance [13]. If the algorithm only handles crashes but not malicious actors it has Crash fault tolerance.

Paxos??

2.5.3 Blockchain

Originally described for Bitcoin [6, 5], blockchain is a technology based on Distributed Ledger Technology for storing transactions without needing a centralized organization. Transactions are represented as simple strings

of characters which allows them to model essentially anything. This is why blockchains can be used for a broad spectrum of applications such as currencies, ownership contracts etc. **(cite)**. The name stems from the setup of a blockchain ledger where groups of, closely related in time, transactions are appended together as a block to the current chain by including a hash of the previous block in the latest one. By grouping transactions together, the throughput of the network improves. A consensus algorithm is used to create a total ordering of the blocks so that every node on the network eventually holds the same ledger.

TODO: Add figure for how one block connects to the next.

TODO: Public vs Private vs Consortium blockchain

2.5.4 Peer-to-peer

TODO: Add information about IPFS

TODO: Summaries several different DLT

2.6 Hyperledger Fabric

Hosted by the Linux Foundation[15], the Hyperledger Fabric, or Fabric, is a permissioned blockchain framework with a novel and flexible approach to DLT. A Fabric network can, for example, choose a consensus algorithm suitable for that particular usecase and define specific requirements for when a change to the ledger may be allowed [16]. This section will describe and discuss the main components of a Hyperledger Fabric network and how they work together.

2.6.1 Overview

The Hyperledger Fabric ledger is permissioned. This means that it is only available to certain participants. This is regulated by Membership Service Providers (MSPs) on the network, verifying the identities of nodes through Certificate Authorities (CAs) **(cite)**. Besides MSPs, the nodes on the network can take on one of the roles of *peer* or *orderer*. Every node on network belongs to some organization whos' MSP determines its role. In this sense, a Fabric network is a network of organizations rather than one of nodes.

Every peer store the network's entire blockchain ledger and validates transactions and changes to the ledger. Orderers, on the other hand, clump together transactions into blocks and delivers them to the peers.

This separation of concern makes consensus algorithm selection possible in Hyperledger Fabric. Changes onto the ledger are made by invoking smart contracts, called chaincodes within Fabric. Chaincodes are authorized programs that are run by peers on the network. If multple peers (according to its endorcement policy) get the same result from running the chaincode, any updates are written to the ledger. For performance reasons, a key-value store representing the current ”world-state” is continuously derrived from the ledger and stored on the peers. This allows both reading and writing to happen without going through the entire ledger itself.

TODO: Bootstraping ordering service with a genesis block containing a configuration transaction [16]

2.6.2 Transaction flow

A transaction in Hyperledger Fabric goes through a number of steps before a change to the ledger happens. Figure 2.1 shows an overview of an example transaction. First, a client application invokes a particular chaincode by (as of version 2.4) sending a transaction proposal to the Fabric gateway on the network. The gateway is a service running on a peer which takes care of the transaction details, allowing the client to focus on application logic [17]. After receiving the proposal from the client, the gateway finds the peer within their own organization with the longest ledger, the *endorsing* peer, and forwards it to them. The endorsing peer runs the transaction (*i.e.,* chaincode) and notes what parts of the world-state it had to read from and which it will write to (the *read-write set*). This information together with the chaincode's Endorsement Policy informs which organizations has to accept, or endorse, the transaction for it to be valid. Only at the time when every necessary organization have endorsed the transaction can any change be made to the ledger.

The Fabric gateway is responsible for forwarding endorsement requests with the transaction proposal to peers of each necessary organization and gathering their responses. Each of these peers will then run the transaction proposal and sign their endorsement for it with their private key if they deem it correct. The gateway receives the read-write sets and endorsements, validates them, and sends a final version of the transaction to the ordering service. The actual transaction contains the read-write set and the endorsements from the different organizations.

As the ordering service runs on other orderer nodes from the peers, how the ordering service is implemented is completely separated from the functionality of the peers. Its purpose is to group transactions into blocks and order and

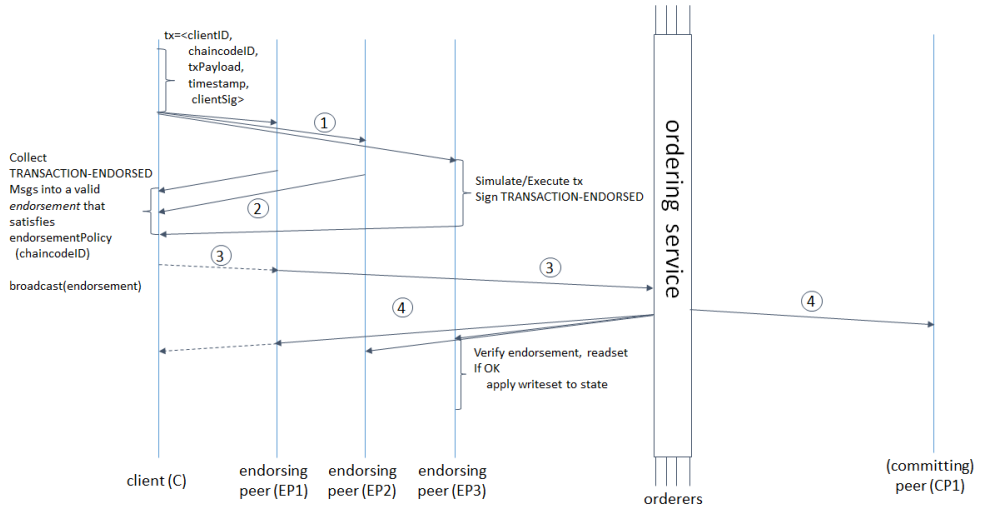

Figure 2.1: Swimlane sequence diagram over the Hyperledger Fabric transaction flow. Note that this is for an earlier version from before the Fabric gateway. As of version 2.4, the behaviour of the client in the diagram is instead performed by the gateway, while the client only initiates a transaction. The image [20] was created by Hyperledger and is licensed under CC BY 4.0 [21].

distribute them to all the peers on the network. By default, Fabrics' ordering service uses Raft, which is a voting based crash-fault tolerant consensus algorithm [18]. Attempts have been made to add a Byzantine-fault tolerant ordering service to Fabric [19], but so far none have been added to the project.

When a peer receives a block from the ordering service they add it to their locally stored ledger, validate each transaction and, if valid, update its local world-state according to the transaction write set. They also notify the client application of the transactions status. Validation has two parts. First, the transaction must fulfill its endorsement policy, and, secondly, the subset of the world-state contained in the read set must not have changed. All transactions, valid and invalid, are added to the ledger, but they are marked to know which ones are which.

2.6.3 Endorsement Policies

An update to the Fabric ledger is only possible if the endorsement policy relevant to a transaction has been fulfilled. Endorsement policies describe which and how many organizations or peers that need to run and endorse a transaction proposal. They are defined as logical formulas referencing relevant

```
OR('Org1.member', AND('Org2.member', 'Org3.member'))
```

Figure 2.2: Endorsement policy syntax example

organization and role for the peers that have to endorse it. Figure 2.2 shows an example endorsement policy with three organizations called Org1, Org2 and Org3 where all endorsing peers must have the *member* role.

An endorsement policy can be defined on three different granularity levels; chaincode-, collection- and key-level. Chaincode- and collection-level policies are decided on when a chaincode is commited to the network. The former is a general policy which always has to be fulfilled everytime the chaincode submitted as a transaction. Collection-level policies on the other hand are rules for when a chaincode reads or writes from a private collection. A chaincode can have multiple private collections, each with its own collection-level policy. When a chaincode accesses such a collection, the additional policies have to be satisfied as well. Key-level policies are similar to collection-level ones in that they only become relevant when a chaincode touches a subset of the world-state. A difference being that key-level policies are declared in the execution of a chaincode. A usecase for this is when adding a new asset to the ledger with a specific owner. By setting a key-level endorsement policy to the key of the asset, any transaction that tries to change the asset will have to be endorsed by, for example, its owner before it is commited to the ledger.

2.6.4 Chaincode

Many current blockchains have some notion of a smart contract [5], *i.e.,* methods to programmatically change the ledger only when certain properties, or contracts, have been fulfilled. Smart contracts make blockchains more general-purpose as they can be used to model many different protocols and applications. **examples plz**

In Hyperledger Fabric, smart contracts are called chaincode. As there is no inherent asset on the Fabric ledger over which peers can make transactions, chaincodes are the only way the ledger can be changed. They are in other words the only way to create, update and remove assets. Chaincodes has to follow the *fabric-contract* Application Programming Interface (API) to be run by peers on the network, but what language they can be written in is flexible. The official language options are Java, Javascript and Go, but other languages can be supported in theory. Listing 1 examplifies how chaincodes can look and

Listing 1 Modified chaincode excerpts from Hyperledgers sample project fabcar [22]. The examples showcases the main chaincode API endpoints `getState` and `putState` for retrieving and, respectively, updating the ledger.

```
/*
* Copyright IBM Corp. All Rights Reserved.
*
* SPDX-License-Identifier: Apache-2.0
*/
⋮
async queryCar(ctx, carNumber) {
  const carAsBytes = await ctx.stub.getState(carNumber);
  if (!carAsBytes || carAsBytes.length === 0) {
    throw new Error(`${carNumber} does not exist`);
  }
  return carAsBytes.toString();
}

async createCar(ctx, carNumber, make, model, color, owner) {
  const car = {
    color,
    docType: 'car',
    make,
    model,
    owner,
  };

  await ctx.stub.putState(carNumber,
                          Buffer.from(JSON.stringify(car)));
}
```

the mechanisms through which it interacts with the worldstate. A chaincode smart contract interacts, through the fabric-contract API, with the world-state key-value representation of the ledger and can query, update and set values in it.

Running a chaincode on the network does not update the ledger directly (see 2.6.2 for how ledger modifications are implemented). Instead a read-write set of the keys that have been queried from and the changes to the ones that have been set during the execution of the chaincode are generated. The result of the chaincode is this read-write set, which is then further used to update the ledger itself.

TODO: Find some good references for chaincode besides the official documentation.

TODO: Describe the core api for chaincode

2.7 Formal specification

Distributed systems can be complex to design and hard to reason about. This is mainly due to the non-deterministic interleaving of subsystems acting individually **(cite)**. To ensure that a design of a distributed system works as intended, formal specification notation and tools can be used. These do not generate actual implementations of a system, but instead a precise description of system properties [23]. By modeling a system with a formal specification, its properties can be automatically verified or refuted. It also forces the developer to think in terms of system invariants instead of *how* the system should be constructed. Because formal specifications are models of (and not actual) systems, there is no guarantee that they correspond correctly to a real implementation. However, because they do not include as many concrete details, testing the correspondance between a specification and an implementation can be done on a higher abstraction level compared to the unit-testing common in software verification.

TODO: Summaries several different formal specification methods

2.8 TLA$^+$

TLA$^+$ [24] is a language for formal specification where a model describes a systems' behaviour over time. It has been used successfully in industry to verify and finding bugs in distributed systems [25, 26] and can be written in both a mathematical notation style and the more pseudocode-esque PlusCal. The specification can then be verified by the TLC tool which simulates executions of the model in order to find potential faults. TLA$^+$ is built on the Temporal Logic of Actions (TLA) [27], but adds improvements for writing more modular and larger specifications.

2.8.1 Temporal Logic of Actions (TLA)

The semantics of TLA are based on infinite sequences of states called behaviours. Here, a state s is a mapping from symbolic variable names to values *e.g.*, $[\mathrm{x} \mapsto 1, \mathrm{y} \mapsto \text{"a"}, \mathrm{z} \mapsto 42]$. Behaviours represent the history of states that a program execution enters, one state for each atomic change. A program incrementing a counter could for example have the behaviour

$\langle [x \mapsto 0, y \mapsto 0, \dots], [x \mapsto 1, y \mapsto 0, \dots], [x \mapsto 1, y \mapsto 1, \dots], [x \mapsto 2, y \mapsto 2, \dots], \dots \rangle$

Figure 2.3: A behaviour where the variables x and y increment concurrently.

$\langle [x \mapsto 0, \dots], [x \mapsto 1, \dots], [x \mapsto 1, \dots], [x \mapsto 2, \dots], \dots \rangle$. Note that x does not increment at every state in this behaviour. This is an example of *stuttering i.e.,* x is allowed to remain the same or increment at every step. Stuttering allows logical formulas, or programs, to be modular. As an example of this, we can imagine a second counter program running concurrently with the first. The two programs are both incrementing variables but not necessarily at the same time, so at certain states we need stuttering to descibe the combined program. An example of this is shown in figure 2.3.

2.8.1.1 Propositional logic in TLA

The core of TLA is propositional logic **propositional?** with common connectives **connectives?** such as $\wedge$, $\vee$, $\implies$, $\neg$, $\forall$ and $\exists$.

2.8.1.2 State Functions and Predicates

TLA allows the use of "regular" mathematics which can be used to form expressions such as $x^2 + 5 * y - 3$. These make up the body of non-boolean state functions and their boolean equivalent predicates. The meaning of such expressions is evaluated relative a state. This is done by substituting the value of a variable in the state for the same variable in the expression. This definition can be written

$s[\![f]\!] \triangleq f(\forall v : s[\![v]\!]/v)$

where

- f is a state function or a predicate
- $\triangleq$ signifies equality by *definition*
- $s[\![v]\!]$ is the value of variable v in state s
- $s[\![v]\!]/v$ substitutes $s[\![v]\!]$ for v

Figure 2.4 shows an example of a substitution in a state function.

$\mathrm{g} \triangleq \mathrm{x} + \mathrm{y} - 2$
$\mathrm{s} \triangleq [\mathrm{x} \mapsto 0, \mathrm{y} \mapsto 2]$
$\mathrm{s}[\![\mathrm{g}]\!] \equiv \mathrm{s}[\![\mathrm{x}]\!] + \mathrm{s}[\![\mathrm{y}]\!] - 2 \equiv 0$

Figure 2.4: Semantic meaning of a state function g given a state s.

2.8.1.3 Actions

So far TLA is quite similar to propositional and predicate logic **which one?** but with the addition of *actions*, it changes quite radically. An action can be seen as the link between two states in the behaviour of a program. It describes change from one state to the next. Syntactically, this is done by separating variables into two groups: *un-primed* variables x, y, $\mathrm{z}, \ldots$ and *primed* variables x', y', $\mathrm{z}', \ldots$. Primed variables represent the value of their un-primed counterpart in the next state, and an action is just a boolean expression with both primed and unprimed variables. Incrementing a variable can for example be written as the action $\mathrm{x}' = \mathrm{x} + 1$. In natural language, this means that the variables value in the next state should be one more than in the previous. Similarly to how we did it for state functions and predicates, we can define the semantic meaning of an action $\mathcal{A}$ as

$\mathrm{s}[\![\mathcal{A}]\!]\mathrm{t} \triangleq \mathcal{A}(\forall \mathrm{v} : \mathrm{s}[\![\mathrm{v}]\!]/\mathrm{v}, \mathrm{t}[\![\mathrm{v}]\!]/\mathrm{v}')$

where s and t are both states and t follows directly after s. In other words, actions are relations between states that are following each other in time.

The changes in the increment counter program can, as mentioned, be represented by an action. To support stuttering we can add the second possibility that the variable stays the same. This is written as the disjunction $(\mathrm{x}' = \mathrm{x} + 1) \vee (\mathrm{x}' = \mathrm{x})$ *i.e.,* either x is incremented or it stays the same. As it turns out, this is a commonly used concept when writing specification so TLA provides a shorthand for it written $[\mathcal{A}]_\mathrm{f}$. We pronounce $[\mathcal{A}]_\mathrm{f}$ as "square $\mathcal{A}$ sub f". f here is any state function, but is often a sequence of the variables that are allowed to stutter. For example, with the increment program we can write $[\mathrm{x}' = \mathrm{x} + 1]_{\langle \mathrm{x} \rangle}$.

2.8.1.4 Temporal operators

Where actions describe a single step of change between two states, we have already mentioned that program executions are represented in TLA by behaviours *i.e.,* sequences of states. To be able to describe whole behaviours we need some way of lifting actions from acting on pairs of states to sequences of states. We can perform this lifting in TLA with the *always* temporal

operator, written as $\Box\mathcal{A}$. Informally, this formula is true only if the action is true for all consecutive pairs of states in a behaviour. More generally, we can write $\Box\mathrm{F}$ where F is a logical formula built from predicates and actions. For a behaviour $\langle \mathrm{s}_0, \mathrm{s}_1, \mathrm{s}_2, \dots \rangle$, the operator can be defined as

$\langle \mathrm{s}_0, \mathrm{s}_1, \mathrm{s}_2, \dots \rangle [\![\Box\mathrm{F}]\!] \triangleq \forall \mathrm{n} \in \mathbb{N} : \langle \mathrm{s}_\mathrm{n}, \mathrm{s}_{\mathrm{n}+1}, \mathrm{s}_{\mathrm{n}+2}, \dots \rangle [\![\mathrm{F}]\!]$

where $\mathbb{N}$ is the set of natural numbers. To understand this notation, it should be noted that $\langle \mathrm{s}_0, \dots \rangle [\![\mathrm{F}]\!]$ is true if and only if F is true in the behaviour's *first* state s_0.

Besides $\Box$, another common temporal operator is called *eventually* and written $\Diamond$. $\Diamond\mathrm{F}$ denotes a formula that will be true at some point, and can be derrived in terms of the *always* operator as

$\Diamond\mathrm{F} \equiv \neg\Box\neg\mathrm{F}$

This is equivalent to the definition

$\langle \mathrm{s}_0, \mathrm{s}_1, \mathrm{s}_2, \dots \rangle [\![\Diamond\mathrm{F}]\!] \triangleq \exists \mathrm{n} \in \mathbb{N} : \langle \mathrm{s}_\mathrm{n}, \mathrm{s}_{\mathrm{n}+1}, \mathrm{s}_{\mathrm{n}+2}, \dots \rangle [\![\mathrm{F}]\!]$

i.e., F should be true in *some* state s_i. Combinations of $\Diamond$ and $\Box$ can describe some interesting properties such as

- $\Box\Diamond\mathrm{F}$, or *infinietly often*
- $\Diamond\Box\mathrm{F}$, or *from some point onwards*
- $\Box(\mathrm{F} \implies \Diamond\mathrm{G})$, or *leads to*

The last one means that if F is true in some state, G has to be true at the same or a later state. This can also be written with the shorthand $\mathrm{F} \rightsquigarrow \mathrm{G}$.

2.8.1.5 TLA formulas

Not all combinations of the above mentioned logical and temporal operators are allowed TLA formulas. Instead, only formulas built from simple predicates (with no temporal operators or actions) or $\Box[\mathcal{A}]_\mathrm{f}$ for some action $\mathcal{A}$ and state function f can be used. This is most noticable from a typical TLA specification of a program. With an initial state predicate $\mathrm{init}_\Phi \triangleq \mathrm{x} = 0$ and an action describing the next state $\mathrm{next}_\Phi \triangleq \mathrm{x}' = \mathrm{x} + 1$, we get the TLA formula

$\Phi \triangleq \mathrm{init}_\Phi \wedge \Box[\mathrm{next}_\Phi]_\mathrm{x}$

i.e., either the value of x is equal to 0 or it is one greater or equal to the value of x in the previous state.

2.8.2 TLC Model Checker

TLA$^+$ is part of a toolbox made for supporting the creation and testing of formal specifications. Instead of validating a TLA model by hand, the TLC model checker allows mechanic verification by simulating its possible executions while looking for invalid states and other errors [28]. If the model checker finds a problem, it terminates the simulation and notifies the user with a timeline of the behaviour that lead up to the particular error. The user can then improve their model, and gain a better understanding of their specification and system. Because verifying a specifcation means the TLC model checker has to simulate every possible behaviour, this can take a long time to do. A practical way to resolve this is to limit the state space in the model, but that also limits the type of properties that can be tested. For example, ensuring the absence of integer overflow from the sum of two 32-bit integers would imply testing all possible pairs, but this would take far too long to test. By instead limiting the possible integer values to, for example, $0 \ldots 5$ the simulation might terminate without error but we have clearly not managed to validate the absence of overflows.

Instead, the TLC model checker is more appropriate for validating time-related and concurrency problems. An overview of some of those properties are described in the following sections.

Safety

A specification that can never do anything "bad" is said to follow its *safety* property. *Bad* in this case is ambiguous but roughly means *unintentional*. There are only certain states that the specification is allowed to enter without breaking its safety property. Variations of this is common to test in software engineering practices such as unit-testing. Safety checking in TLC is straightforward as it is done by simply testing every new state during simulation for the relevant property. To examplify this, we can consider type invariants as safety properties. A variable might for example only be allowed to be an integer and nothing else.

Liveness

While a safe program is guaranteed to never do anything bad, whether or not it will actually do anything at all is not certain. Liveness properties describe what "good" things a specification necessarily will do. Some examples can be that an execution is guaranteed to terminate, that no deadlock between processes

can happen, or that all processes will progress.

In TLA$^+$, liveness properties are written with temporal operators such as $\Box$ or $\Diamond$. Reaching a certain value can for example be written as $\Diamond\Box \mathrm{F}$ *i.e.,* eventually a state is reached from which F is always true.

Fairness

Two additional examples of liveness properties are the weak and strong fairness properties. A *fair* specification is guaranteed to execute an action as long as it is possible. If the action is weakly fair then it will be performed as long as it is repeatedly possible to do so. If it is strongly fair, then it will be executed unless it is no longer possible to do so at least once. More formally they are defined, for action $\mathcal{A}$ and state function f, as

$\mathrm{WF}_\mathrm{f}(\mathcal{A}) \triangleq (\Box\Diamond\langle\mathcal{A}\rangle_\mathrm{f}) \vee (\Box\Diamond\neg\mathrm{Enabled}\langle\mathcal{A}\rangle_\mathrm{f})$
$\mathrm{SF}_\mathrm{f}(\mathcal{A}) \triangleq (\Box\Diamond\langle\mathcal{A}\rangle_\mathrm{f}) \vee (\Diamond\Box\neg\mathrm{Enabled}\langle\mathcal{A}\rangle_\mathrm{f})$

where

- $\langle\mathcal{A}\rangle_\mathrm{f} \triangleq \mathcal{A} \wedge (\mathrm{f}' \neq \mathrm{f})$ *i.e.,* the action A is executed and changes variables in f
- $\neg\mathrm{Enabled}\langle\mathcal{A}\rangle_\mathrm{f}$ means that $\mathcal{A}$ is impossible to execute.

2.8.3 PlusCal

TLA is, as can be seen in section 2.8.1, quite different from a regular programming language. This has the benefit of being simple and flexible, but can result in hard-to-read code as specifications start to grow in size. It is also not entirely clear from its syntax how an algorithm described in for example pseudocode can be translated to it.

PlusCal is an alternative syntax specifically made for describing concurrent algorithms exactly while bringing the simplicity of writing pseudocode [29]. It is written within a comment in a TLA$^+$ file and translated into TLA$^+$ as part of the parsing step of TLC. PlusCal is

2.9 Commitment scheme

A commitment scheme is a cryptographic primitive for proving to a *reciever* that a *commiter* had some knowledge or stake at an earlier point in time without having to disclose it directly [30]. Given that the commiter has some public (known by both parties) value h and stake m, they calculate a commitment

c and an opening value d by some method $\mathcal{C}$ *i.e.,* $\mathcal{C}(\mathrm{h}, \mathrm{m}) = (\mathrm{c}, \mathrm{d})$. The commitment c is sent to the reciever in this first phase of the protocol. The stake m and the opening value d is later sent in the second phase, from which the reciever can verify that m was the initial value with some boolean function $\mathcal{V}(\mathrm{h}, \mathrm{m}, \mathrm{c}, \mathrm{d})$.

2.10 Related work area

2.10.1 Decentralized File Distribution

A number of proposals for distributed and decentralized data management are recorded in the research litterature. Ince, Ak, and Gunay [31] describe a combination of blockchain and the P2P network InterPlanetary File System (IPFS) for package storage. They envision a proof-of-work consensus algorithm based on the act of rebuilding a package where builders gain rewards in terms of a productiviy score with every rebuild they add to the ledger. At a certain score, a builder is promoted to an approver and can validate other builders rebuilds. Because blockchains are limited in storage space, only packages' addresses are stored in the ledger with the actual artifacts being distributed through IPFS. While an interesting concept, no prototype or evaluation is provided by the paper. A similar approach was taken by Zichichi, Ferretti, and D'Angelo [32] but with the application of managing personal data. They managed different kinds of personal data by partitioning it through smart contracts, each with its own access list for node authorization.

Instead of using blockchain and P2P technologies together, Blähser, Göller, and Böhmer [33] show a prototype system for distributed package management using only a peer-to-peer technology called Hypercore protocol. They rely on Hypercore protocol to act both as a distributed file system as well as an append only ledger. This approach is convenient but does not have any built-in safeguards against malicious actors or packages. On the other hand, Liu et al. [34] used blockchain technology single-handledly to construct a distributed Domain Name System (DNS). Because of the limited amount of data in a zone file, no separate distributed file system was needed for their application. Each request to the service was done through a smart contract and their prototype system were able to serve requests with a 0.006025 seconds average response delay and a failure resolution rate of 2.14%.

2.10.2 Formal verification of Smart contracts

Writing smart contracts that works correctly is hard. To aid this, several researchers have looked into using formal methods to verify them. Bhargavan et al. [35] translated the Solidity language for writing smart contracts into the general-purpose language F* made for program verification. The authors then used the type system of F* to enforce certain safety properties in the smart contract. Beckert et al. [36] took a similar approach but for the Hyperledger Fabric chaincode. By adding pre- and postconditions in comments to chaincode written in Java and translating these to Java Modeling Language **(acronym)** they managed to deduce smart contract safety properties statically. In a slightly different direction, Latif, Rehman, and Zafar [37] modelled a blockchain for waste management using TLA$^+$. Their initial system description was written in UML **(acronym, cite)** which turned out to be relatively straightforward to translate into a formal specification language. The system's safety and liveness properties could then be validated with the TLC model checker.

Xu and Fink [38] examplifies how a design-by-contract methodology [39] when designing smart contracts can be enacted with TLA$^+$ modeling and verification. They specify a system for purchasing and selling estates directly in TLA$^+$ and uses its safety checks to ensure that any drawn up contract (between buyer and seller) is followed. As part of their specification, they also include checks for some vulnerabilities common in smart contracts. These include eliminating invalid and additional states and *trap doors i.e.,* invalid events or transitions.

In their PhD thesis, Elsayed [40] implemented a solution for trapping computer worms in a network. When a worm was detected by a host on the network, its signature was added to a blockchain built on Hyperledger Fabric. This acted as an immutable threat log, used by the network to be able to find and stop the worm. From the use of a blockchain, the log has high availability and other interesting security properties that makes it resistant to attacks. Besides implementing the system, the author moddeled with TLA$^+$ to model check its correctness, safety and liveness properties. This model included both the ineractions between smart contracts as well as the consensus algorithm used by the blockchain.

To reduce the friction between writing a veryfiable specification of a smart constract and implementing it in a regular programming language, some researchers have worked on intermediate representations from which both specifactions and implementations can be derived. Kolb et al. [41]

describe the *Quartz* language for this purpose. *Quartz* is a statically typed language with which smart contracts are written as transitions in a finite-state machine. Simple authorization requirements and invariants can be annotated onto the transitions. An implementation in the Solidity smart contract language and a model in PlusCal can be derived from a *Quartz* program. The finalized translation in TLA$^+$ includes a specification of the Solidity execution environment to allow a wider set of requirements to be verified while retaining ease of use. In a series of case studies they found that smart contracts written in *Quartz* were on average 0.68 the number of lines of equivalent Solidity programs, while keeping execution overheads at less than 20% for all cases but one.

TODO: Add work on infering formal specifications from logs

2.11 Summary

Sammanfattning

Det är trevligt att få detta kapitel avslutas med en sammanfattning. Till exempel kan du inkludera en tabell som sammanfattar andras idéer och fördelar och nackdelar med varje - så som senare kan du jämföra din lösning till var och en av dessa. Detta kommer också att hjälpa dig att definiera de variabler som du kommer att använda för din utvärdering.

It is nice to have this chapter conclude with a summary. For example, you can include a table that summarizes other people's ideas and benefits and drawbacks with each - so as later you can compare your solution to each of them. This will also help you define the variables that you will use for your evaluation.

Chapter 3

Method

3.1 Research Process

One of the primary goals of the research process is to construct and evaluate a system for enhanced traceability and integrity of `.buildinfo` files. The main steps of this process include (I) defining the participating actors of such a system, what is assumed from them and what it means for the system to be correct, (II) selecting a Distributed Ledger Technology on which to build the system, (III) designing appropriate algorithms taking the underlying technology and assumptions under consideration, (IV) modeling the system in a formal specification tool, (V) evaluating the system correctness within the model, and (VI) evaluate the feasability to construct an implementation of the system. Steps (III) to (VI) are in practice done iteratively to raise the reliability and validity of the result.

3.1.1 Validity of method

Throughout the methodology, an assumption is made that the formal specification tool TLA$^+$ can be used to ensure the validity of the system model with regards to underlying assumptions and correctness specifications. This is a slightly naive perspective as the model checking is bounded in size and not a formal proof, but is intuitively reasonable because the studied behaviours (the interactions with the system) are themselves bounded (not really though, they just look the same).

Given that the modeling tools have these properties, the validity of the method is based on arguing the validity of the system assumptions and that an implementation of the system is feasable given the model. The first of

these arguments is done by specifying assumptions and correctness definitions in a simple and succinct manner and connect them closely to the context and purpose within which they act. This way, the validity of the system assumptions should be intuitive to the reader. The second argument revolves around building a prototype implementation of relevant parts of the system and motivate the translation from model to prototype.

3.1.2 Reliability of method

The use of a system model written in TLA$^+$ instead of an actual implementation is only as reliable as they are similar to each other. If the model is unfaithful in its representation of the system, then very little can be reliably stated based on the method. However, assuming the model corresponds well with the implementation, it is a very exact tool. The crucial part is to define the model boundaries so as to not confuse the reader under which conditions the method is reliable.

The ideal method for this project would be building the system and evaluating it with real world actors interessted in using it. That would give a clear indication of the systems' properties and the outcomes from utilizing it. It would, however, be quite out of scope for this project. To diminish the distance between this ideal method and the one used, the model is made in such a way that the number of assumptions on actors are as few as possible and clearly formulated. As every assumption is encoded in TLA$^+$, they are defined semantically and can be verified by the reader.

3.2 System overview

To answer this projects' research question, a system is designed and evaluated for distributing the reproducibility of packages in the Free Open Source Software (FOSS) ecosystem. The system takes names and checksums of `.buildinfo` files as input and stores *judgements* on the reproducibility of the packages built from those file. Judgements are created by a consensus of *builders* communicating over a Hyperledger Fabric network, on which they are stored in an append-only blockchain. The packages to be judged are introduced into the system by the builders, after which a voting scheme takes place where the packages are judged as reproducible or not reproducible. Each builders vote represent the result from them, individually, rebuilding the relevant package from its `.buildinfo` file and verifying wether it was reproducible.

3.2.1 System actors

As described in 1.1, the state-of-the-art for verifying reproducible builds are a number of public servers building packages from `.buildinfo` files and releasing their results separately. The work these *builders* perform would not be changed for the system described in this thesis, only the way they distribute their results. As there is currently no reward besides personal information on package reproducibility for their work, an intial assumption on the motivation of the workers is that

> *all builders are interested in valid judgments for some packages.*
> **(label with a number, like an equation)**

In other words, every builder has an interest in information regarding the reproducibility of at least one package. These packages are denoted as the builders' *preferences* in this document. Without assuming that every builder has some non-empty prefered set of packages, there is little reason for them to build any packages at all. This is therefore a neccessary requirement of the system. To be noted is that there is nothing stopping a builders set of prefered packages to be exactly all packages. The assumption only states that this set have to be non-empty. The consequence, or definition, of builders having prefered packages is that those are also the packages they prefer to build themselves. This is a natural consequence from the first assumption because a builder would prefer to build a package they are themselves motivated to gain information on. This can be stated as

> *builders prefer to judge (and build) some packages over other.*

This means in particular that any package not prefered by any of the builders would never be built. To counteract this in the model, an additional assumption on the relationship between builders and packages state that

> *every package is prefered by at least one builder.*

While it would be problematic in practice if there are packages that no builder prefers, given that the current public build servers build seemingly every package, this is mainly important for a model definition and not an implementation.

Ensuring that the validity of the judgments on packages made by the system are more trustwordy than those of individual builders, an assumption has to be made that

builders do not collude or share knowledge with each others through other means than via the system itself.

If a builder were to be influenced in their judgment of a package by some other builder than their combined trustwordiness would only be as great as the trustwordiness of the influencer.

3.2.2 Model correctness

The model correctness is defined in terms of safety and liveness properties. As defined in 2.8.2, the safety property descibe all the allowed behaviours of the model, while the liveness property ensures that they happen. The properties are stated as

Safety Only valid judgments on `.buildinfo` files are stored;

Liveness Every `.buildinfo` file is eventually judged, as long as every builder has at least one not-yet judged prefered package.

(connect these with the assumptions on builders)

Valid judgment means that if and only if a package is reproducible, it is also judged to be so. In other words, no non-reproducible packages are stored in the system as reproducible and wise versa. As both of these safety and liveness properties are ambiguous by their natural language definitions, they are better stated in semantically defined TLA$^+$.

Given a set of `.buildinfo` files Files, a mapping from files to *valid* judgments $\text{Validity} : \text{Files} \mapsto \text{Boolean}$, a mapping from files to system judgments $\text{Judgement} : \text{Files} \mapsto \text{Boolean}$ and a mapping with each builders prefered packages $\text{Prefered} : \text{Builders} \mapsto \{\text{f} \in \text{Files}' | \text{Files}' \subseteq \text{Files}\}$, the correctness of the system is defined as

Safety $\forall \text{f} \in \text{range}(\text{Judgment}) : \text{Judgment}[\text{f}] = \text{Validity}[\text{f}]$

Liveness $(\forall \text{b} \in \text{Builders} : |\text{Prefered}[\text{b}]| > 0) \implies \Diamond(\forall \text{f} \in \text{Files} : \text{f} \in \text{range}(\text{Judgment}))$ **(is this really what you mean?)(Use labels like in an equation)**

3.2.3 Modelling assumptions

Hyperledger Fabric is selected as the DLT to build the system on...

The benefits for this project to use Hyperledger Fabric are: permissioned, voting-based, private-collections...

The modell does not include these features of Hyperledger Fabric: ordering, ...

instead they are assumed as...

3.2.4 Malicious actors / Threat model

Builders control the input to the system.

We don't care about how builders get their hands on .buildinfo files or other tools.

Any builder that does not conform to the assumptions in section 3.2.1 are denoted as malicious.

Malicious actors are modelled as: random?, ... **(how?)**

No malicious actors in model, just discuss how this is solved by the hyperledger fabric.

Chapter 4

Judgment algorithm

4.1 Algorithm: reward scheme

Each builder holds a wallet of build tokens (BT), and a set of packages they prefer to be judged.

Each prefered package has a trust level connected to it, that directly corresponds to how many build tokens the builder is willing to pay for the package to be judged. A package with a trust level of 1, requires one additional builder to judge the package for the initiator to be satisfied with the judgment. The initiator then pays 1 BT to the other builder. For each added trust level, one more builder is required to judge the package. The cost per added builder goes up by one, such that with n builders, the k^{th} one to judge a package recieves $\mathrm{n} - \mathrm{k} + 1$ BT from the initiator. The minimum cost for a judgment at trust level l is then $1 + 2 + \ldots + \mathrm{l} = \frac{\mathrm{l}(\mathrm{l}+1)}{2}$.

A package judgment can be initiated if the initiator has enough build tokens to pay for its cost.

If a decision can be made on the reproducibility of a package, the initiator pays out the respective number of build tokens to each builder of the winning side. Everyone of those builders except the initiator also recieve one (1) additional build token from the system.

In order to bootstrap the system each node recieves an initial 1 BT, except for one node which recieves 3 BT. This last node has the responsibility of being the first initiator

4.2 Algorithm: hidden vote judgment

A description of the voting scheme follows and is split into a single-package and a multi-package case. The single-package algorithm denote how a judgment is made on the reproducibility of a single package, while the multi-package variant generalizes this algorithm to scenarios with multiple packages through a reward scheme to motivate builders.

4.2.1 Single-package algorithm

TODO: Should include: Two phase commit, Details for how HMAC is used *i.e.,* what's being hashed

A definition of *what* the single-package judgment algorithm does can be stated as:

> Given the name of a `.buildinfo` file n_p corresponding to the binary package p, a set of builders $b_1, b_2, \ldots, b_k$, a cryptographic hash function H, a function for generating message authentication codes M, judge the validity and reproducibility of p.

```
Given
    name and checksum of .buildinfo file f_name and f_hash,
    builders b1,b2, ..., bk,
    rebuilding function B,
    cryptographic hash function H,
    HMAC function HMAC, and
    world state W1 = W2 = W3 = W4 = {},
judge the validity and reproducibility of f_name.

1. For each builder bi:
    a) Pick key ki
    b) Build the package p = B(f_name)
    c) Calculate p:s checksum h = H(p)
    c) Verify that f_name should create p (f_name=>p)
    d) ei = if f_name=>p then HMAC(ki, h) else HMAC(ki, "invalid")
    e) Store ki, h privately
    f) W1[bi] = ei
2. When appropriate (timeout or |W1|): lock W1 from changing
```

```
3. For each builder bi: W2[bi] = ei
4. When appropriate (timeout or |W2|): lock W2 from changing
5. For each builder bi: calculate the validity of builder bi:s wo
      W3[bi] = W1[bi] == HMAC(W2[bi], h) || W1[bi] == HMAC(W2[b
      6. For each builder bi: judge f_name
      if W3[bi]
      then W4 = if W1[bi] == HMAC(W2[bi], h)
                then True  // valid .buildinfo
                else False // invalid .buildinfo
                7. For each builder bi where W3[bi] = True: B
```

Chapter 5

TLA+ model

To develop and study the judgment algorithm, a model was created as a TLA+ specification. This chapter seeks to describe how this model is structured and to detail its core components. The specification has been split into three parts with some details removed to make the explanation more manageable for the reader. A full version of the specification can be found in appendix A. This section has been divided into 5.1 on the data structures used in the model, chaincode definitions in 5.2 and how system actors interact under 5.3.

5.1 Data structures

The models main data structures, variables and module setup are shown in listing 5.1. It begins by declaring the module name and then listing its module dependencies on line 3. These modules makes available operators for working with real numbers and list-like sequences, as well as ensuring that sets are finite in the model. The last point is mainly important for the model checker. Lines 4-5 declares all the models mutable variables as well as the model checking goal as an immutable constant. While this constant is declared in the module, it is set by the configuration of the model checker and can be thought of as a parameter of the model. The three variables respectively represent: public information known to all system actors, private information only known by a single actor and a counter to generate unique package names.

Lines 6-7 define sets containing all the system actors, called *nodes* in the model, and which system actors that act maliciously. The last lines define the initial state of the `public` and `private` variables and the correct information on whether a package is reproducible or not. As can be noted, the `private` variable contains a mapping from system actor to their preferred

packages. These preferred packages are disjunct between nodes to simplify the rest of the model. Each package preference stores how many nodes that has to judge the package for the node to be satisfied with the result and whether the package has been judged yet. While the level is set at a hard coded value initially, this is also only to simplify the model. The `public` variable has instead two different parts. One describes the number of tokens a node has and the other stores the package judgments created during the execution of model checking. Because only one node starts of with tokens, they are the only ones who can initialize a package judgment at the start.

Listing 5.1: Variables and TLA+ model dependencies

```
1
2  ──────────────────── MODULE Judgment ────────────────────
3  EXTENDS TLC, FiniteSets, Reals, Sequences
4  VARIABLE public, private, nextPackageId
5  CONSTANT NumberOfClosedJudgmentsGoal

6  Nodes ≜ {"node1", "node2", "node3", "node4"}
7  MaliciousNodes ≜ {"node4"}

8  InitialPrivate ≜ private = [
9      node1 ↦ [
10         preferences ↦ ⟨
11             [package ↦ "package1", level ↦ 2, status ↦ "not-processed"],
12             [package ↦ "package2", level ↦ 2, status ↦ "not-processed"]
13         ⟩
14     ],
15     node2 ↦ [
16         preferences ↦ ⟨
17             [package ↦ "package3", level ↦ 2, status ↦ "not-processed"],
18             [package ↦ "package4", level ↦ 2, status ↦ "not-processed"]
19         ⟩
20     ],
21     node3 ↦ [
22         preferences ↦ ⟨
23             [package ↦ "package5", level ↦ 2, status ↦ "not-processed"],
24             [package ↦ "package6", level ↦ 2, status ↦ "not-processed"]

25         ⟩
```

```
26      ],
27      node4 ↦ [
28          preferences ↦ ⟨
29              [package ↦ "package7", level ↦ 2, status ↦ "not-processed"],
30              [package ↦ "package8", level ↦ 2, status ↦ "not-processed"]
31          ⟩
32      ]
33  ]
34  InitialPublic ≜ public = [
35      nodes ↦ [
36          node1 ↦ [wallet ↦ 3],
37          node2 ↦ [wallet ↦ 0],
38          node3 ↦ [wallet ↦ 0],
39          node4 ↦ [wallet ↦ 0]
40      ],
41      judgments ↦ ⟨⟩
42  ]
43  IsReproducibleData ≜    [package1 ↦ TRUE,
44                           package2 ↦ FALSE,
45                           package3 ↦ TRUE,
46                           package4 ↦ TRUE,
47                           package5 ↦ TRUE,
48                           package6 ↦ TRUE,
49                           package7 ↦ TRUE,
50                           package8 ↦ TRUE,
51                           package9 ↦ FALSE,
52                           package10 ↦ FALSE,
53                           package11 ↦ FALSE,
54                           package12 ↦ FALSE,
55                           package13 ↦ FALSE,
56                           package14 ↦ FALSE,
57                           package15 ↦ FALSE,
58                           package16 ↦ FALSE,
59                           package17 ↦ FALSE,
60                           package18 ↦ FALSE,
61                           package19 ↦ FALSE,
62                           package20 ↦ FALSE]
```

5.2 Chaincode

Listings 5.2, 5.3, 5.4, 5.5 and 5.6 contains the TLA+ specifications of what would be written as chaincode in a system implementation. They are defined as a number of operators, each one representing a distinct chaincode. Each operator take some parameters such as who is invoking the chaincode, which judgment or package it relates to and other relevant information. They then verify whether the particular transaction is allowed or not and, if it was, updates the `public` variable. This is exemplified in the operator for initializing a new package judgment `InitializeJudgment` on lines 2-19. Firstly, checks are made to ensure that the invoker `owner` has enough funds to initialize a package judgment and that there are no other judgments initialized by them currently active. If these predicates are fulfilled, a corresponding judgment is appended to the state. Note that all of these operators are in practice written as logical conjunctions, where every sub-expression must be true for the entire operator to be true. While intuitive for predicates, this is not quite obvious with an action such as on line 19. For model checking and software development purposes, this can be thought of as an assignment where the `public` variable is updated. From a logical point of view, though, this is an equivalence check which is true only for those behaviors where the `public` variable in the next state is exactly the one as the current with the exception of an appended judgment to the `public.judgments` sequence. In practice these become equivalent statements because any behavior where the relationship between `public'` and `public` is different (and the equivalence on line 19 therefore is false) are irrelevant as they do not follow the specification.

To clarify the notation, LET IN allows locally scoped definitions and in the EXCEPT at line 19, ! is short for `public` and @ is short for `public.judgments`. Definitions for operators `Cost` and `ActiveJudgments` can be found in appendix A.

Listing 5.2: Chaincode for initializing a package judgment

```
1
2  InitializeJudgment(package, owner, targetVotes) ≜
3      Guards
4      ∧ Cost(targetVotes) ≤ public.nodes[owner].wallet
5      ∧ ∀ j ∈ ActiveJudgments : j.owner ≠ owner
6      Update
7      TODO: Better ids. Currently there can only be one judgment perpackage.
8      ∧ LET judgmentId ≜ package
```

```
9            judgment ≜ [id ↦ judgmentId,
10                       tally ↦ [for ↦ 0, against ↦ 0],
11                       finalResult ↦ "undecided",
12                       package ↦ package,
13                       owner ↦ owner,
14                       targetVotes ↦ targetVotes,
15                       status ↦ "active",
16                       phase ↦ "secretVotes",
17                       secretJudgments ↦ ⟨⟩,
18                       openJudgments ↦ ⟨⟩] IN
19        public′ = [public EXCEPT !.judgments = Append(@, judgment)]
```

5.2.1 Submitting a hidden vote

To add a hidden vote to a package judgment, the operator in listing 5.3 is used. It takes the id of the judgment, the name of the node adding the vote, and the vote in question as parameters. The disjunctions on lines 3-4 is a pattern common for the rest of the chaincode specifications. If there are no judgments then line 3 ensures that this operator does nothing, otherwise some `index` is picked corresponding to the position of a particular judgment in the `public.judgments` sequence. This works because sequences in TLA+ are essentially functions from positions to values and so the domain of a sequence is the set of all those positions.

The rest of this operator is fairly straightforward, but line 10 could need an explanation. Symmetric to the domain of the sequence, its range is a set of its values. Line 10 can then be understood as testing if the set of secret votes submitted by node `judge` is empty.

Listing 5.3: Chaincode for adding a hidden vote

```
1
2  AddSecretJudgment(judgmentId, judge, secretVote) ≜
3      ∨ Len(public.judgments) = 0
4      ∨ ∃ index ∈ DOMAIN public.judgments :
5          LET j ≜ public.judgments[index] IN
6              ∧ j.id = judgmentId
7              ∧ j.status = "active"
8              ∧ j.phase = "secretVotes"
9              Has 'judge' added their vote before?
10             ∧ {sj ∈ Range(j.secretJudgments) : sj.judge = judge} = {}
```

```
11              Update
12          ∧ public′ =
13                [public EXCEPT !.judgments[index].secretJudgments =
14                   Append(@, [judge ↦ judge,
15                              vote ↦ secretVote])]
```

5.2.2 End hidden vote submissions

After enough hidden votes have been added to a package judgment, this phase of the process can be ended by the node that initialized it. The requirements for this are listed on lines 5-9 in listing 5.4. Most notably, *enough* hidden votes is defined to guarantee that there are at least `targetVotes` number of votes on one side for or against the package being reproducible. In other words, it is guaranteed that at least one side has at least `targetVotes` number of votes.

Listing 5.4: Chaincode stopping submissions of hidden votes

```
1
2  EndSecretSubmissions(judgmentId, owner) ≜
3      ∨ Len(public.judgments) = 0
4      ∨ ∃ index ∈ DOMAIN public.judgments :
5              ∧ j.id = judgmentId
6              ∧ j.status = "active"
7              ∧ j.phase  = "secretVotes"
8              ∧ j.owner = owner
9              ∧ 2 ∗ j.targetVotes − 1 ≤ Len(j.secretJudgments)
10             ∧ public′ = [public EXCEPT !.judgments[index].phase
11                             = "openVotes"]
```

5.2.3 Revealing a vote

To reveal ones hidden vote, the operator `ShowJudgment` shown in listing 5.5 is invoked. If the invocation is valid, *i.e.,* there is a hidden vote by this node which has not been revealed, the vote count for or against the reproducibility of the package is updated. The vote itself is also appended to a sequence of all revealed votes.

Listing 5.5: Chaincode for revealing a vote

```
1
2  ShowJudgment(judgmentId, judge, openVote) ≜
```

```
3       ∨ Len(public.judgments) = 0
4       ∨ ∃ index ∈ DOMAIN public.judgments :
5           LET j ≜ public.judgments[index] IN
6               ∧ j.id = judgmentId
7               ∧ j.status = "active"
8               ∧ j.phase = "openVotes"
9               Has 'judge' added their vote before?
10              ∧ {sj ∈ Range(j.secretJudgments) : sj.judge = judge} ≠ {}
11              Has 'judge' showed their vote before?
12              ∧ {oj ∈ Range(j.openJudgments) : oj.judge = judge} = {}
13              Secret and open votes should be the same
14              This validation is done with HMAC in practice
15              ∧ ∃ sj ∈ Range(j.secretJudgments) :
16                  ∧ sj.judge  = judge
17                  ∧ openVote = sj.vote
18              Update
19              ∧ public′ = [public EXCEPT !.judgments[index] = [@ EXCEPT
20                              !.openJudgments = Append(@,
21                                  [ judge ↦ judge,
22                                    vote ↦ openVote]),
23                              !.tally.for = IF openVote = "TRUE"
24                                            THEN @ + 1
25                                            ELSE @,
26                              !.tally.against = IF openVote = "FALSE"
27                                                THEN @ + 1
28                                                ELSE @]]
```

5.2.4 End package judgment

The final step of a package judgment is begun by the node who initialized it invoking the `CloseJudgment` operator shown in listing 5.6. Similar to section 5.2.2, a package judgment can only be ended when the number of revealed votes is enough to ensure that there are at least `targetVotes` number of votes on one side for or against reproducibility. If their is a majority for one side, the `Rewards` operator seen in listing 5.7 updates the nodes' wallets, otherwise the package judgment is closed and marked with *undecided* as a final result.

Listing 5.6: Chaincode to end a package judgment

```
1
2  CloseJudgment(judgmentId, owner) ≜
3      ∨ Len(public.judgments) = 0
4      ∨ ∃ index ∈ DOMAIN public.judgments :
5          LET j ≜ public.judgments[index]
6              finalResult ≜ ToString(j.tally.for > j.tally.against) IN
7              ∧ j.id = judgmentId
8              ∧ j.status = "active"
9              ∧ j.phase = "openVotes"
10             ∧ j.owner = owner
11             ∧ 2 * j.targetVotes − 1 ≤ Len(j.openJudgments)
12                 We have a majority!
13             ∧ ∨ ∧ j.tally.for ≠ j.tally.against
14                 ∧ public′ = [public EXCEPT
15                     !.judgments[index] =
16                         [@ EXCEPT
17                             !.status = "closed",
18                             !.phase = "judgment",
19                             !.finalResult = finalResult],
20                     !.nodes = Rewards(j)]
21                 Everyone has voted, and we don't have a majority
22               ∨ ∧ j.tally.for = j.tally.against
23                 ∧ public′ = [public EXCEPT !.judgments[index] = [@ EXCEPT
24                             !.status = "closed",
25                             !.finalResult = "undecided"]]
```

The `Rewards` operator and its two sub-operators `WalletUpdatesForVoters` and `WalletUpdatesForNotVoting` in listing 5.7 work by updating the `public.nodes` wallets. Together, they partition the nodes in four different cases for how these updates are done based on their respective role in the judgment: the initializer of the package judgment pays out a cost related to `targetVotes`, minority voters' wallets neither increase nor decrease, majority voters receive a reward based on how quickly they added their vote and a bonus token for the correctness of their vote, and the rest loose one token for not voting.

Listing 5.7: Operator updating wallets for judgment

```
1
2  RECURSIVE WalletUpdatesForVoters(_, _, _, _)
```

```
3  WalletUpdatesForVoters(judgment, votes, reward, updates) ≜
4     LET finalResult ≜ ToString(judgment.tally.for > judgment.tally.against)
5         judge ≜ Head(votes).judge
6         vote ≜ Head(votes).vote
7     IN
8        IF Len(votes) = 0
9           THEN updates
10        ELSE IF judge = judgment.owner
11           Skip the owner
12           THEN WalletUpdatesForVoters(
13              judgment, Tail(votes), reward, updates)
14        ELSE IF vote ≠ finalResult THEN LET
15           Minority voter
16              newUpdates ≜ [updates EXCEPT ![judge].wallet = @]
17           IN  WalletUpdatesForVoters(
18                judgment, Tail(votes), reward, newUpdates)
19        ELSE LET
20           Majority voter
21              newUpdates ≜ [updates EXCEPT ![judge].wallet = @ + reward + 1]
22                newReward ≜ IF reward = 0 THEN 0 ELSE reward − 1
23           IN  WalletUpdatesForVoters(
24                   judgment, Tail(votes), newReward, newUpdates)

25 RECURSIVE WalletUpdatesForNotVoting(_, _)
26 WalletUpdatesForNotVoting(nonVoters, updates) ≜
27    IF nonVoters = {}
28       THEN updates
29       ELSE
30          LET v ≜ CHOOSE voter ∈ nonVoters : TRUE
31                newUpdates ≜ [updates EXCEPT ![v].wallet = @ − 1]
32          IN  WalletUpdatesForNotVoting(nonVoters \ {v}, newUpdates)
33 Rewards(judgment) ≜
34    LET openVotes ≜ judgment.openJudgments
35        topReward ≜ judgment.targetVotes
36        wallets ≜ public.nodes
37        openVoters ≜ OpenJudges(judgment)
38        nonVoters ≜ Nodes \ openVoters
39        ownerCost ≜ Cost(judgment.targetVotes)
40        updatesForVoters ≜
```

```
41            WalletUpdatesForVoters(judgment, openVotes, topReward, wallets)
42          updatesForNonVoters ≜
43            WalletUpdatesForNotVoting(nonVoters, updatesForVoters)
44      IN  [updatesForNonVoters EXCEPT ![judgment.owner].wallet = @ − ownerCost]
```

5.3 Behavior of system actors

The last main parts of the model are the assumptions for how the nodes behave, certain system properties and how a successful run of the model checker is defined. Line 79 of listing 5.8 shows the main operator of the specification, defining the initial variable values according to `Init` and all their allowed changes by `Next`. This last operator is interesting in that it follows a slightly different pattern than the other ones. Rather than being mainly a large conjunction, `Next` is instead a set of disjunctions. For the TLC model checker, this implies that only one, and exactly one, of these sub-expressions will be executed for each state or else there will be a deadlock if all of the sub-expressions are false. The limit of at most one executed expression comes for the shortcut behavior of TLC which will only evaluate the first of all truthful expressions in a disjunction.

Listing 5.8: System actor behavior in TLA+ specification

```
1
2  Init ≜
3      ∧ InitialPublic
4      ∧ InitialPrivate
5      ∧ nextPackageId = 9
6  Next ≜
7          Initializing a package judgment
8          ∨ ∃ n ∈ Nodes :
9              ∃ index ∈ DOMAIN private[n].preferences :
10                 LET p ≜ private[n].preferences[index] IN
11                     ∧ RunSimulation
12                     ∧ p.status = "not-processed"
13                     ∧ InitializeJudgment(p.package, n, p.level)
14                     ∧ private′ =
15                         [private EXCEPT ![n].preferences[index].status = "started"]
16                     ∧ UNCHANGED ⟨nextPackageId⟩
```

```
17          Adding a secret vote
18        ∨ ∃ n ∈ Nodes :
19            ∃ j ∈ Range(public.judgments) :
20              LET secretVote ≜ IF n ∈ MaliciousNodes
21                               THEN ¬IsReproducible(j.package)
22                               ELSE IsReproducible(j.package)
23              IN
24                  ∧ RunSimulation
25                   Nodes only build/judge if they have to
26                  ∧  ∨ FutureCost(n) > public.nodes[n].wallet − 1
27                     ∨ j.owner = n
28                     ∨ j.package ∈ PreferredPackages(n)
29                  ∧ AddSecretJudgment(j.id, n, ToString(secretVote))
30                  ∧ UNCHANGED ⟨private, nextPackageId⟩

31          End submission of secret votes
32        ∨ ∃ n ∈ Nodes :
33            ∃ j ∈ Range(public.judgments) :
34              ∧ RunSimulation
35               Assume that every node that *needs* to vote will have the time to do so
36              ∧ ∀ nonVoter ∈ Nodes \ SecretJudges(j) :
37                    ∨ IsFinanciallyIncentivizedToVote(nonVoter)
38                    ∨ n ∈ MaliciousNodes
39              ∧ EndSecretSubmissions(j.id, n)
40              ∧ UNCHANGED ⟨private, nextPackageId⟩

41          Add an open vote
42        ∨ ∃ n ∈ Nodes :
43            ∃ j ∈ Range(public.judgments) :
44              LET openVote ≜ IF n ∈ MaliciousNodes
45                             THEN ¬IsReproducible(j.package)
46                             ELSE IsReproducible(j.package)
47              IN
48                  ∧ RunSimulation
49                  ∧  ∨ FutureCost(n) > public.nodes[n].wallet − 1
50                     ∨ j.owner = n
51                     ∨ j.package ∈ PreferredPackages(n)
52                  ∧ ShowJudgment(j.id, n, ToString(openVote))
53                  ∧ UNCHANGED ⟨private, nextPackageId⟩
```

```
54          Close judgment
55        ∨ ∃ n ∈ Nodes :
56            ∃ j ∈ Range(public.judgments) :
57              ∧ RunSimulation
58                Assume that every node that *needs* to vote will have the time to do so
59              ∧ ∀ nonVoter ∈ Nodes \ OpenJudges(j) :
60                    ∨ IsFinanciallyIncentivizedToVote(nonVoter)
61                    ∨ n ∈ MaliciousNodes
62              ∧ CloseJudgment(j.id, n)
63                Update the nodes preferences
64              ∧ ∃ preferenceIndex ∈ DOMAIN private[n].preferences :
65                    ∧ private[n].preferences[preferenceIndex].package
66                          = j.package
67                    ∧ private′ =
68                      [private EXCEPT ![n].preferences[preferenceIndex].status
69                            = "processed"]
70              ∧ UNCHANGED ⟨nextPackageId⟩

71          Add additional package to node
72        ∨ ∃ n ∈ Nodes :
73            ∧ RunSimulation
74            ∧ AddPreferencedPackage(n)
75            ∧ UNCHANGED ⟨public⟩

76          End simulation
77        ∨ ∧ ¬RunSimulation
78            ∧ UNCHANGED ⟨private, public, nextPackageId⟩

79  Spec ≜ Init ∧ □[Next]⟨public, private, nextPackageId⟩
```

5.3.1 Model checking goal

Deadlocks happen if the model checker finds a state at which no sub-expression in the `Next` operator evaluates to true. While this is convenient for finding bugs in the specification, it can also lead to false-negatives if the state space of the model is designed to be finite. In other words, it is problematic if the model checker ends up in a deadlock when it is done. To combat this situation, the predicate `RunSimulation` shown in listing 5.9 is used in `Next` to ensure the existence of a valid next state even after the model checking goal has been reached. Lines 76-78 in listing 5.8 are true exactly when the model checking

goal has been reached. At that point, the other sub-expressions in `Next` are false because they are dependent on `RunSimulation` to be true. When the goal has been fulfilled, the TLC model checker finds the sub-expression at lines 76-78 to be the only one that is true. Because that sub-expression also does not change any variables value, TLC infers that no new states can be made and the behavior finishes successfully.

Listing 5.9: Test to check if model checking goal is met

```
1
2 RunSimulation ≜
3     Cardinality(ClosedJudgments) < NumberOfClosedJudgmentsGoal
```

5.3.2 Adding packages

In the initial state, each node has a number of preferred packages as a means of goals. As stated in section 5.1, these packages are set statically to simplify the model. To introduce a bit of dynamic behavior into the model, the sub-expression at lines 71-75 in listing 5.8 has the possibility of adding a package to one of the nodes. The target vote level of that package is based on the wallet and any other current preferred packages of a node. This simulates new packages and package versions being added to the eco-system and nodes being willing to pay more tokens to get a more certain result for packages if they can.

5.3.3 System actor assumptions

Besides the sub-expressions described in sections 5.3.1 and 5.3.2, the rest of the sub-expressions of the `Next` operator all relate to the behavior of the nodes. For each chaincode defined in the model, there is a sub-expression in the main disjunction of the `Next` operator.

Chapter 6

Results and Analysis

6.1 Model evaluation

To evaluate the correctness of the TLA$^+$ model, a number of scenarios are tested with the TLC model checker. Because TLC is a bounded model checker, these scenarios do not prove the correctness of the model in general but gives an indication to under which assumptions it is correct. Particularly, they are selected to show that the system makes progress in non-trivial cases, rather than stopping in a deadlocked state, and that it yields valid results. In all scenarios, a limit as well as goal is set in terms of the number of packages the system should evaluate correctly before finishing. In other words, for each behaviour (or state sequence) that is tested in a scenario, either the goal is reached or the model has failed the scenario.

6.1.1 Scenario 1: No malicious builders

This scenario is a positive test of the model where every builder is assumed to take egoistical but non-malicious actions, following the behaviour described under section 3.2.1. There are three total builders, each one with two preferred packages at a vote target of two. Two of the builders begin with 0BT in their respective wallets while the third one starts with 3BT. This allows the last builder to initialize the first package judgment, because 3BT is exactly the cost for a package with a vote target of two. The judgment goal of the scenario scales from one up to and including four, thus ensuring that the initially preferred packages of at least one builder have been judged.

6.1.2 Scenario 2: Single malicious builder

To test the model under a more realistic scenario, this scenario extends the one in 6.1.1 with a malicious builder. The malicious builder acts similarly to the builders from 3.2.1, but will always judge packages incorrectly. With the added malicious builder, this scenario has a total of four builders. To improve model checking time with the additional builder, the judgment goal is lessened to up to and including two packages. The main purpose of this scenario is to ensure that the model works as intended when not all judgments are the equal.

Max #closed	Diameter	States	Distinct states	Time (hh:mm::ss)	Collision Calculated
1	10	734	297	00:00:04	7E-15
2	19	53,438	21,609	00:00:06	3.7E-11
3	31	32,017,982	9,987,859	00:04:27	1.2E-5
4	40	2,432,997,950	625,847,049	04:53:55	0.061

Table 6.1: The result from running the model checker on a three node scenario. 1 and 2 was ran on a laptop with 6 cores and 12GB memory.

Max #closed	Diameter	States	Distinct states	Time (hh:mm::ss)	Collision Calculated	C
3	31	23,523,125	9,241,353	00:03:47	7.2E-6	

Table 6.2: V2. The result from running the model checker on a three node scenario. 1 and 2 was ran on a laptop with 6 cores and 12GB memory.

6.2 Model relevance

While TLA$^+$ models are useful to test and describe complex systems, to show their relevance they need to correspond to a real implementation. While this work does not include a system implementation, this section describe how one could be made which behaves equivalently to the model with regards to the models correctness properties. The main difference between the system model and a possible implementation is that the later is constrained as well as enhanced by Hyperledger Fabric, on which foundation it would be built. Many of the key security assumptions of the system such as integrity, availability, authentication and authorization rely on Fabrics default behaviour. An implementation built on Hyperledger Fabric can be seen as a refinement of

(parts of) the model. To, then, show that an implementation of the model exists, an informal argument is given to claim that the TLA$^+$ model is a refinement of an implementation built on Hyperledger Fabric.

A second key difference between the model and a real implementation lies in the modelled behaviour of the system actors.

A third one is the use of HMAC.

6.2.1 Hyperledger fabric highlights

The Hyperledger Fabric blockchain is extensively described in section 2.6, but to aid the reader this section highlights the parts most relevant to a model-implementation translation. In Hyperledger Fabric, systems are defined as a set of organizations, a network of nodes each owned by one of the organizations, a set of general policies for how the network is managed and a set of chaincode smart contracts which can read and update the blockchain and worldstate. Every node has some role on the system, such as peers that store the blockchain and run chaincode or orderers that ensures all nodes have the same blockchain history. To support high availability, participating organizations can have several nodes with the same role, thus distributing the load on any one node as well as mitigating risk in the case where some node is not functioning properly. Chaincodes are written in regular turing-complete programming languages such as Java or Go. For them to be accepted by the network, chaincodes should be deterministic with regards to the read-write sets they generate. If a chaincode contains non-deterministic behaviour, different peers would not be able to reach the same result when running the chaincode. This would lead the network to reject the execution. Whether they are accepted or not is highly dependent on the chaincodes' endorsement policies which describe what organizations has to accept the run. While chaincodes can read any parts of the world state, the request parameters of a chaincode call can include information private only to the organization that invoked the request in first hand.

6.2.2 Model to network design

The TLA$^+$ model uses a simplified network topology compared to what is expected in a production system. In the model, each organization is represented by a single `builder`. These builders are actors in the model and play the roles of clients and peers in the network. While not recommended, there is nothing in Hyperledger Fabric stopping a network to have such

single node organizations. In fact, this is precisely how the Hyperledger test-network is set up. While the model can be said to represent clients and peers, it does not have anything similar to orderer nodes. Instead, the model abstracts the transaction flow (see 2.6.2) as guaranteed and atomic state updates. This is consistent with the guarantees Hyperledger Fabric makes, where any chaincode invocation should lead to the same state updates on every peer.

To represent the Hyperledger Fabric world state, the key-value map variable `public` contains all publicly known (throughout the network) information. Similarly to how the world state on the blockchain can only be updated by chaincode, there is a limited number of operators that reads or writes to the `public` variable.

6.2.3 Model to chaincode

Because Hyperledger Fabric chaincode are written in turing-complete languages it is fully possible to translate TLA$^+$ code to one of those languages. This greatly simplifies the argument for whether a corresponding implementation *can* be found for the model. The resulting chaincode definitions should be functional as long as adherence is made to follow the Hyperledger Fabric chaincode API. Relevant to this translation are five TLA$^+$ operators, each containing the functionality of a corresponding chaincode. In general, these operators all have the form of taking some parameters from a caller, verifying whether the call is valid and updating the `public` state. This way of defining chaincode can be seen in many of the Hyperledger Fabric examples **cite**. As mentioned in 6.2.1, chaincodes should be deterministic and can rely on private data only available to nodes of the same organization as the invoking client. The five operators in the model corresponding to chaincodes are all deterministic.

Model state is split into private and public (there should be a third one as well so private state is split from builder assumptions). Chaincode can only touch public data from the world state, and private data sent in a request (only if from same organization).

The model assumes that all builders are weakly fair and won't stall forever. This is reasonable because each organization probably have multiple nodes so if one has crashed they can use another one.

6.2.4 Client behaviour

6.2.5 Translation summary

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Appendix A

TLA+ model

Listing A.1: TLA+ model in its entirety

```
1
2  ──────────── MODULE Judgment ────────────
3  EXTENDS TLC, FiniteSets, Reals, Sequences
4  VARIABLE public, private, nextPackageId
5  CONSTANT NumberOfClosedJudgmentsGoal

6  Nodes ≜ {"node1", "node2", "node3", "node4"}
7  MaliciousNodes ≜ {"node4"}
8  InitialPrivate ≜ private = [
9      node1 ↦ [
10         preferences ↦ ⟨
11             [package ↦ "package1", level ↦ 2, status ↦ "not-processed"],
12             [package ↦ "package2", level ↦ 2, status ↦ "not-processed"]
13         ⟩
14     ],
15     node2 ↦ [
16         preferences ↦ ⟨
17             [package ↦ "package3", level ↦ 2, status ↦ "not-processed"],
18             [package ↦ "package4", level ↦ 2, status ↦ "not-processed"]
19         ⟩
20     ],
21     node3 ↦ [
22         preferences ↦ ⟨
```

```
23              [package ↦ "package5", level ↦ 2, status ↦ "not-processed"],
24              [package ↦ "package6", level ↦ 2, status ↦ "not-processed"]
25          ⟩
26      ],
27      node4 ↦ [
28          preferences ↦ ⟨
29              [package ↦ "package7", level ↦ 2, status ↦ "not-processed"],
30              [package ↦ "package8", level ↦ 2, status ↦ "not-processed"]
31          ⟩
32      ]
33  ]
34  InitialPublic ≜ public = [
35      nodes ↦ [
36          node1 ↦ [wallet ↦ 3],
37          node2 ↦ [wallet ↦ 0],
38          node3 ↦ [wallet ↦ 0],
39          node4 ↦ [wallet ↦ 0]
40      ],
41      judgments ↦ ⟨⟩
42  ]
43  IsReproducibleData ≜    [package1 ↦ TRUE,
44                           package2 ↦ FALSE,
45                           package3 ↦ TRUE,
46                           package4 ↦ TRUE,
47                           package5 ↦ TRUE,
48                           package6 ↦ TRUE,
49                           package7 ↦ TRUE,
50                           package8 ↦ TRUE,
51                           package9 ↦ FALSE,
52                           package10 ↦ FALSE,
53                           package11 ↦ FALSE,
54                           package12 ↦ FALSE,
55                           package13 ↦ FALSE,
56                           package14 ↦ FALSE,
57                           package15 ↦ FALSE,
58                           package16 ↦ FALSE,
59                           package17 ↦ FALSE,
```

```
60                          package18 ↦ FALSE,
61                          package19 ↦ FALSE,
62                          package20 ↦ FALSE]

63  Range(f) ≜ {f[k] : k ∈ DOMAIN f}

64  KeyValues(m) ≜ {⟨k, m[k]⟩ : k ∈ DOMAIN m}

65   Source: https://learntla.com/libraries/sets/
66  Pick(S) ≜ CHOOSE s ∈ S : TRUE
67  RECURSIVE SetReduce(_, _, _)
68  SetReduce(Op(_, _), S, value) ≜ IF S = {} THEN value
69                                  ELSE LET s ≜ Pick(S)
70                                  IN  SetReduce(Op, S \ {s}, Op(s, value))

71  Sum(S) ≜
72      LET _op(a, b) ≜ a + b
73      IN  SetReduce(_op, S, 0)

74  IsReproducible(p) ≜ IsReproducibleData[p]

75  RECURSIVE Cost(_)
76  Cost(level) ≜ IF level = 0 THEN 0 ELSE level + Cost(level − 1)

77  RECURSIVE LevelHelp(_, _)
78  LevelHelp(available, stepCost) ≜
79      IF stepCost > available
80          THEN 0
81          ELSE 1 + LevelHelp(available − stepCost, stepCost + 1)

82  Level(cost) ≜ LevelHelp(cost, 1)

83  RECURSIVE WalletUpdatesForVoters(_, _, _, _)
84  WalletUpdatesForVoters(judgment, votes, reward, updates) ≜
85      LET finalResult ≜ ToString(judgment.tally.for > judgment.tally.against)
86          judge ≜ Head(votes).judge
87          vote ≜ Head(votes).vote
88      IN
89          IF Len(votes) = 0
90              THEN updates
91          ELSE IF judge = judgment.owner
92               Skip the owner
93              THEN WalletUpdatesForVoters(
```

```
94                judgment, Tail(votes), reward, updates)
95          ELSE IF vote ≠ finalResult THEN LET
96              Minority voter
97                newUpdates ≜ [updates EXCEPT ![judge].wallet = @]
98            IN  WalletUpdatesForVoters(
99                 judgment, Tail(votes), reward, newUpdates)
100         ELSE LET
101             Majority voter
102               newUpdates ≜ [updates EXCEPT ![judge].wallet = @ + reward + 1]
103                 newReward ≜ IF reward = 0 THEN 0 ELSE reward − 1
104           IN  WalletUpdatesForVoters(
105                    judgment, Tail(votes), newReward, newUpdates)

106 RECURSIVE WalletUpdatesForNotVoting(_, _)
107 WalletUpdatesForNotVoting(nonVoters, updates) ≜
108     IF nonVoters = {}
109         THEN updates
110         ELSE
111           LET v ≜ CHOOSE voter ∈ nonVoters : TRUE
112                 newUpdates ≜ [updates EXCEPT ![v].wallet = @ − 1]
113           IN  WalletUpdatesForNotVoting(nonVoters \ {v}, newUpdates)

114 FutureCost(node) ≜
115     LET NotProcessedYet ≜
116             {p ∈ Range(private[node].preferences) : p.status ≠ "processed"}
117     IN  Sum({Cost(p.level) : p ∈ NotProcessedYet})

118 AllPreferences ≜
119     LET op(a, b) ≜ a ∘ b
120     IN  SetReduce(op, {p.preferences : p ∈ Range(private)}, ⟨⟩)

121 Min(S) ≜
122      CHOOSE e ∈ S ∪ {0} :
123          ∀ e2 ∈ S : e ≤ e2

124 SecretJudges(judgment) ≜
125     {j.judge : j ∈ Range(judgment.secretJudgments)}

126 OpenJudges(judgment) ≜
127     {j.judge : j ∈ Range(judgment.openJudgments)}
```

```
128 Rewards(judgment) ≜
129     LET openVotes ≜ judgment.openJudgments
130         topReward ≜ judgment.targetVotes
131         wallets ≜ public.nodes
132         openVoters ≜ OpenJudges(judgment)
133         nonVoters ≜ Nodes \ openVoters
134         ownerCost ≜ Cost(judgment.targetVotes)
135         updatesForVoters ≜
136             WalletUpdatesForVoters(judgment, openVotes, topReward, wallets)
137          updatesForNonVoters ≜
138              WalletUpdatesForNotVoting(nonVoters, updatesForVoters)
139     IN   [updatesForNonVoters EXCEPT ![judgment.owner].wallet = @ − ownerCost]


140 AddPreferencedPackage(node) ≜
141     LET currentBalance ≜ public.nodes[node].wallet
142         pendingPackagesCount ≜ Level(FutureCost(node))
143         maxJudgmentCost ≜ currentBalance − FutureCost(node)
144         maxJudgmentLevel ≜ Level(maxJudgmentCost)
145         packageLevel ≜ maxJudgmentLevel
146         packageName ≜ "package" ∘ ToString(nextPackageId)
147         package ≜ [package ↦ packageName,
148                    level ↦ packageLevel,
149                    status ↦ "not-processed"]
150     IN
151         ∧ packageLevel > 1
152         ∧ pendingPackagesCount < 2
153         ∧ private′ = [private EXCEPT ![node].preferences
154             = Append(@, package)]
155         ∧ nextPackageId′ = nextPackageId + 1

156 ActiveJudgments ≜
157     {j ∈ Range(public.judgments) : j.status = "active"}

158 ClosedJudgments ≜
159     {j ∈ Range(public.judgments) : j.status = "closed"}

160 RunSimulation ≜
161     Cardinality(ClosedJudgments) < NumberOfClosedJudgmentsGoal

162 IsFinanciallyIncentivizedToVote(node) ≜
```

```
163     FutureCost(node) ≤ public.nodes[node].wallet − 1

164 PreferredPackages(node) ≜
165     {p.package : p ∈ Range(private[node].preferences)}

166  ——— Chaincode ———

167 InitializeJudgment(package, owner, targetVotes) ≜
168      Guards
169     ∧ Cost(targetVotes) ≤ public.nodes[owner].wallet
170     ∧ ∀ j ∈ ActiveJudgments : j.owner ≠ owner
171      Update
172      TODO: Better ids. Currently there can only be one judgment perpackage.
173     ∧ LET judgmentId ≜ package
174           judgment ≜ [id ↦ judgmentId,
175                       tally ↦ [for ↦ 0, against ↦ 0],
176                       finalResult ↦ "undecided",
177                       package ↦ package,
178                       owner ↦ owner,
179                       targetVotes ↦ targetVotes,
180                       status ↦ "active",
181                       phase ↦ "secretVotes",
182                       secretJudgments ↦ ⟨⟩,
183                       openJudgments ↦ ⟨⟩] IN
184        public′ = [public EXCEPT !.judgments = Append(@, judgment)]

185 AddSecretJudgment(judgmentId, judge, secretVote) ≜
186     ∨ Len(public.judgments) = 0
187     ∨ ∃ index ∈ DOMAIN public.judgments :
188         LET j ≜ public.judgments[index] IN
189             ∧ j.id = judgmentId
190             ∧ j.status = "active"
191             ∧ j.phase = "secretVotes"
192              Has 'judge' added their vote before?
193             ∧ {sj ∈ Range(j.secretJudgments) : sj.judge = judge} = {}
194              Update
195             ∧  public′ =
196                   [public EXCEPT !.judgments[index].secretJudgments =
197                       Append(@, [judge ↦ judge,
198                                  vote ↦ secretVote])]
```

```
199 EndSecretSubmissions(judgmentId, owner) ≜
200     ∨ Len(public.judgments) = 0
201     ∨ ∃ index ∈ DOMAIN public.judgments :
202         LET j ≜ public.judgments[index] IN
203             ∧ j.id = judgmentId
204             ∧ j.status = "active"
205             ∧ j.phase = "secretVotes"
206             ∧ j.owner = owner
207             ∧ 2 * j.targetVotes − 1 ≤ Len(j.secretJudgments)
208             ∧ public′ = [public EXCEPT !.judgments[index].phase
209                                 = "openVotes"]

210 ShowJudgment(judgmentId, judge, openVote) ≜
211     ∨ Len(public.judgments) = 0
212     ∨ ∃ index ∈ DOMAIN public.judgments :
213         LET j ≜ public.judgments[index] IN
214             ∧ j.id = judgmentId
215             ∧ j.status = "active"
216             ∧ j.phase = "openVotes"
217             Has 'judge' added their vote before?
218             ∧ {sj ∈ Range(j.secretJudgments) : sj.judge = judge} ≠ {}
219             Has 'judge' showed their vote before?
220             ∧ {oj ∈ Range(j.openJudgments) : oj.judge = judge} = {}
221             Secret and open votes should be the same
222             This validation is done with HMAC in practice
223             ∧ ∃ sj ∈ Range(j.secretJudgments) :
224                 ∧ sj.judge  = judge
225                 ∧ openVote = sj.vote
226             Update
227             ∧ public′ = [public EXCEPT !.judgments[index] = [@ EXCEPT
228                             !.openJudgments = Append(@,
229                                 [ judge ↦ judge,
230                                   vote ↦ openVote]),
231                             !.tally.for = IF openVote = "TRUE"
232                                           THEN @ + 1
233                                           ELSE @,
234                             !.tally.against = IF openVote = "FALSE"
235                                               THEN @ + 1
236                                               ELSE @]]
```

```
237 CloseJudgment(judgmentId, owner) ≜
238     ∨ Len(public.judgments) = 0
239     ∨ ∃ index ∈ DOMAIN public.judgments :
240         LET j ≜ public.judgments[index]
241             finalResult ≜ ToString(j.tally.for > j.tally.against) IN
242              ∧ j.id = judgmentId
243              ∧ j.status = "active"
244              ∧ j.phase = "openVotes"
245              ∧ j.owner = owner
246              ∧ 2 * j.targetVotes − 1 ≤ Len(j.openJudgments)
247                  We have a majority!
248              ∧ ∨ ∧ j.tally.for ≠ j.tally.against
249                  ∧ public′ = [public EXCEPT
250                        !.judgments[index] =
251                          [@ EXCEPT
252                              !.status = "closed",
253                              !.phase = "judgment",
254                              !.finalResult = finalResult],
255                        !.nodes = Rewards(j)]
256                  Everyone has voted, and we don't have a majority
257                ∨ ∧ j.tally.for = j.tally.against
258                  ∧ public′ = [public EXCEPT !.judgments[index] = [@ EXCEPT
259                                  !.status = "closed",
260                                  !.finalResult = "undecided"]]

261  ———— Invariants ————

262 OwnOneJudgmentAtATime ≜
263     For all active judgments j, j2 where j ≠ j2: j.owner ≠ j2.owner
264     Needed to ensure that judgments can be paid for.
265   ∀ j ∈ Range(public.judgments) : j.status = "active" ⟹
266     (∀ j2 ∈ Range(public.judgments) : j2.status = "active" ∧
267       j.id ≠ j2.id ⟹ j.owner ≠ j2.owner)

268 LessActiveThenNodes ≜
269     There should never be more active judgments than nodes
270   LET active ≜ {j ∈ Range(public.judgments) : j.status = "active"}
271   IN Cardinality(active) ≤ Cardinality(Nodes)

272 NoPackagesAreWronglyJudged ≜
```

```
273     ∀ j ∈ Range(public.judgments) :
274       ∨ j.finalResult = ToString(IsReproducible(j.id))
275       ∨ j.finalResult = "undecided"

276   ——————— Spec ———————

277 Init ≜
278     ∧ InitialPublic
279     ∧ InitialPrivate
280     ∧ nextPackageId = 9

281 Next ≜

282         Initializing a package judgment
283       ∨ ∃ n ∈ Nodes :
284           ∃ index ∈ DOMAIN private[n].preferences :
285             LET p ≜ private[n].preferences[index] IN
286                 ∧ RunSimulation
287                 ∧ p.status = "not-processed"
288                 ∧ InitializeJudgment(p.package, n, p.level)
289                 ∧ private′ =
290                     [private EXCEPT ![n].preferences[index].status = "started"]
291                 ∧ UNCHANGED ⟨nextPackageId⟩

292         Adding a secret vote
293       ∨ ∃ n ∈ Nodes :
294           ∃ j ∈ Range(public.judgments) :
295             LET secretVote ≜ IF n ∈ MaliciousNodes
296                              THEN ¬IsReproducible(j.package)
297                              ELSE IsReproducible(j.package)
298             IN
299                 ∧ RunSimulation
300                  Nodes only build/judge if they have to
301                 ∧  ∨ FutureCost(n) > public.nodes[n].wallet − 1
302                    ∨ j.owner = n
303                    ∨ j.package ∈ PreferredPackages(n)
304                 ∧ AddSecretJudgment(j.id, n, ToString(secretVote))
305                 ∧ UNCHANGED ⟨private, nextPackageId⟩

306         End submission of secret votes
307       ∨ ∃ n ∈ Nodes :
308           ∃ j ∈ Range(public.judgments) :
```

```
309             ∧ RunSimulation
310              Assume that every node that *needs* to vote will have the time to do so
311             ∧  ∀ nonVoter ∈ Nodes \ SecretJudges(j) :
312                   ∨  IsFinanciallyIncentivizedToVote(nonVoter)
313                   ∨  n ∈ MaliciousNodes
314             ∧  EndSecretSubmissions(j.id, n)
315             ∧ UNCHANGED ⟨private, nextPackageId⟩

316          Add an open vote
317         ∨  ∃ n ∈ Nodes :
318            ∃ j ∈ Range(public.judgments) :
319               LET openVote ≜ IF n ∈ MaliciousNodes
320                              THEN ¬IsReproducible(j.package)
321                              ELSE IsReproducible(j.package)
322               IN
323                  ∧ RunSimulation
324                  ∧  ∨  FutureCost(n) > public.nodes[n].wallet − 1
325                     ∨  j.owner = n
326                     ∨  j.package ∈ PreferredPackages(n)
327                  ∧ ShowJudgment(j.id, n, ToString(openVote))
328                  ∧ UNCHANGED ⟨private, nextPackageId⟩

329          Close judgment
330         ∨  ∃ n ∈ Nodes :
331            ∃ j ∈ Range(public.judgments) :
332               ∧ RunSimulation
333                Assume that every node that *needs* to vote will have the time to do so
334               ∧  ∀ nonVoter ∈ Nodes \ OpenJudges(j) :
335                     ∨ IsFinanciallyIncentivizedToVote(nonVoter)
336                     ∨ n ∈ MaliciousNodes
337               ∧  CloseJudgment(j.id, n)
338                Update the nodes preferences
339               ∧  ∃ preferenceIndex ∈ DOMAIN private[n].preferences :
340                     ∧ private[n].preferences[preferenceIndex].package
341                           = j.package
342                     ∧ private′ =
343                       [private EXCEPT ![n].preferences[preferenceIndex].status
344                           = "processed"]
345               ∧ UNCHANGED ⟨nextPackageId⟩
```

```
346         Add additional package to node
347       ∨ ∃ n ∈ Nodes :
348           ∧ RunSimulation
349           ∧ AddPreferencedPackage(n)
350           ∧ UNCHANGED ⟨public⟩

351         End simulation
352       ∨   ∧ ¬RunSimulation
353           ∧ UNCHANGED ⟨private, public, nextPackageId⟩

354   Spec ≜ Init ∧ □[Next]⟨public, private, nextPackageId⟩

355 ╚═══════════════════════════════════════════════════════════════════════
```

Appendix B

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Appendix C

Gzip .buildinfo file

```
Format: 1.0
Source: gzip
Binary: gzip gzip-win32
Architecture: all amd64
Version: 1.10-2
Checksums-Md5:
 c7e557d5ab0394257f6d0898d5fc08b9 105300 gzip-dbgsym_1.10-2_amd64.deb
 19dd1ec2e527dae5ced4fb54ce083f95 125036 gzip-win32_1.10-2_all.deb
 162a6f2e4337f69526b96cb5022fce60 130872 gzip_1.10-2_amd64.deb
Checksums-Sha1:
 acee910fe4ff96636e33290887718e8309a2599e 105300 gzip-dbgsym_1.10-2_amd64.deb
 9809588beac4adaa36096501ed07f8cf92bb7b48 125036 gzip-win32_1.10-2_all.deb
 c2e9085981422beda78cad9adc1ec5493c66ce64 130872 gzip_1.10-2_amd64.deb
Checksums-Sha256:
 f4f835ca2bf07fd33f6876704f71cbf656d3686ae7e16eaf804ac8fe8a92b3c6 105300 gzip-
 6281eaf565098d0161efad7c3d46b132ad37e42038509bfe72c5c7b5542fccf9 125036 gzip-
 68b46db19445c3f1956291a68104672931f9f37162723120c6dfb28995cedc4a 130872 gzip_
Build-Origin: Debian
Build-Architecture: amd64
Build-Date: Wed, 30 Mar 2022 09:17:04 +0000
Build-Path: /build/gzip-1.10
Installed-Build-Depends:
 autoconf (= 2.69-11.1),
 automake (= 1:1.16.1-4),
 autopoint (= 0.19.8.1-10),
 autotools-dev (= 20180224.1),
 base-files (= 11),
 base-passwd (= 3.5.47),
 bash (= 5.0-6),
 binutils (= 2.34-4),
 binutils-common (= 2.34-4),
 binutils-mingw-w64-i686 (= 2.34-3+8.8),
```

```
binutils-mingw-w64-x86-64 (= 2.34-3+8.8),
binutils-x86-64-linux-gnu (= 2.34-4),
bsdmainutils (= 11.1.2+b1),
bsdutils (= 1:2.34-0.1),
build-essential (= 12.8),
bzip2 (= 1.0.8-2),
coreutils (= 8.30-3+b1),
cpp (= 4:9.2.1-3.1),
cpp-7 (= 7.5.0-5),
cpp-9 (= 9.3.0-3),
dash (= 0.5.10.2-6),
debconf (= 1.5.73),
debhelper (= 12.9),
debianutils (= 4.9.1),
dh-autoreconf (= 19),
dh-strip-nondeterminism (= 1.6.3-2),
diffutils (= 1:3.7-3),
dpkg (= 1.19.7),
dpkg-dev (= 1.19.7),
dwz (= 0.13-5),
fdisk (= 2.34-0.1),
file (= 1:5.38-4),
findutils (= 4.7.0-1),
g++ (= 4:9.2.1-3.1),
g++-9 (= 9.3.0-3),
g++-mingw-w64 (= 8.3.0-22+21.5),
g++-mingw-w64-i686 (= 8.3.0-26+21.5+b1),
g++-mingw-w64-x86-64 (= 8.3.0-26+21.5+b1),
gcc (= 4:9.2.1-3.1),
gcc-10-base (= 10-20200312-2),
gcc-7 (= 7.5.0-5),
gcc-7-base (= 7.5.0-5),
gcc-8-base (= 8.4.0-1),
gcc-9 (= 9.3.0-3),
gcc-9-base (= 9.3.0-3),
gcc-mingw-w64 (= 8.3.0-22+21.5),
gcc-mingw-w64-base (= 8.3.0-26+21.5+b1),
gcc-mingw-w64-i686 (= 8.3.0-26+21.5+b1),
gcc-mingw-w64-x86-64 (= 8.3.0-26+21.5+b1),
gettext (= 0.19.8.1-10),
gettext-base (= 0.19.8.1-10),
grep (= 3.4-1),
groff-base (= 1.22.4-4),
gzip (= 1.10-1),
hostname (= 3.23),
init-system-helpers (= 1.57),
intltool-debian (= 0.35.0+20060710.5),
```

```
less (= 551-1),
libacl1 (= 2.2.53-6),
libarchive-zip-perl (= 1.68-1),
libasan4 (= 7.5.0-5),
libasan5 (= 9.3.0-3),
libatomic1 (= 10-20200312-2),
libattr1 (= 1:2.4.48-5),
libaudit-common (= 1:2.8.5-2),
libaudit1 (= 1:2.8.5-2+b1),
libbinutils (= 2.34-4),
libblkid1 (= 2.34-0.1),
libbsd0 (= 0.10.0-1),
libbz2-1.0 (= 1.0.8-2),
libc-bin (= 2.30-2),
libc-dev-bin (= 2.30-2),
libc6 (= 2.30-2),
libc6-dev (= 2.30-2),
libcap-ng0 (= 0.7.9-2.1+b2),
libcc1-0 (= 10-20200312-2),
libcilkrts5 (= 7.5.0-5),
libcroco3 (= 0.6.13-1),
libcrypt-dev (= 1:4.4.15-1),
libcrypt1 (= 1:4.4.15-1),
libctf-nobfd0 (= 2.34-4),
libctf0 (= 2.34-4),
libdb5.3 (= 5.3.28+dfsg1-0.6),
libdebconfclient0 (= 0.251),
libdebhelper-perl (= 12.9),
libdpkg-perl (= 1.19.7),
libelf1 (= 0.176-1.1),
libfdisk1 (= 2.34-0.1),
libffi7 (= 3.3-3),
libfile-stripnondeterminism-perl (= 1.6.3-2),
libgcc-7-dev (= 7.5.0-5),
libgcc-9-dev (= 9.3.0-3),
libgcc-s1 (= 10-20200312-2),
libgcc1 (= 1:10-20200312-2),
libgcrypt20 (= 1.8.5-5),
libgdbm-compat4 (= 1.18.1-5),
libgdbm6 (= 1.18.1-5),
libglib2.0-0 (= 2.64.1-1),
libgmp10 (= 2:6.2.0+dfsg-4),
libgomp1 (= 10-20200312-2),
libgpg-error0 (= 1.37-1),
libicu63 (= 63.2-3),
libisl22 (= 0.22.1-1),
libitm1 (= 10-20200312-2),
```

```
liblsan0 (= 10-20200312-2),
liblz4-1 (= 1.9.2-2),
liblzma5 (= 5.2.4-1+b1),
libmagic-mgc (= 1:5.38-4),
libmagic1 (= 1:5.38-4),
libmount1 (= 2.34-0.1),
libmpc3 (= 1.1.0-1),
libmpfr6 (= 4.0.2-1),
libmpx2 (= 8.4.0-1),
libncursesw6 (= 6.2-1),
libpam-modules (= 1.3.1-5),
libpam-modules-bin (= 1.3.1-5),
libpam-runtime (= 1.3.1-5),
libpam0g (= 1.3.1-5),
libpcre2-8-0 (= 10.34-7),
libpcre3 (= 2:8.39-12+b1),
libperl5.30 (= 5.30.0-9),
libpipeline1 (= 1.5.2-2),
libquadmath0 (= 10-20200312-2),
libseccomp2 (= 2.4.3-1),
libselinux1 (= 3.0-1+b1),
libsigsegv2 (= 2.12-2),
libsmartcols1 (= 2.34-0.1),
libstdc++-9-dev (= 9.3.0-3),
libstdc++6 (= 10-20200312-2),
libsub-override-perl (= 0.09-2),
libsystemd0 (= 245.2-1),
libtext-unidecode-perl (= 1.30-1),
libtinfo6 (= 6.2-1),
libtool (= 2.4.6-14),
libtsan0 (= 10-20200312-2),
libubsan0 (= 7.5.0-5),
libubsan1 (= 10-20200312-2),
libuchardet0 (= 0.0.6-3),
libudev1 (= 245.2-1),
libunistring2 (= 0.9.10-2),
libuuid1 (= 2.34-0.1),
libxml-libxml-perl (= 2.0134+dfsg-2),
libxml-namespacesupport-perl (= 1.12-1),
libxml-sax-base-perl (= 1.09-1),
libxml-sax-perl (= 1.02+dfsg-1),
libxml2 (= 2.9.10+dfsg-4),
linux-libc-dev (= 5.4.19-1),
login (= 1:4.8.1-1),
lsb-base (= 11.1.0),
m4 (= 1.4.18-4),
make (= 4.2.1-1.2),
```

```
 man-db (= 2.9.1-1),
 mawk (= 1.3.4.20200120-2),
 mingw-w64 (= 7.0.0-2),
 mingw-w64-common (= 7.0.0-2),
 mingw-w64-i686-dev (= 7.0.0-2),
 mingw-w64-x86-64-dev (= 7.0.0-2),
 ncurses-base (= 6.2-1),
 ncurses-bin (= 6.2-1),
 patch (= 2.7.6-6),
 perl (= 5.30.0-9),
 perl-base (= 5.30.0-9),
 perl-modules-5.30 (= 5.30.0-9),
 po-debconf (= 1.0.21),
 sed (= 4.7-1),
 sensible-utils (= 0.0.12+nmu1),
 sysvinit-utils (= 2.96-2.1),
 tar (= 1.30+dfsg-7),
 tex-common (= 6.13),
 texinfo (= 6.7.0.dfsg.2-5),
 ucf (= 3.0038+nmu1),
 util-linux (= 2.34-0.1),
 xz-utils (= 5.2.4-1+b1),
 zlib1g (= 1:1.2.11.dfsg-2)
Environment:
 DEB_BUILD_OPTIONS="parallel=8"
 LANG="C"
 LC_ALL="C"
 SOURCE_DATE_EPOCH="1584637306"
```

For DIVA