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Trust in your friends, on the ledger

Safer reproducible builds through decentralized distribution of .buildinfo files

JOHAN MORITZ

Stockholm, Sweden, 2022

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Abstract

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- Short problem statement
- Why was this problem worth a Bachelor's/Master's thesis project? (*i.e.*, why is the problem both significant and of a suitable degree of difficulty for a Bachelor's/Master's thesis project? Why has no one else solved it yet?)
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Choice of typeface with \textit, \textbf, and \texttt: *x*, **x**, and `x`

Text superscripts and subscripts with \textsubscript and \textsuperscript: A_x and A^x

Some useful symbols: \textregistered, \texttrademark, and \textcopyright. For example, copyright symbol: \textcopyright Maguire 2021, and some superscripts: ^{99m}Tc, A*, A^{\textregistered}, and A\texttrademark : ©Maguire 2021, and some superscripts: ^{99m}Tc, A*, A®, and A™. Another example: H\textsubscript{2}O: H_2O

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

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Acknowledgments

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I would like to thank xxxx for having yyyy.

Stockholm, March 2022
Johan Moritz

Contents

List of Figures

List of Tables

Listings

If you have listings in your thesis. If not, then remove this preface page.

List of acronyms and abbreviations

API	Application Programming Interface
DLT	Distributed Ledger Technology
DNS	Domain Name System
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 projects [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. .buildinfo files are by this notion the crucial link to ensure reproducibility, 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 is it if the comparison is between source and a hash of a binary. 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 we trust that the builder is not forging their results, we can be confident in that the binaries were all built the same way. The proof, though, is only as strong as our trust in the builder; an actor which could be compromised without us knowing. With multiple builders, we reduce this risk and our trust can increase likewise.

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, we ask

how such a system can be designed and implemented in order to maximize user trust in that the packages they use have been derrived from the correct 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. 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

- 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 safely is to first downloade 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 and therefore not particularly user friendly. The purpose of this project is to give alternative solutions with a focus on user trust while not relying on users' building packages themselves. Further more, 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 of and context within .buildinfo files exist. The storage plan should be formulated based on this context and written as a formal specification.

1.5 Research Methodology

The project will take three different phases. Initially, a pre-study focusing on reproducible builds, Distributed Ledger Technologies and formal specifcation will take place. Its purpose will be finding 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 produce 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 going to be produced during it. More specifically, the interessting part of .builfinfo 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 will most likely be represented in an abstract manner in any implementations and artifacts.

Chapter 2

Background

To bring the reader up to speed, 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.

2.2 Reproducible builds

In 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 correct.

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 **is this true??** between them is the use of some kind of specification for the build-environment.

2.2.1 Nix

2.2.2 Debian

2.2.3 Package archive

2.2.4 .buildinfo

In order for builds to be reproducible in different computing environments, 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 (if the package is reproducible). .buildinfo files include, among other, name and version of the source package, architecture it was built on, checksums for the build artifacts and other packages available on the system [2]. 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)**. As 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.

2.2.5 Rebuilding Debian packages

2.3 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 ambiguous. Other examples of DLTs are Certificate Transparency logs **(cite)** and peer-two-peer networks.

2.3.1 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.

2.3.2 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 in-valid 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 of voting based. 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 control it 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 [13] or that it has Byzantine fault tolerance [14]. If the algorithm only handles crashes but not malicious actors it has Crash fault tolerance.

Paxos??

2.3.3 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; *e.g.,* 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 throuput 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

2.3.4 Peer-to-peer

TODO: Add information about IPFS

TODO: Summaries several different DLT

2.4 Hyperledger Fabric

Run under the umbrella of the Linux Foundation **(cite)**, 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 use case, and define specific requirements for when a particular change to the ledger may be allowed [15]. This section will describe and discuss the main components of a Hyperledger Fabric network and how they work together.

2.4.1 Overview

The Hyperledger Fabric ledger is permissioned which, compared to a public one (such as Bitcoin **(cite)**), 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 a some organization whos' MSP determines its role. In this sense, a Fabric network is really a network of organizations rather than one of nodes.

Every peer stores' the networks 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 is one of the unique features of Hyperledger Fabric,

and makes consensus algorithm selection possible. 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 [15]

2.4.2 Transaction flow

A transaction in Hyperledger Fabric goes through a number of steps before a change to the ledger happens. 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 [16]. After recieving 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 Endorcement Policy informs which organizations has to accept, or endorse, the transaction for it to be valid. Only at the time when every necessary organization has endorsed the transaction can any change be made to the ledger.

The Fabric gateway is responsible for forwarding endorcement requests with the transaction proposal to peer's of each necessary organization, and gather their responses. Each of these peers will then run the transaction proposal and sign their endorsment for it with their private key, if they deem it correct. The gateway recieves the read-write sets and endorcements, validates them, and sends a final version of the transaction to the ordering service. The actual transaction contains the read-write set as well as the endorcements from the different organizations.

As the ordering service is run on other, orderer, nodes on the network, how the ordering service is implemented is completety separated from the functionality of the peers. Its purpose is to group transactions into blocks,

order and distribute them to all the peers on the network. By default, Fabrics' ordering service uses Raft, which is voting based crash fault tolerant consensus algorithm [17]. Attempts have been made to add a Byzantine-fault tolerant ordering service to Fabric [18] but so far none has been added to the project.

When a peer recieves a block from the ordering service they add it to their locally stored ledger, validates each transaction and, if valid, updates its local world-state according to the transaction write set. They also notify the client application the status of the transaction. Validation has two parts. First, the transaction must fulfill its endorcement 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.

TODO: Add figure of transaction flow.

2.4.3 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 organization and role for the peers that have to endorse it. Figure 2.1 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.

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

Figure 2.1: Endorsement policy syntax example

2.4.4 Chaincode

Many current blockchains have some notion of a smart contract [5], *i.e.,* methods to programatically change the ledger only when certain properties, or contracts, have been fulfilled. Smart contracts makes a blockchain 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. 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 2.4.2 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: Add chaincode example

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

TODO: Describe the core api for chaincode

2.5 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 [19]. 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

2.6 TLA+

TLA+ [20] 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 [21, 22] 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 **(acronym)** tool which simulates executions of the model in order to find potential faults. TLA+ is built on the Temporal Logic of Actions (TLA) [23], but adds improvements for writing more modular and larger specifications.

2.6.1 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.,* $[x \mapsto 1, y \mapsto \text{"}a\text{"}, z \mapsto 42]$. 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 $\langle [x \mapsto 0, \dots], [x \mapsto 1, \dots], [x \mapsto 1, \dots], [x \mapsto 2, \dots], \dots \rangle$. 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 is an important concept because it 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 2.2.

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

Figure 2.2: A behaviour where the variables x and y increment concurrently.

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

Figure 2.3: Semantic meaning of a state function g given a state s.

2.6.1.1 Propositional logic in TLA

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

2.6.1.2 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 2.3 shows an example of a substitution in a state function.

2.6.1.3 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, z, ... and *primed* variables x', y', z', ... 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 $x' = x + 1$. 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

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

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 $(x' = x + 1) \vee (x' = x)$ *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 $[\mathcal{A}]_f$. We pronounce $[\mathcal{A}]_f$ 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 $[x' = x + 1]_{\langle x \rangle}$.

2.6.1.4 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 is a formula that is true only if the action is true for all pairs of states in a behaviour. More generally, we can write $\Box F$ where F is a logical formula built from predicates and actions. For a behaviour $\langle s_0, s_1, s_2, \dots \rangle$, the operator can be defined as

$\langle s_0, s_1, s_2, \dots \rangle[\![\Box F]\!] \triangleq \forall n \in \mathbb{N} : \langle s_n, s_{n+1}, s_{n+2}, \dots \rangle[\![F]\!]$

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

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

$\Diamond F \equiv \neg\Box\neg F$

This is equivalent to the definition

$\langle s_0, s_1, s_2, \ldots\rangle[\![\Diamond F]\!] \triangleq \exists n \in \mathbb{N} : \langle s_n, s_{n+1}, s_{n+2}, \ldots\rangle[\![F]\!]$

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

- $\Box\Diamond F$, or *infinietly often*
- $\Diamond\Box F$, or *from some point onwards*
- $\Box(F \implies \Diamond G)$, 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 $F \rightsquigarrow G$.

2.6.1.5 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 $\Box[\mathcal{A}]_f$ 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 $init_\Phi \triangleq x = 0$ and an action describing the next state $next_\Phi \triangleq x' = x + 1$, we get the TLA formula

$\Phi \triangleq init_\Phi \wedge \Box[next_\Phi]_x$

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.

2.6.2 TLC (acronym) 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 **(acronym)** model checker allows mechanic verification by simulating its possible executions while looking for invalid states and other errors. If TLC **(acronym)** 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 TLC **(acronym)** 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 TLC **(acronym)** can test. 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. If we instead limit 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 **(acronym)** model checker is instead more appropriate for validating time-related and concurrency problems. Here follows a short description of some of the properties that TLC **(acronym)** can test.

2.6.2.1 Safety

A specification that can never do anything "bad" is said to follow its *safety* property. Variations of this is common to test in software engineering practices such as unit-testing. Safety checking in TLC **(acronym)** 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. An variable might for example only be allowed to be an integer and nothing else.

2.6.2.2 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 specifcation 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 $\Diamond\Box F$ *i.e.,* eventually a state is reached from which F is always true.

2.6.2.3 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. More formally they are defined, for action $\mathcal{A}$ and state function f, as

$WF_f(\mathcal{A}) \triangleq (\Box\Diamond\langle\mathcal{A}\rangle_f) \vee (\Box\Diamond\neg Enabled\langle\mathcal{A}\rangle_f)$
$SF_f(\mathcal{A}) \triangleq (\Box\Diamond\langle\mathcal{A}\rangle_f) \vee (\Diamond\Box\neg Enabled\langle\mathcal{A}\rangle_f)$

where

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

2.7 Related work area

2.7.1 Decentralized File Distribution

A number of proposals for distributed and decentralized data management are recorded in the research litterature. Ince, Ak, and Gunay [24] 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 [25] 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 [26] 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. [27] 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%.

2.7.2 Formal verification of Smart contracts

Writing smart contracts correctly and with high safety is hard. To aid this, several researchers have looked into using formal methods to verify them. Bhargavan et al. [28] 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. [29] 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 [30] modelled a blockchain for waste management using TLA$^+$. Their initial system description was written in UML **(acronym, cite)** which turned out to be a relatively straithforward to translate into a formal specification language. The systems' safety and liveness properties could then be validated with the TLC **(acronym)** model checker.

TODO: Add work on infering formal specifications from logs

2.8 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.

For DIVA