

# Disciplina: Blockchain for Education

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## Abstract

In this paper we analyze the main issues that arise from storing educational records in blockchain and propose the architecture of the Disciplina platform – a domain-specific blockchain implementation. The platform is designed to act as a decentralized ledger, with special regard for privacy and mechanisms of data disclosure. We present an overview of the main entities, their roles and incentives to support the network. Please note that the project is a work-in-progress and the descriptions provided are subject to change.

## 1 Introduction

Recent advances in blockchain technology and decentralized consensus systems open up new possibilities for building untamperable domain-specific ledgers with no central authority. Since the launch of Bitcoin [9] blockchains had been primarily used as a mechanism for value transfers. With the growth of the Ethereum platform [13], the community realized that by using a chain of blocks and consensus rules one can not only store value and track its movement, but, more generally, store some state and enforce conditions upon which this state can be modified.

Bitcoin, Ethereum and other permissionless blockchains were developed with the assumption that everyone is free to join the network and validate transactions, that are public. However, the industry often requires privacy, and thus the permissive solutions with private ledgers came to exist. These solutions include Tendermint [6], Hyperledger [2], Kadena [4] and others.

The increased interest and the variety of the blockchain technologies lead to the growth of their application domains. The idea of storing educational records in the blockchain has been circulating in the press and academic papers for several years. For example, [12] and [3] focus on the online education and propose to create a system based on the educational smart contracts in a public ledger. Recently, Sony announced a project that aims at incorporating educational records in a permissioned blockchain based on Hyperledger [11]. The ledger is going to be shared between major offline educational institutes.

The main issue these solutions have in common is that they target a certain subset of ways people get knowledge. We propose a more general approach that would unite the records of large universities, small institutes, schools and online educational platforms to form a publicly verifiable chain. Contrary to the solutions like Ethereum, we do not aim at proposing a programmable blockchain that fits all the possible applications. Rather, we believe, that we should harness all the latest knowledge that emerged in the last few years in the fields of consensus protocols, authenticated data structures and distributed computations to offer a new domain-specific ledger. In this paper we introduce Disciplina — the platform based on blockchain technology that aims to transform the way educational records are generated, stored and accessed.

## 2 Architecture overview

Due to the nature of the platform, it has to operate on sensitive data, such as courses, assignments, solutions and grades. Permissionless blockchains, like Ethereum or EOS, would require disclosing this data to the public, whereas the permissive ones, like Hyperledger, lack public verifiability. Our

architecture splits the blockchain into two layers: the private layer contains sensitive data, and the public one contains the information necessary to validate the integrity and authenticity of the private blocks. The key entities of the proposed blockchain architecture are presented in Figure 8.

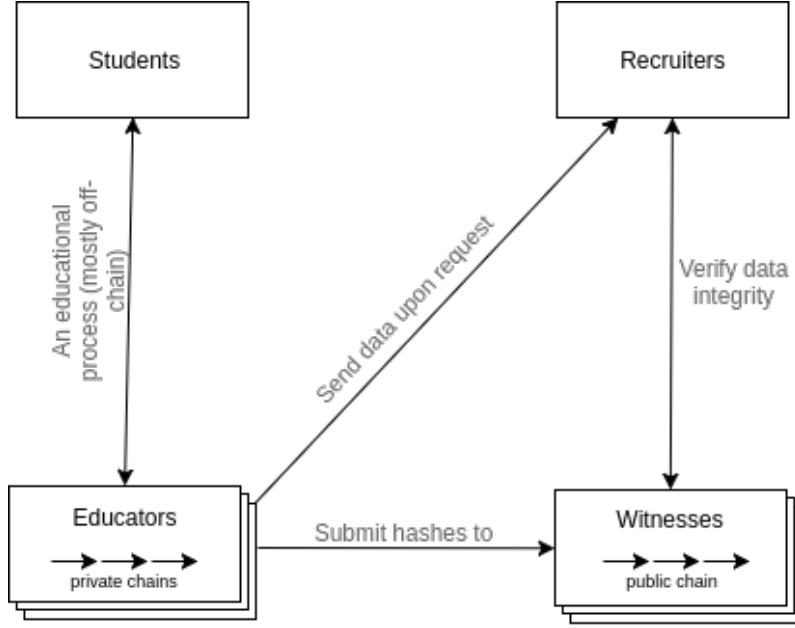


Figure 1: Key entities of the Disciplina platform

The private layer is maintained by each Educator independently of others. Educators can be either large educational institutes, capable of running their own nodes, or some trusted party that runs the chain for the self-employed teachers and small institutions. This layer contains the personalized information on the interactions between the students and the Educator. All the interactions, such as receiving an assignment, submitting solutions, or being graded, are treated as transactions in the private chain.

Students get access to the platform through web and mobile applications. Using the applications they choose Educators, enroll in courses, get assignments and submit solutions. The scores and the criteria of whether the Student has finished the course successfully are determined by the Educator. The education process from the platform’s perspective is as follows:

1. A Student chooses an Educator and a course that she wants to enroll in.
2. If the course is offered on a pre-paid basis, the Student uses her app to pay the fee.
3. During the course, the Educator provides assignments that the Student has to complete in order to get the score.
4. The Student acquires the assignment, completes it and sends the signed solution back to the Educator (communication between the Student and the Educator happens off-chain).
5. The Educator then stores the solution locally, grades it with a score in range  $[0..100]$ , and transfers the score with the hash of the solution to the blockchain.
6. Upon the completion of the course, the Student acquires a final score based on the scores she got for her assignments. This final score is also added to the Educator’s chain.

Making the Educators’ chains private opens the possibility for Educators to tamper with the data in their chains. To overcome this issue and make the private transactions publicly verifiable, we introduce the second, public, layer of the blockchain. The public part of the network consists of Witnesses — the special entities that witness the fact that a private block was produced by an Educator.

They do so by writing the authentication information of a private block into the public chain, which is used in the future by an arbitrary Verifier to substantiate a proof of transaction inclusion

given to it by a Student or an Educator. Witnesses also process public information issued by the Educators, such as announcements that an Educator has started or stopped offering a course in a particular discipline. The Witnesses agree on which public blocks are valid using the specified consensus rules.

The Recruiters are the entities interested in gathering data about students from educational institutions. They buy this data from Educators using a secure data disclosure protocol, described in detail in section 3.7. Validity and security of every data trade is also ensured by Witnesses, because corresponding transactions and actions of each party are also stored in public blockchain.

### 3 Implementation choices

In this section we describe the proposed architecture in more detail. We present the excerpt on the internal structure of both public and private chains and the reasoning behind these choices.

In order to deduce the internal structure of our system, we first analyze its use-cases. The overview of the education process is given in Section 2. The communication between the Student and the Educator is saved as transactions in the private chain. However, the implementation details of this chain mostly depend on the data disclosure process.

We will start from analyzing this process and determining the main issues that arise from the need to disclose and verify the validity of the private blocks. Then we will propose the structure of the private and public blocks that addresses these issues.

#### 3.1 Anonymity and certification

The permissionless nature of our public chain leads to the ability for malevolent students to create educational institutes in order to get the scores for the courses they did not attend. Moreover, the knowledge students actually get by completing the course, and the conditions upon which the course is considered completed, vary significantly between the educational institutions.

These issues currently can not be solved solely on the protocol level: they require an external source of information to determine the physical existence and the reputation of an Educator. Although we leave the public chain open for the Educators to submit their private block headers, we propose to add a separate layer of reputation and trust on top of the protocol.

We do so by disallowing a new Educator to join the network without an approval from another Educator. Educators are supposed to rate another Educators basing on off-chain sources of information – such as a publication on an official site of a university, which claims that given Disciplina public key is issued by this university. By approving each other, Educators form a *web of trust*. Ratings of Educators are backed up by ratings of Educators which trust them.

#### 3.2 Activity Type Graph

When a Recruiter makes a request to one of the Educators, the Educator has to provide as minimal set of entries as possible. This set has to be verifiable, which means that the Educator provides the proof of the data validity along with the data being disclosed.

In order to achieve these goals, we divide the data that the Educators store into atomic Activity Types. Each Educator maintains a journal of transactions per each Activity Type that the Educator offers.

All the Activity Types are grouped into courses that are further grouped into larger entities such as subjects and areas of knowledge. This grouping can be stored as the Activity Type Graph  $G_A$  with the following properties:

1°  $G_A$  is a directed graph:

$$G_A : \langle V : \{\text{Vert}\}, e_{out} : \text{Vert} \rightarrow \{\text{Vert}\} \mid \text{rest} \rangle \quad (1)$$

2° Each vertex of  $G_A$  is associated with depth:

$$G_A : \langle d : \text{Vert} \rightarrow \text{Int} \mid \text{rest} \rangle \quad (2)$$

3° Law of pointing down:

$$G_A : \langle v \in e_{out}(u) \implies d(v) > d(u) \rangle \quad (3)$$

4°  $G_A$  has special *et cetera* vertices  $u$ :

$$\forall v \in V \exists u (u \in e_{out}(v) \wedge e_{out}(u) = \emptyset) \quad (4)$$

The example of the Activity Type Graph (ATG) is shown in Figure 2. The vertex  $v$  of the graph is a *leaf* if  $e_{out}(v) = \emptyset$ . Otherwise we call it an *internal vertex*. Every internal vertex of the graph has a special *etc.* child (some of these are omitted in the figure).

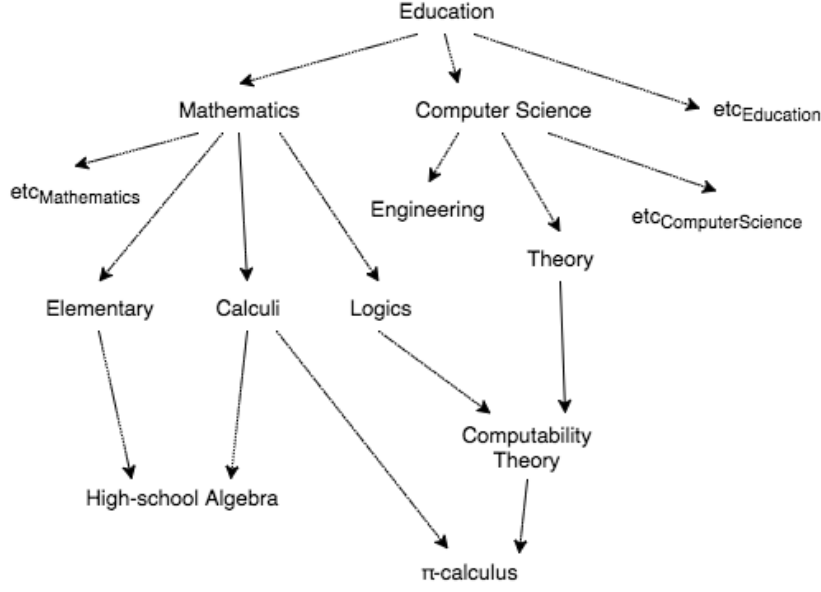


Figure 2: An example of the Activity Type Graph. Some of the vertices are not shown

The need for *etc.* vertices arises from the fact that not all of the Educators teach courses exactly in leaves — some of them offer general courses that provide just the necessary background. For example, some of the universities teach the basic “Computer science” course, that contains the basics of the discipline. In this case, when the particular category is hard to define, the university would use the  $etc_{ComputerScience}$  vertex.

On the protocol level, the Educators can announce that they teach a particular course, but can not modify the Activity Type Graph structure. The structure of the graph is maintained by the core developers and updated upon request from the Educators.

For every pair of vertices  $(v, u)$ ,  $weight(v, u)$  defines how the score of a course from the field of study  $u$  affects the summary grade for the field of study  $v$ . Let’s define  $weight(v, u) = (d(u) - d(v) + 1)^{-1}$  if  $u$  reachable from  $v$ , and  $weight(v, u) = 0$  otherwise. The motivation of the aforementioned weights is that less specific subject implies the wider knowledge. After that we can define  $avgGrade_{subjectId}$  as a weighted average with weights described above.

### 3.3 Search queries

An educator can answer one of the following queries:

- For a set of pairs  $(subjectId_1, minGrade_1), (subjectId_2, minGrade_2), \dots, (subject_n, minGrade_n)$  and some  $Count$ , find no more than  $Count$  students with grades satisfying the following inequalities:

$$\begin{cases} avgGrade_{subjectId_1} \geq minGrade_1 \\ avgGrade_{subjectId_2} \geq minGrade_2 \\ \vdots \\ avgGrade_{subjectId_n} \geq minGrade_n \end{cases}$$

- For the given identifier of a student, return all info about this student.

### 3.4 Private chain

Every educator has a private chain. It stores the data about students, and can generate answers for the queries described above.

Private chain comprises of two main data structures:

- Set of transactions batched into blocks. Every block contains a list of transactions packed into a Merkle tree.
- Links to the transactions stored in the B+-tree with keys (studentId, studentGrade). Indexes constructed in such a way that more popular activities go first.

The structure of the private block is shown in Figure 3. The block consists of a public *header* that the Educators relay to the Witnesses, and the private *body* that remains in the educational institute until it receives a data disclosure request.

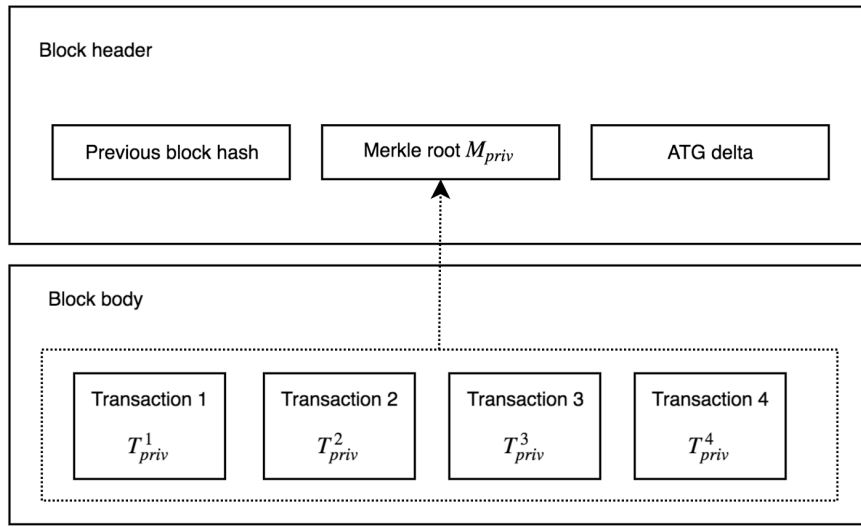


Figure 3: Private block structure

During the educational process the Educators emit atomic *private transactions*. These transactions represent the modifications to the journal of academic achievements (thus, making a transaction means appending the data to the journal). The transactions can be of the following types:

- student enrolls in a course;
- student gets an assignment;
- student submits an assignment;
- student gets a grade for an assignment;
- student gets a final grade for the course.

The first two types should be initiated by a student, and should include student's signature to prevent spam from partially-honest educator. The structure of the transaction is shown in Figure 4.

Let us denote an  $i$ -th transaction in a block as  $T_{priv}^i$ . The Educators group the transactions that occurred during the current block time slot, and construct a Merkle tree [8] for these journal modifications:

$$M_{priv} = \text{mtree}(T_{priv}^i) \quad (5)$$

The Educator's private block body comprises an ordered set of Merkle-authenticated transactions. These transactions are indexed so that the Educator can quickly find a particular transaction that satisfies some predicate.

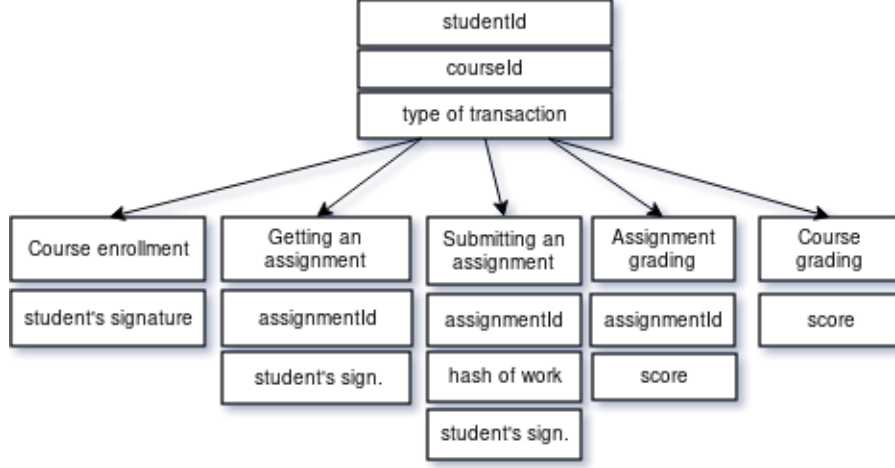


Figure 4: Transaction structure

The private block header consists of the transactions Merkle root along with the previous block hash and the information on the Activity Type Graph modifications (ATG delta). The *ATG delta* part allows the Educators to inform the Witnesses of the modifications to the courses they teach.

An Educator collects private transactions into the blocks with no more than  $K_{max}$  transactions per each block. After that, an Educator submits signed block header to the Witnesses so that private transactions can be confirmed by the public chain. Thus, the private blocks form a publicly verifiable chain of events.

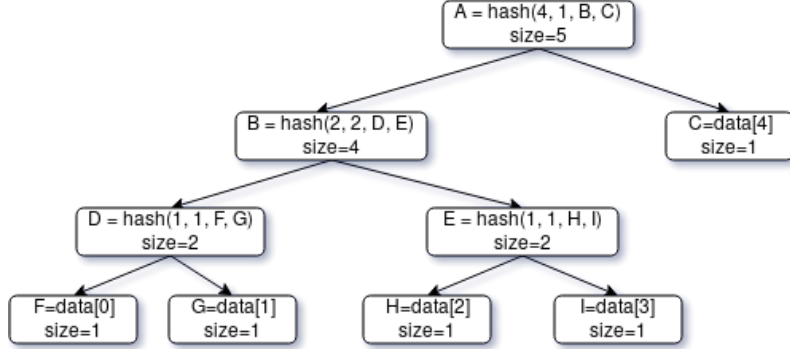


Figure 5: Example of sized Merkle tree

To incentivize Witnesses to include private block headers into the public chain, an Educator should pay some amount of coins per each private block. We should take into consideration that an educator may be both a local tutor and some big university. Depending on that, a number of transactions per each block, as well as paying capacity, may differ. So the cost of a digest publication should linearly grow with the size of a block. Let the cost for publishing a public block header be

$$C_{pub}(B) = \alpha_{pub} + \beta_{pub} \cdot N_{tr}(B) \quad (6)$$

, where  $N_{tr}(B)$  is the number of transactions in private block  $B$  and  $\alpha_{pub}$  and  $\beta_{pub}$  are parameters of the network – a small constant fee and a linear price coefficient accordingly.

To achieve the ability to prove the number of transactions in the Merkle tree, we will store it together with a hash in each node (as shown in 5). So every transaction disclosure will also verify the size.

We also consider a possibility for small educators to form pools and release blocks together in order to reduce costs for each individual educator. See appendix A.4 for details.

### 3.5 Public chain

The Witnesses maintain a public chain – a distributed ledger that contains publicly available information. If one wishes to perform a transaction on the public chain, she has to pay a certain fee that serves two purposes. First of all, the fee incentivizes the Witnesses to participate in the network and issue new blocks. Second, by requiring a fee for each transaction, we protect the public ledger from being spammed.

We present the structure of the public blocks in Figure 6. The public ledger contains the following information:

1. Modification history of the Activity Type Graph.
2. Private transaction proofs.
3. Account balances and value transfer history.

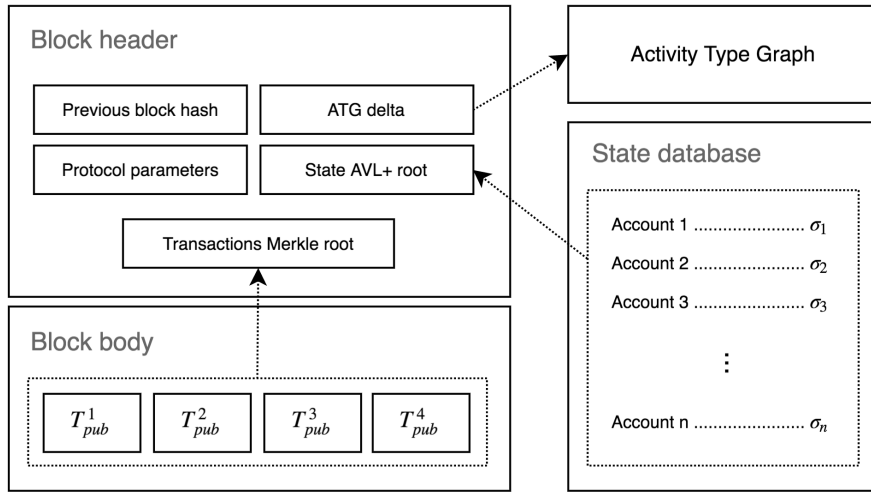


Figure 6: Public block structure

There are two major ways to store the account balances and other state information: UTXO and account-based architectures. UTXO is an unspent transaction output, that contains some predicate – a condition that has to be fulfilled in order to spend the coins. To prove the money ownership, the spender provides a witness – an input that makes the predicate true. Thus, the UTXO-based architecture requires the transactions to be stateless, effectively limiting the application domain [1]. The unspent outputs with an associated state can be treated as smart-contracts in the account-based architectures like Ethereum [13]. The state is stored in an off-chain storage – the state database. The transactions are treated as the modifications of the world state.

Disciplina uses an account-based ledger with contracts programmable in Plutus language [7]. Each account has an associated state, which comprises the account balance and other information (e. g.  $\log L$  of a data disclosure contract). The world state is a mapping between accounts and their states. In order to make this mapping easily verifiable, we use a structure called the *authenticated AVL+ tree* introduced in [10]. This structure is based on state-of-the-art research that enables for faster verification of the mapping and allows us to never disclose it: the Witnesses would not have to store the whole blockchain like Bitcoin or Ethereum nodes do. Rather, they would just have to check the private block headers in order to confirm that none of the private blocks were tampered with.

The recent achievements in the field of consensus protocols, like the provably secure Ouroboros [5], allow us to build a public chain based on the Proof of Stake consensus rules. Thus, we can increase the transaction speed and drop the need for the expensive mining. However, with mining being dropped, we need to provide incentives for the Witnesses to maintain the chain and participate in the network.

### 3.6 Fair CV

One of the main goals of the Disciplina platform is to provide a way for the Students to easily prove their educational records. We propose to duplicate the records in the Student's *digital CV*. This CV contains all the records that the parties have generated during the Student's educational process along with the validity proofs of that data (see Figure 7).

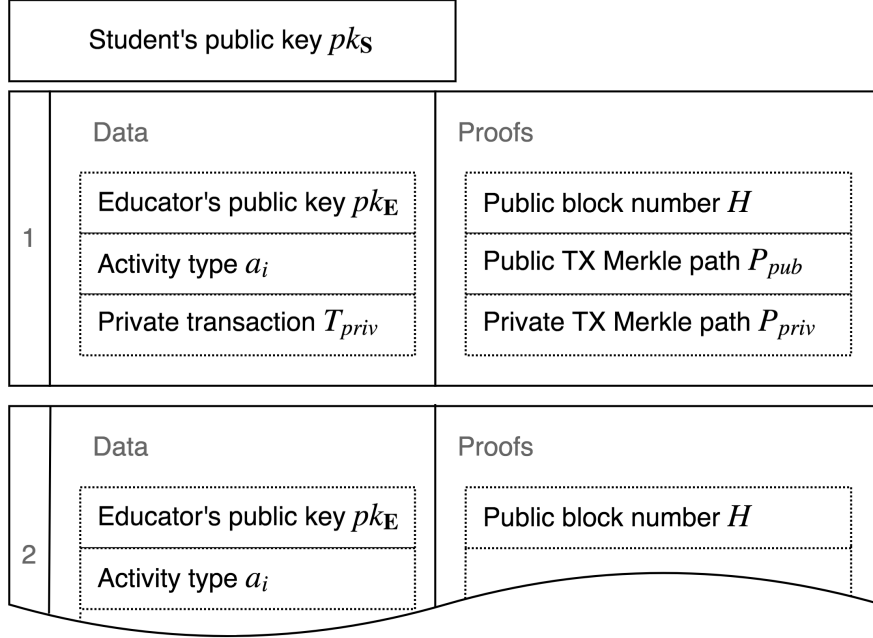


Figure 7: Student's authenticated CV

In order to prove that some transaction actually occurred in some private block of the concrete Educator, the student has to provide the cryptographic proofs along with the actual data. The cryptographic proof of the inclusion of an element in an authenticated data structure is generally a path of hashes. Let us denote the path of the element  $e$  in some authenticated data structure  $X$  as  $\text{path}(e, X)$ . Thus, the Student has to provide the following data:

- The Student's and the Educator's public keys  $pk_S$  and  $pk_E$ .
- The course  $a_i$  and the a private transaction  $T_{priv}$  with the score.
- The Merkle path of the transaction in the journal:  $P_{priv} = \text{path}(T_{priv}, M_{priv})$ , where  $M_{priv}$  is a Merkle tree of the transactions in the private block.
- The public block number  $H$  and the Merkle path of the transaction  $T_{pub}$  that pushed the private block into the public chain:  $P_{pub} = \text{path}(T_{pub}, M_{pub})$ , where  $M_{pub}$  is a Merkle tree of the transactions in the block  $H$ .

Having this data one can prove the occurrence of a certain transaction in one of the Educator's private blocks without the need to request any data from the Educator during the validation process. Thus, any party can check the validity of the Student's CV for free if the Student wishes to disclose it.

Let  $\rho(e, P)$  be the function that substitutes the element  $e$  in path  $P$  and computes the root hash of the authenticated data structure. Then the validation process is as follows:

1. Query the public chain to find the block  $H$  and obtain the Merkle root of the transactions:  $\text{root}(M_{pub})$ .
2. Check whether  $\rho(T_{pub}, P_{pub}) = \text{root}(M_{pub})$ .
3. Check that the public transaction  $T_{pub}$  was signed with the Educator's public key  $pk_E$ .



4. From the public transaction  $T_{pub}$  obtain the Merkle root of the private transactions:  $\text{root}(M_{priv})$ .
5. Check that  $\rho(T_{priv}, P_{priv}) = \text{root}(M_{priv})$ .

These validation steps can prove that an Educator with a public key  $pk_E$  issued a transaction  $T_{priv}$  in one of its private blocks. One can attribute the  $pk_E$  to a particular real-world educational institution by checking the Educator's certificate as described in Section 3.1.

### 3.7 Data Disclosure

The process of data disclosure involves direct communication between a particular Educator, willing to disclose a part of the data, and an interested party **B** (e. g. a recruiter), willing to pay for this data. Suppose an Educator **E** has some data  $D$ . To mitigate the risk of secondary market creation, one should ensure that the majority of the data remains in the private blocks. We propose to increase the cost of the data exponentially to its size, thus incentivizing the buyers to make as accurate requests as possible.

Before the deal **E** ought to perform some preparation steps. **E** should:

1. Divide  $D$  into  $N$  chunks of size no more than 1 KiB:

$$D = \bigoplus_{i=1}^N d_i, \quad \text{sizeof}(d_i) \leq 1 \text{ KiB} \quad (7)$$

2. Generate a symmetric key  $k$
3. Encrypt each  $d_i$  with  $k$  and make an array of encrypted chunks:

$$D_{\blacksquare} = \{E_k(d_1), E_k(d_2), \dots, E_k(d_N)\} \quad (8)$$

4. Compute a Merkle root of the encrypted chunks:

$$R = \text{root}(\text{mtree}(D_{\blacksquare})) \quad (9)$$

5. Determine the size of the data she is going to reveal:

$$s = \text{sizeof}(D_{\blacksquare}) \quad (10)$$

6. Calculate the cost of the data ( $\alpha$  is some constant coefficient):

$$C_D = \alpha \exp(s) \quad (11)$$

The protocol fairness is guaranteed by a contract on the public chain. The contract is able to hold money and is stateful: it is capable of storing a log  $L$  with data. All the data that parties send to the contract are appended to  $L$ .

1. **E** creates a contract on the public chain and sends the following data to the contract:  $\text{Sig}_E(C_D, \text{sizeof}(D_{\blacksquare}), R)$ . She also sends a predefined amount of money  $C_E$  to the contract address.  $C_E$  is a security deposit: if **E** tries to cheat, she would lose this money.
2. The buyer generates a new keypair  $(pk_B, sk_B)$ , and sends  $C_D$  worth of money to the contract address. Along with the money, **B** sends the public key  $pk_B$  of the newly generated keypair, and the size of the data.
3. **E** transfers the encrypted data chunks  $D_{\blacksquare}$  to the buyer. **B** computes the Merkle root  $R'$  and the size  $s'$  of the received data  $D_{\blacksquare}'$ :

$$R' = \text{root}(\text{mtree}(D_{\blacksquare}')) \quad (12)$$

$$s' = \text{sizeof}(D_{\blacksquare}') \quad (13)$$

4. **B** makes a transaction with a receipt  $\text{Sig}_{\mathbf{B}}(\{R', s'\})$  to the contract address. The parties can proceed if and only if the following is true:

$$(R' = R) \wedge (s' = s) \quad (14)$$

Otherwise, the protocol halts.

5. **E** sends  $\text{Sig}_{\mathbf{E}}(\mathbf{E}_{\mathbf{B}}(k))$  to the contract.
6. **B** decyphers and checks the received data. In case some data chunk  $e_i \in D_{\mathbf{A}}$  is invalid, **B** sends a transaction with  $\{sk_{\mathbf{B}}, e_i, \text{path}(e_i, \text{mtree}(D_{\mathbf{A}}))\}$  to the contract. By doing so, **B** reveals the data chunk  $d_i$  corresponding to the encrypted chunk  $e_i$ . She also shares proof that  $e_i$  was indeed part of a Mekle tree with root  $R$ . The contract checks the validity of  $d_i$  and decides whether **B** has rightfully accused **E** of cheating.

The on-chain communications of the parties (steps 2, 4, 5, 6) are bounded by a time frame  $\tau$ . In order for the transaction to be valid, the time  $\Delta t$  passed since the previous on-chain step has to be less than or equal to  $\tau$ . In case  $\Delta t > \tau$  the communication between the parties is considered over, and one of the protocol exit points is automatically triggered. The protocol exit points are described in detail in Table 1.

Table 1: Data disclosure protocol exit points

Condition	Step	Consequence
$\Delta t > \tau$	2	<b>B, E</b> get their money back because <b>E</b> wasn't able to correctly transfer the data to <b>B</b> .
$\Delta t > \tau$	4	
$R' \neq R$	4	
$s' \neq s$	4	
$\Delta t > \tau$	5	<b>B, E</b> get their money back because <b>B</b> has received the encrypted data, but <b>E</b> has not been able to share the key $k$ for it
$\Delta t > \tau$	6	<b>E</b> gets $C_E$ and $C_D$ : <b>E</b> correctly shared data to <b>B</b>
Protocol finishes		The dispute situation. In case <b>B</b> proves <b>E</b> cheated, <b>E</b> loses her security deposit $C_E$ . Otherwise, <b>E</b> receives both $C_E$ and $C_D$ .

## 4 Future work

The current architecture of the Disciplina platform heavily relies on the fact that a new Educator should gain acceptance from other Educators to join the network, and ratings of a new Educator are determined by other Educators accepting it. However, it is possible that other Educators would provide unfair ratings: for example, they could ignore the existence of private teachers, thus making their contributions less valuable, or purposefully lower the ratings of competitors entering the network.

Such problems can be avoided if we carefully integrate the algorithm of rating computation into our architecture (A.2). The ratings would be based on the on-chain sources of information and provide equal opportunities for both private teachers and large educational institutions. However, integrating the rating system into the architecture poses several design challenges that we have to solve.

## 5 Conclusion

In this paper we presented the architecture of the Disciplina platform. The described architecture provides a way to store educational records in the blockchain while preserving the privacy of these records. The concepts of private chains and a digital CV make it possible to verify the educational records of a particular person. Educational institutions are connected in a web of trust to provide credibility for each institution and, consequently, to digital CVs of their alumni.

We developed our platform not only as the source of trust, but also as a database of the students from all over the world. We believe that the data that is stored in the system has a value in itself. The need to disclose this data was also addressed in the paper: we described a mechanism for the fair data trade and the measures against the secondary market creation.

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## A Appendix

### A.1 Notations

Notation	Description
$\mathbf{A}$	A party that takes part in the protocol
$H(m)$	Result of applying a collision-resistant hash-function $H$ to a message $m$
$\text{mtree}(a)$	Merkle tree of the data array $a$
$\text{root}(M)$	Root element of the Merkle tree $M$
$\text{path}(e, M)$	Path of the element $e$ in the Merkle tree $M$
$k$	Symmetric key
$pk_{\mathbf{A}}, sk_{\mathbf{A}}$	Public and secret keys of $\mathbf{A}$
$E_k(m)$	Symmetric encryption with the key $k$
$E_{\mathbf{A}}(m)$	Asymmetric encryption with the key $pk_{\mathbf{A}}$ <sup>1</sup>
$\text{Sig}_{\mathbf{A}}(m)$	Tuple $(\mathbf{A}, m, \text{sig}(sk_{\mathbf{A}}, H(m)))$ , where $\text{sig}$ is a digital signature algorithm <sup>1</sup>
$\text{sizeof}(m)$	Size of $m$ in bytes
$\oplus$	Binary string concatenation

### A.2 Rating system

#### Rationale

The current architecture of the platform relies on connecting the Educators in a *web of trust* to ensure the existence of the Educators and the quality of education. We suppose that in the beginning there would be an initial clique of large Educators, backed up by developers, which will later add another Educators to their web of trust. However, we suppose that these large Educators would tend ignore private teachers and small schools. Thus, it worth examining whether we can allow new Educators to join the network without approval of existing Educators.

However, removing this constraint leads to the following security concerns:

- A malevolent student can forge educational records by creating a fake Educator node.
- A corrupted Educator can create fake students to increase the size of the dataset.

Moreover, a *grade* is a biased measure of students' knowledge. However, a recruiter is generally interested in an unbiased one. It is clear that unbiased measures are hard to achieve in the current setting, but it is safe to assume that the better the quality of education is, the less biased the grades are.

#### Requirements

1. The rating system should define at least two mappings:
  - Student's rating  $R_S : (\text{studentId}, \text{subjectId}) \rightarrow \text{Int}$
  - Educator's rating  $R_E : (\text{educatorId}, \text{subjectId}) \rightarrow \text{Int}$

The implementation, however, can define additional rated entities if necessary.

2. The mappings should be temporal: they should adjust in time to reflect changes in education quality and students' knowledge.
3.  $R_S(\mathbf{S}_1, x) > R_S(\mathbf{S}_2, x) \iff$  the student  $\mathbf{S}_1$  has deeper understanding of the subject  $x$  than  $\mathbf{S}_2$ .

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<sup>1</sup>The particular keys  $pk_{\mathbf{A}}$  and  $sk_{\mathbf{A}}$  belonging to the party  $\mathbf{A}$  are generally deducible from the context

4.  $R_E(\mathbf{E}_1, x) > R_E(\mathbf{E}_2, x) \iff$  the students of the educator  $\mathbf{E}_1$  on average have deeper understanding of the subject  $x$  than the students of  $\mathbf{E}_2$ .

Let  $\Omega_{i,x}$  be the set of the students that have acquired a rating in some ATG subgraph of the subject  $x$  by taking courses of the educator  $\mathbf{E}_i$ . Then for every pair of educators  $\mathbf{E}_1$  and  $\mathbf{E}_2$  and subject  $x$  the following should hold true:

$$\begin{aligned} R_E(\mathbf{E}_1, x) &> R_E(\mathbf{E}_2, x) \\ \iff \\ \frac{1}{|\Omega_{1,x}|} \sum_{s \in \Omega_{1,x}} R_S(s, x) &> \frac{1}{|\Omega_{2,x}|} \sum_{t \in \Omega_{2,x}} R_S(t, x) \end{aligned}$$

5. The ratings should be based solely on the on-chain sources of information and should not require third-party oracles.
6. The ratings should be protected from fraud:
- It should not be possible for any student with rating  $R_S(\mathbf{S}, x) = r_1$  to get new rating  $r_2 > r_1$  without completing courses in  $x$ .
  - It should not be possible for any educator with rating  $R_E(\mathbf{E}, x) = r_1$  to get new rating  $r_2 > r_1$  without teaching students in  $x$ .

### A.3 Data Object Storage

In the section 2 we supposed that all student's solutions, papers, assignments and so on are stored locally on the educator's servers. But it should be possible to introduce the new entity called "Data Object Storage" to our model (fig. 8). This entity should support an encrypted distributed access to all student's works. The main purposes of the data object storage are:

- to make publications more accessible for everyone.
- to get rid educators of the need to store a lot of information locally without loss of security.

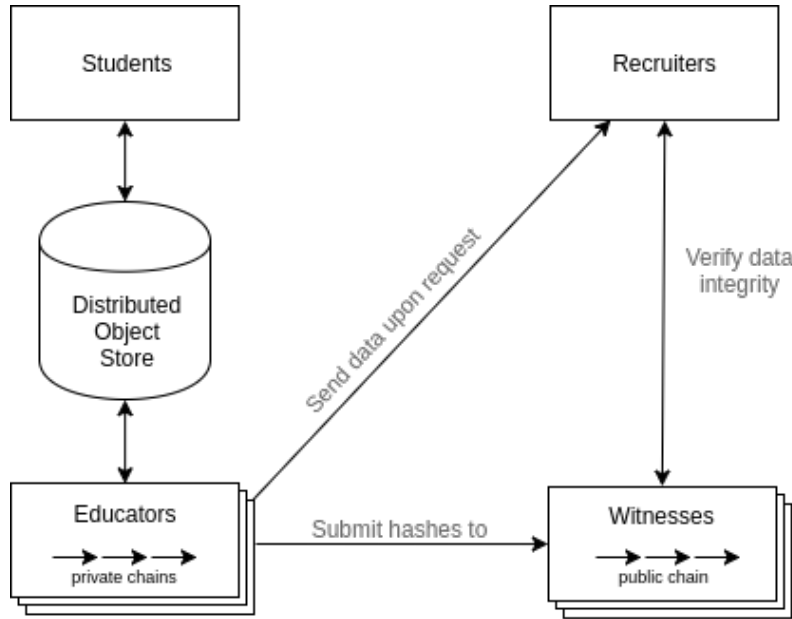


Figure 8: Entities of the Disciplina platform including distributed object storage

## A.4 Partially centralized educators

In the Section 3.4 we have concluded that the cost of the private block proof publication should depend on the size of the corresponding Merkle tree. This is done in order to scale spendings of different educators with amount of data they produce and store in their private blockchains.

But this solution has a disadvantage: the Witnesses are more incentivized to include proofs from large educators in public blocks rather than from small educators, as proofs from large educators contain more fees. If block size is limited, it may lead to delays of inclusion of small educators' proofs in the public blockchain.

In order to resolve this problem, small educators can use trusted third-party services (e. g. [teachmeplease.com](https://teachmeplease.com)) for interacting with Disciplina platform instead of running Educator nodes by themselves. But this means that third-party service has access to all the educator's data, including marks and assignments of her students, and also receives all the revenue for trading this data. Some small educators might find this option unacceptable.

Therefore, we propose a mechanism of *educator pools*, which allow small educators to delegate block proof publishing to a third party in a trustless way.

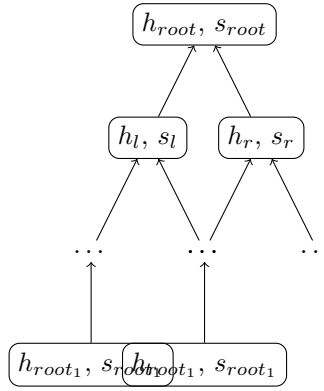


Figure 9: Two-level hierarchical Merkle tree for a block published by a pool manager

### A.4.1 General approach

The idea is the following:

- Every small Educator still maintains her own small private chain
- When a small Educator forms a block in her private chain, she sends the block header to a third party called *pool manager* instead of publishing it directly to Witnesses.
- A *pool manager* collects block headers from Educators until total number of transactions in all Educator's blocks is more than some threshold  $K_{min}$ .
- Then pool manager builds a sized Merkle tree over the list of received Educator's block headers, forming a *second-level block* (A.4). The header of second-level block gets published on the public blockchain.
- After constructing a second-level block, pool manager sends each of the small Educators a path to their block headers in a second-level sized Merkle tree.
- Having this path, each Educator can construct a publicly verifiable proof for any transaction in her private block by simply concatenating this path with a path to transaction in a first-level Merkle tree.

For every processed block header small educator pays pool manager a fee calculated by this formula:

$$C_{pool}(B) = \alpha_{pool} + \beta_{pub} \cdot N_{tr}(B) \quad (15)$$

where  $\beta_{pub}$  is a network price coefficient from 6, and  $\alpha_{pool}$  is a constant fee set by the pool manager.

If a pool manager sets such  $\alpha_{pool}$  that  $\alpha_{pool} < \alpha_{pub}$ , but  $\alpha_{pool}N > \alpha_{pub}$ , then for every published second-level block a pool manager gains  $\alpha_{pool}N - \alpha_{pub}$  coins, while every Educator in pool pays less for the block header publishing then if published directly to Witnesses.