Blockchain for science and knowledge creation

A technical fix to the reproducibility crisis ?

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Abstract:

Blockchain technology has the capacity to make digital goods immutable, transparent, externally provable, decentralized, and distributed. Besides the initial experiment or data acquisition, all remaining parts of the research cycle could take place within a *blockchain system*. Attribution, data, data postprocessing, publication, research evaluation, incentivisation, and research fund distribution would thereby become comprehensible, open (at will) and provable to the external world. Currently, scientists must be trusted to provide a true and useful representation of their research results in their final publication; *blockchain* would make much larger parts of the research cycle open to scientific self-correction. This bears the potential to be a technical solution to the current reproducibility crisis in science, and could 'reduce waste and make more research results true'.

Introduction

Currently **blockchain** is being hyped. Many claim that the *blockchain* revolution will affect not only our online lives, but will profoundly change many more aspects of our society [1–4]). Many foresee these changes as potentially being more far-reaching than those brought by the internet in the last two decades. If this holds true, it is certain that research and knowledge creation will also be affected by this. So, why is that the case, and what is this all about? More importantly, could knowledge creation benefit from it? Adoption of new technologies is good, however, it should not be an end in itself - there should be problems that could be solved. Currently, there is a credibility and reproducibility crisis in science [5–14].

In this publication, we will first provide some abstractions and technical points of *blockchain*, then discuss application examples, and finally (or lastly), identify problems in the research world that might be solved by means of *blockchain*.

Blockchain - the data structure

In a literal sense, blockchain is a computer data structure. A row of data blocks that are connected through a cryptographic function, the earliest description of this data structure dates back to 1991 [15]. If one changes the the content of one block, all following blocks need to change as well.

Blockchain became widely known by being the data structure (= ledger) in Bitcoin [16,17]. Bitcoin is an online payment processing tool that lacks centrality and trusted third parties such as banks or companies (like Paypal). It is distributed, the blockchain ledger is stored on many computers, and there is no single point of failure. In Bitcoin, long known concepts have been successfully implemented together and found wide use for the first time, as they are:

- Cryptographic tools such as public key cryptography and hashes
- Consensus mechanisms (=ways to settle discrepancies within same data sets that are stored on different computers) [18,19]
- Proof-of-work (=methods that uses laborious computer calculations to prevent a system from being flooded with ‘spam’ or fake identities) [20]
- Economic incentives (miners are paid with Bitcoins) to agree upon the right state of the blockchain ledger

Bitcoin continues to function reliably, despite several billion dollars worth of value now within its network. Breaking Bitcoin could potentially make large portions of this money accessible to the attacker.

Blockchain - the (r)evolution

However, payment processing is just one application of *blockchain* systems. To differentiate the characteristics of the upcoming online (r)evolution from the payment processing tool and implementation of Bitcoin itself, the term ‘blockchain’ is nowadays used in a much wider meaning. It stands for a system of organizing all kinds of digital things, be it files, databases, or assets, in ways that were first widely perceived in Bitcoin. Attributes of this system include:

- **Decentralized**
- **Distributed**
- **Immutable**
- **Transparent (provable to the external world)**

Before we explain in more detail what this means, let us first take a look at how we use computer services today:

For us nowadays, it is clear that whoever provides online services, be it a cloud storage service, a bank, an email provider, or a scientific publisher, needs to be trusted to do what they are supposed to do. We know that the provider could technically alter our accounts, change scientific results, or indeed our emails and files at will. We rely on those trusted third parties not to do so (Figure 1). Furthermore, we know that once data is digitalized, it can be arbitrarily changed at will without leaving a trace (e.g. by researchers).

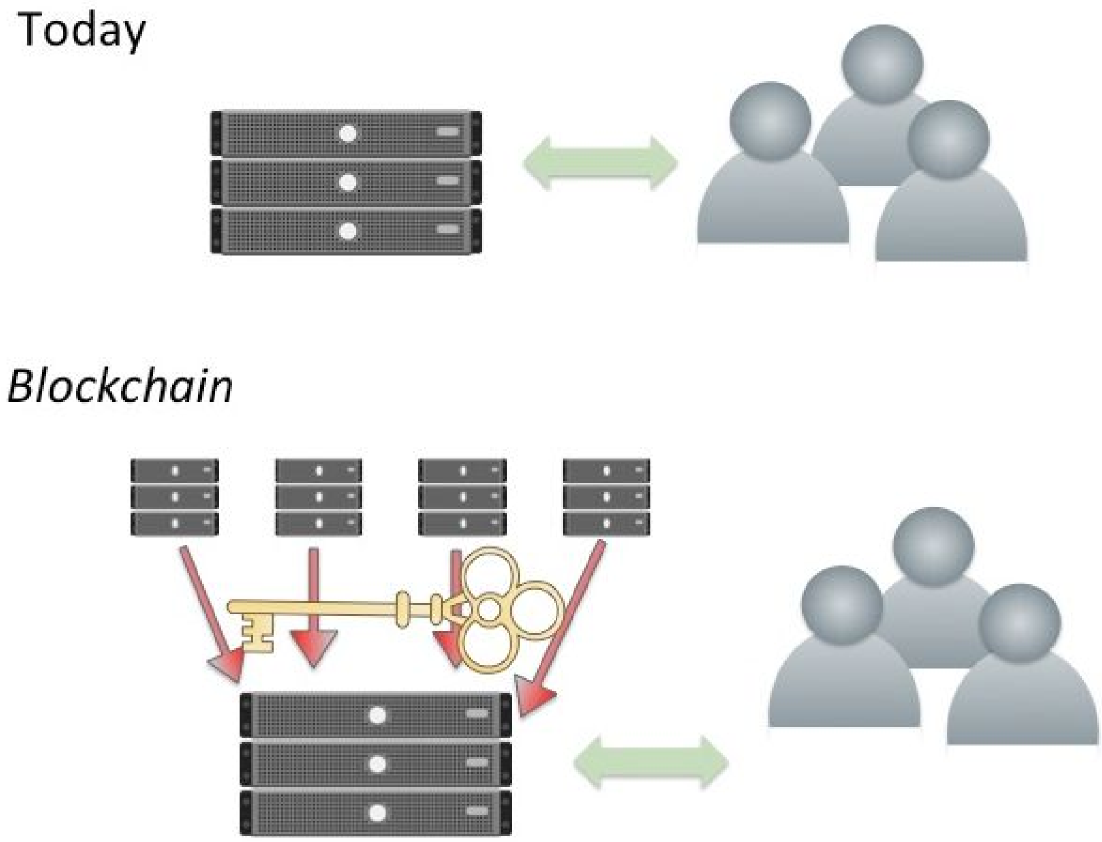

Figure 1: Today the owner (or researcher, academic publisher, data-repository etc.) has full control over their computer, data, and services they run (e.g. a database). After the blockchain revolution, this is no longer the case, as decentralized trust providing systems provide 'cryptographic power' to ensure the integrity of a computer service and authenticity of the underlying database.

After the *blockchain* revolution, this changes fundamentally. The following things may sound a bit nerdish, but they have far reaching implications and it is worthwhile understanding the terms - they will be used much more often in the future.

Decentralization means that there is no single point of failure: there is no computer system that can be switched off, censored, or otherwise blocked in order to stop a service.

Distributed means that there is no single hardware infrastructure holding the service. Often, this means that a copy of a database exists on several computers, however, it may also be the case that a database is split between many computers.

Immutability means that strictly speaking data cannot be changed. However, in practice, this means that data cannot be changed without leaving a trace. Most of the time, this means that old versions can be recovered and that any changes will be protocolled in a system. It is like comparing an excel sheet in which values can be changed at will to a piece of paper. On paper a trace of every manipulation is left displayed (Figure 2).

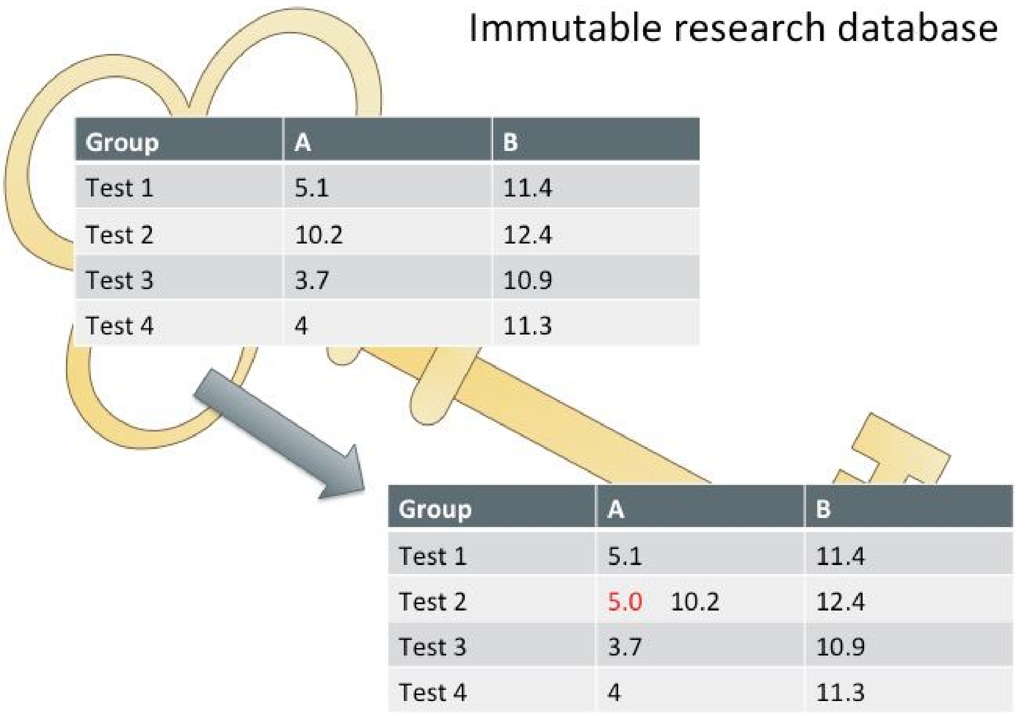

Figure 2: *Blockchain* can make research databases immutable, meaning that they cannot be changed without leaving a trace.

Transparent (provable to the external world) means that a computer program is really running as is publicised (advertised). At the moment, we must rely upon others to calculate things (e.g. impact factor) or to apply post-processing tools to research data as they claim that they are doing it; after blockchain revolution, this will be transparent and provable to peers.

In what follows, blockchain will refer to the data structure and *blockchain* will refer to a system that comprises the above features.

Blockchain revolution - the technical implementations

Blockchain characteristics are being realized through cryptographic methods and consensus protocols. All of these are long since known, and were initially described to handle hardware failures, e.g. inside big databases [18]. Nowadays, they are used to provide trust among sometimes unknown and distributed entities.

Blockchain systems rely on many discrete computers to secure the *blockchain* system and provide the trust or security that is today provided by administrators (Figure 1). These computers can be anonymous entities (miners) which are incentivized to do so by intrinsic value inherent to the system (e.g. Bitcoin, Ethereum) [21]. They can also be defined by a central authority. For example, the securing computers could be provided by trusted and independent research institutes [22] or governmental organizations. However, in contrast to what trusted third party administrators can do today, the blockchain-securing computers cannot alter data stored in the *blockchain* systems in an undetermined manner, even if someone wanted them to do so. They simply provide 'cryptographic power' so as to secure the *blockchain*. However, if a certain amount of them are compromised, data that is stored in a *blockchain* system becomes completely unreliable and mutable. This is not a bug, but an inherent characteristic of the consensus mechanisms. If they are selected carefully and guarded, such an event would be very unlikely.

Blockchain revolution - beyond Bitcoin

There are many Bitcoin-like blockchain systems. Focusing on their 'coin' aspect, they are called 'altcoins' [23]. Many are just copycats and/or scam attempts, but others provide very interesting new features and functionalities that extend far beyond payment processing. A discussion of these is beyond the scope of this article, and would actually be difficult to provide, since innovations and interesting new concepts are being published on almost a daily basis [24]. A list based on current market capitalization can be found here. Here, we will mention some that implement concepts or provide an organizational structure that are especially interesting for research.

A programming language is directly implemented on the Ethereum blockchain to run distributed, unstoppable, and provable applications [25]. This includes smart contracts [26] which can be used to realize distributed, autonomous applications and organizations [27].

Storj and MaidSAFE are also interesting concepts. They can be seen as *blockchain*-based, distributed cloud services to store data and files. Coins are used to incentivise resource providers who provide hard drive space and network bandwidth.

Namecoin is one of the first Bitcoin forks and is purposely built to store key-value pairs, in the foremost case, this is being used to register domain (.bit) names without a central entity like ICANN.

Steem is a blockchain-backed social media platform that pays internal steem value coins to content provider and curators (e.g. through 'commenting' or 'liking' of content). Steem combines concepts from social media with lessons learned from building crypto-currencies and their communities. An important key to inspiring participation in any community, currency or free market economy is a fair accounting system that consistently reflects each person's contribution. Steem is the first crypto-currency that attempts to accurately and transparently reward an unbounded number of individuals who make subjective contributions to its community (https://steem.io/SteemWhitePaper.pdf). Steem could provide a way to incentivize scientific efforts within the scientific community [28].

Most altcoins work on their own blockchain. However, to make things really confusing, all concepts could technically be implemented in one single blockchain, e.g. the Bitcoin blockchain (For example, the Ethereum concept is also implemented in the Bitcoin blockchain: here, it is called Counterparty).

Hyperledger project is a cross-industry collaborative effort, started in December 2015 by the Linux Foundation to support blockchain-based distributed ledgers. The project aims to bring together a number of independent efforts to develop open protocols and standards, by providing a modular framework that supports different components for different uses. This would include a variety of blockchains with their own consensus and storage models, and services for identity, access control, and contracts.

The scalability of most blockchain implementations, e.g. the amount of transactions per time, is limited compared to other, centralized technologies; the optimization of this scalability is a part of ongoing blockchain research. Sidechains are one option (e.g. LISK). Another option would be using standard database infrastructure with blockchain features on top of it (BigchainDB).

Blockchain revolution - and beyond blockchains

In the *blockchain* revolution, other systems that show characteristics of *blockchain* systems, such as being distributed, without a single point of failure, decentralized and immutable, and that are **not** based on a blockchain (the data structure), would exist. Actually, they could play a much larger role in the long term than actual blockchain systems.

IPFS (interplanetary filesystem) "is a peer-to-peer distributed file system that seeks to connect all computing devices with the same system of files. In some ways, IPFS is similar to the World Wide Web, but IPFS could be seen as a single BitTorrent swarm, exchanging objects within one Gitrepository." Research data or publications that are being stored in IPFS would be available without a centralized server and be very effectively distributed among reusers.

There are database systems that have blockchain characteristics. For example, BigchainDB is a "big data distributed database and then adds blockchain characteristics - decentralized control, immutability and the transfer of digital assets." (https://www.bigchaindb.com/whitepaper/bigchaindb-whitepaper.pdf). Many other companies exist providing similar solutions (e.g. ERIS).

Blockchain and the research cycle

In this section, we collect and propose applications of *blockchain in* science and knowledge creation. We organize this around the research circle (Figure 3). Ideas and concepts that are published are marked with a green X, while ideas that are newly introduced (to the best of our knowledge) here by us (see publication date of the living doc or its earlier version) are marked with a red Y. Copying of ideas and text from blog posts about *blockchain* for science and its unattributed reuse in scientific journals has recently caused controversy [29]. We expect established journals and authors to give appropriate credits in their upcoming articles about blockchain for science that includes *all means of current* publication methods.

Ideas

- X *Blockchains* provide a 'notarization' functionality. Through posting a digest (e.g. cryptographic hash) of a text, data, or general purpose file to a blockchain database, it can be proven that this file or text existed at a certain time point. From this digest, one cannot conclude on the topic or content of the text or file, but the owner of the text or file can always prove that he or she was in possession of the file at a certain time point. The time point is defined by the time the block was created in which the digest was posted. This concept is also named 'time-stamping' and 'proof-of-existence' [15]. One easily accessible implementation can be found here [30]. Researchers could post their ideas, research results, or anything else to a *blockchain* system to prove their existence at a certain time point [31][32].
- X For innovations, instead of sending faxes to the patent offices, one could provide a proof-of-existence by posting it to a *blockchain* database. [33]
- X Lab books could post digests to a *blockchain* system to make them immutable by means of time-stamped entries.

Proposal

- X A study design can be pre-registered to a *blockchain*, so that it would prevent the arbitrary alteration of study design after the experiment [34,35]. This can also prevent the arbitrary suppression of research studies from being published in case the results do not meet certain expectations (publication bias) [36]. A registration of studies is recommend to increase the value of research [5,9].

Experiment / data acquisition

- X Using *blockchain* technology, data integrity for approval studies for novel therapy or drugs can be proven to auditors.
- Y All research data that is acquired could go to a *blockchain* database (Figure 3). All data that is acquired during an experiment could then be available first to a certain audience. It could become openly available and could be reused by other

researchers. However, this must not necessarily be the case as a researcher could control who may access the data. For example, they could send research data (or representations (e.g. hashes) of it) to a *blockchain* system after initial acquisition, time-stamp it, and still keep it secret up to a certain time point. After this time point (e.g. final publication), they could then release cryptographic codes so as to make the research data publicly available. This could address one issue that is a reason for 'Why Most Clinical Research Is Not Useful' and could restore trust in research, which is currently low, because `research is not transparent, when study data, protocols, and other processes are not available for verification or for further use by others.` [37,38].

- Y Research data could be acquired by a 'blockchain-ready' sensor (microscope, MRI-scanner, Western-Blot scanner, etc.) in an internet-of-things [39]. Such a sensor would directly encrypt the data (potentially on a hardware level).

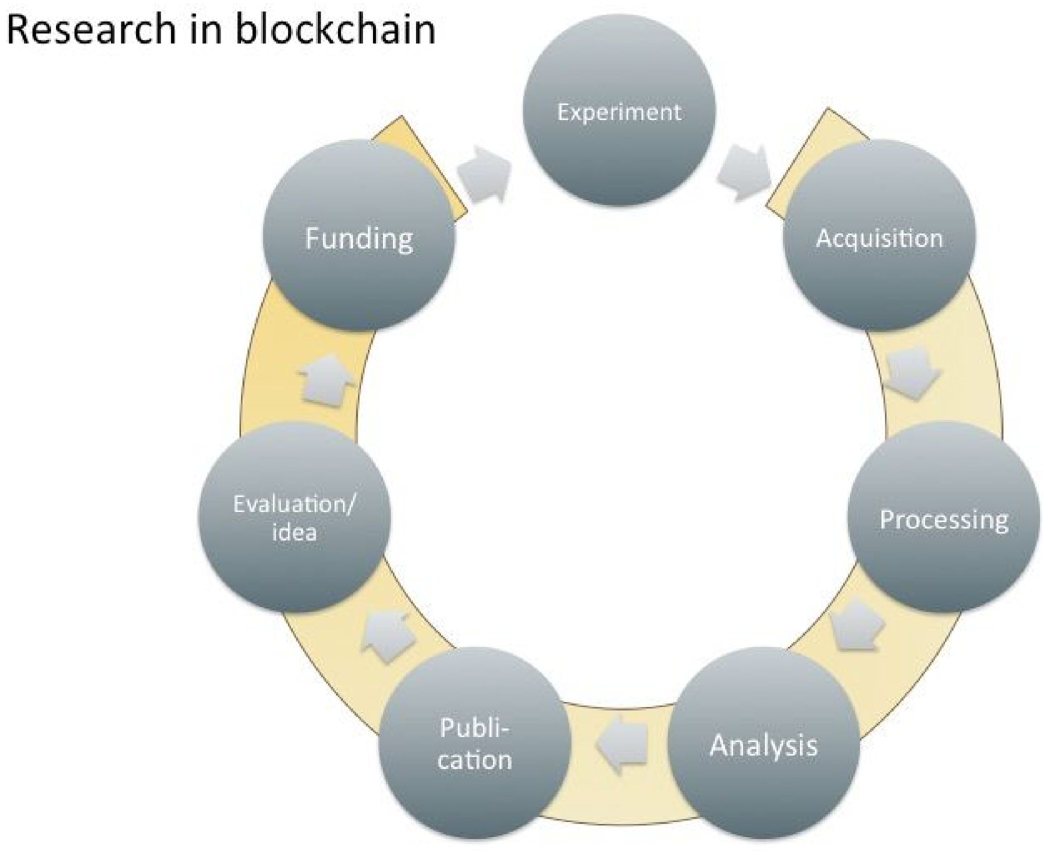

Figure 3: Large parts of the research cycle can make use of *blockchain* (yellow arch); only the experiment itself cannot. From data collection onwards, the rest of the research circle would then become immutable, comprehensible, and externally provable. This would make larger parts of the research cycle open to scientific self-correction and may make more research results reproducible, true, and useful.

- Y As soon as the data is stored in a *blockchain* database it can be rendered immutable. This means that it cannot be manipulated without leaving a trace

(Published at the same time [40]). This can prevent arbitrary data manipulations, be it conscious or inadvertently (e.g. by biased researchers). For example, researchers can prove that they did not drop 'outliers' from the initially acquired datasets, or if so, they would then need to explain as to why they dropped them. Research result manipulations (resulting from whichever motivation it may be) at the level of the initial raw data acquisition would require much more effort than data manipulation in a post-processing sheet - which might only require changing a single digit or image. This could improve scientific reproducibility and may make more research results true.

- Y This would significantly extend the ideas and motivations of open data research, since the integrity of the research data can be proven by means of *blockchain*.

Data management / analysis

- X Bitcoin and many altcoins use large amounts of computational power for the proof-of-work algorithms. The mining incentives could be set in a way so that some of it is also being used for laborious scientific calculations [41].
- X The recommendation to reduce waste in science which reads: 'Public availability of raw data and complete scripts of statistical analyses could be required by journals and funding agencies sponsoring new research' [5,37] could be realized through *blockchain*.
- Y The analysis of the data, postprocessing, and statistics can be protocolized in the *blockchain* database and proven to peers. Potentially, statistical analyses and other post-processing steps can run on a *blockchain* system and become provable to the research community.
- Y Above´s concepts allows anyone to propose (and demonstrate) a different way of doing an analysis. This provides the opportunity for science to act more like a "free-market" where there may be a lab that is really good at producing hypotheses and methodologies, another that has the capacity to run the experiments, and yet another that excels in statistics (Zach Ramsay, personal comment).

Data sharing

- X Through *blockchain* databases, data can be stored and shared. Blockchain technologies can provide a redundancy and availability of data, e.g. IPFS. This would be a great way to realize open data research.
- X Associated cryptography can assure that the data is only available to certain people, groups and from defined time points onwards. If subject anonymity is of concern, this can be organized by means of using strong cryptography, e.g. in case of healthcare data [42], even without a trustee.
- X Blockchain technology could also be used to 'store' grant money for research and only release it after the publication and/or reproduction of research data/results [35].

Publication

- X Publications can be notarized in the blockchain, meaning they can be time-stamped.
- X A decentralized peer-review group (DPG) has been proposed to assure that quality of research [43] or peer-review can be organized using *blockchain [32]*.
- X Ideally *blockchain* systems will be used to time-stamp and attribute publications and especially low-threshold dynamic publications [44], such as wikis, in which every change can become time-stamped and attribute in *blockchain* (many publications, including personal communication with Lambert Heller).
- X Publications and comments can be shared on a social-media platform and likes, comments, or other interaction can then result in pay-out of coins to incentivise research result sharing [45].
- Y *Blockchain* systems make it possible to publish research anonymously or with a second online identity - and yet one could still get money or other research impact appreciation for it [46,47]. This may make sense if very controversial results are generated and scientists are afraid that this results are 'too disruptive'. Due to the fear of suppression by peers in the complex research social network, they might be afraid to publish such research results or interpretations with their full name.
- Y In the form of a 'whistle-blowing' function, this could also contribute to the internal self-correction of scientific misconduct. If wanted, publications can be claimed later, and the researcher can replace a name placeholder with their real name.
- Y *Blockchain* technology could be used to 'sign' anonymous publications with credibility providing 'signatures'. For example, the publication could be signed with 'An english professor in physics with a Hirsch factor of 15' or 'A German medical doctor'. A research institute could issue cryptographic certificates to do so [48,49].

Research evaluation

- X A *blockchain* (e.g. Namecoin) can be used to register and maintain unique research identifiers like (ORCID) or links to publications or datasets (like DOI) [50].
- X A social network community that incentives content creation and curations can be used to incentives idea, data and results research sharing [28].
- Y The quality of research is currently assessed using impact factor and other altmetrics (like RG score, Altmetric). One has to trust the third parties issuing these to correctly calculate such metrics. With *blockchain* technology and smart contracts, this could change so that the way the metrics are being calculated is externally provable.
- Y A 'research currency' as an incentivization system to 'make more published research results true' as described in [6] could be realized using *blockchain* technology and without a trusted third party.
- Y Science reputation systems can be built using blockchain without a trusted third party.
- X As such, a Decentralized Autonomous Academic Endorsement System has been proposed and interesting implementation ideas and next implementation steps have been disclosed [47].

Research funding

- X Prediction markets [51] to confirm results and to incentivise research could also be used in science [52–55] and could be implemented on *blockchain*.
- X Blockchain could be used to realize a `money-back` functionality for irreproducible research results [40].
- Y New methods of research fund distribution could easily be realized with blockchain technology and smart contracts. For example, a system in which researchers redistribute 50% of their research money among peers [56] can be realized using smart contracts [57]. Research funds could be sent completely anonymously, without trusted third parties.
- Y Similar to a DAO (distributed autonomous organization)[27,58] that could complement functions provided by companies, a DARO (distributed autonomous research organization) can be used to complement research funding agencies.
- Y Concepts similar to colored coins could be used to relate research funds to some conditions, even if the distribution mechanism is anonymous and 'black boxed' on *blockchain*. For example, a funding agency could direct the research funds to certain research fields, locations, or institutions. Only researchers that fulfill those requirements would be able to claim those coins.

Challenges

One fundamental challenge of *blockchain* is the real-world/blockchain interface problem. How can the blockchain world learn about real-world facts ? One instance of this problem is the fact that one has to trust the researcher, sensors, etc. to correctly collect the initial research data. Another example of this problem is the question as to how individual researchers are recognized within the blockchain world and how their identity is confirmed. This could be done by research institutes (often an institutional email is used to this end, or indeed cryptographic certificates) or other entities that already have a large database of researchers (e.g. online social networks or publishers).
The current legislation did not foresee the *blockchain* revolution. Many legal and tax questions remain currently unresolved. These challenges are not specific to blockchain for knowledge creation, but they also exist in other applications of blockchain technology, and are an exciting, evolving field.

Conclusion

To make one thing clear, first of all, all abovementioned functionalities and concepts could also be realized without the *blockchain*, if all participants are fully trustworthy and would act purely in the overall aim to produce good scientific knowledge. However, the research world has so many different stakeholders and developed cultures that might not be in best alignment with their initial noble aim to produce scientific knowledge anymore. The *blockchain revolution* is a game changer and hence chances are that this can be used to break with inappropriate cultures. Indeed, blockchain technology could be used to 'Increase value and reduce waste' [5], by opening the research cycle to scientific self-control beyond just the final publication and might therefore be a fix to the current reproducibility crisis in science.

This publication is an extension of an earlier, pseudonymous, cryptographically signed and hash-time-stamped publication [59]. The living document can be found here, including other instances and publications of this document. CC-BY and attributed 1:1 figure and text reuse most welcome.

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