Article

DeSci - Decentralized Science

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Abstract: Fundamental science and applied research and technology development (RTD) are facing significant challenges that particularly compound to the notorious credibility, reproducibility, funding and sustainability crises. The underlying, serious shortcomings are substantially amplified by a metrics-obsessed publication culture, and a growing cohort of academics fishing for fairly stagnant (public) funding budgets. This work presents, for the first time, a groundbreaking strategy to successfully address these severe issues; the novel strategy proposed here leverages the distributed ledger technology (DLT) "blockchain" to capitalize on cryptoeconomic mechanisms, such as tokenization, consensus, crowdsourcing, smart contracts, reputation systems as well as staking, reward and slashing mechanisms. This powerful toolbox, which is so far widely unfamiliar to traditional scientific and RTD communities ("TradSci"), is synergistically combined with the exponentially growing computing capabilities for virtualizing experiments through digital twin methods in a future scientific "metaverse". Project contributions, such as hypotheses, methods, experimental data, modelling, simulation, assessment, predictions and directions are crowdsourced using blockchain, and captured by so-called non-fungible tokens ("NFTs"). The so enabled, highly integrative approach, termed decentralized science ("DeSci"), is destined to move research out of its present silos, and to markedly enhance quality, credibility, efficiency, transparency, inclusiveness, sustainability, impact, and sustainability of a wide spectrum of academic and commercial research initiatives.

Keywords: digitization; virtualization; digital twin; blockchain; crowdsourcing; decentralization; non-fungible token; NFT; smart contract; oracle; tokenization; digital ownership; consensus; governance; trust; incentivization; staking; reputation systems; reproducibility crisis; exponentiality; digital twin; metaverse; DeSci; decentralized science; citizen science; open science; distributed ledger; digital scarcity

1. Introduction

Blockchain ranks amongst the fastest expanding technologies mankind has ever seen. Comparing user numbers, global blockchain adoption compares to the level of the internet in the second half of the 1990s, but at a markedly stronger growth rate. Its ingenious concept was conceived by an – arguably – still unknown persona or group publishing a famous white paper [1] "Bitcoin: A peer-to-peer electronic cash system" under the pseudonym "Satoshi Nakamoto" [2], likely in response to the global banking crises in the later part of the 2000s.

Its underlying blockchain technology provided a practical solution to the double-spending dilemma pertaining to digital assets, specifically by its unspent transaction output (UTXO) accounting model [3]. Bitcoin [4, 5] and its technological precursors [6-13], or objective-sharing initiatives [14-16], thus laid the foundation for digital scarcity in public decentralized networks, which nowadays extends way beyond cryptocurrencies into a whole slew of other, still emerging digital asset classes. Over now more than a decade, Bitcoin has continued to remain the dominant player amongst a plethora of cryptocurrencies, possessing a total market capitalization in the vicinity of 1 trillion US$ (status:

December 2021), which is roughly on par with common fiat money [17], like the Russian Ruble or the Swiss Franc.

Another seminal technological milestone was the launch of the Ethereum blockchain [18] with its (quasi) Turing-complete Ethereum Virtual Machine (EVM) [19]. Its so-called "smart contracts" [20, 21], occasionally also referred to as "programmable money", set the foundation of decentralized finance ("DeFi"), which, after only a few years, emerged into a rapidly growing industry. Moreover, Ethereum set the groundwork of an entirely new, burgeoning asset class called non-fungible token [22-28]; these "NFTs" are also traded on a growing number of platforms [29-41]. While crypto-currencies themselves are, by their very design, interchangeable, in a sense that swapping equal amounts of the same coin leaves the economic impact for their owners unaltered, NFTs are unique, and their rarity is secured by code.

NFTs are touted to play a paramount role in the ongoing uprise of the metaverse [42], a notion coined in a 1992 book by Neal Stephenson [43], and later, for example, picked up by the 2018 Spielberg film "Ready player One" [44]; in 2021, the metaverse garnered major attention in the general public through the rebranding of a major social media giant [45, 46], and the accompanying, rather mind-blowing dynamics in their individual valuation and supporting blockchains [47, 48].

Since the mid-2010s, these NFTs have been used to capture, trade, and immutably track provenance and (digital) ownership of assets via a tamper-proof, decentralized blockchain; these NFTs may represent physical items like property, e.g., real estate [49, 50] and artistic paintings [51], virtual collectables, e.g., digital graphics of kittens [52], apes [53], pixelated "cypherpunks" [54], collectibles and fan tokens [55], in-game items [56], and virtual land [57, 58], or "negative value" assets, e.g., loans, burdens and other responsibilities [59, 60] with the potential to decisively disrupt present finance systems.

While initially rather modest, the market volume for NFTs has shot up to US$40 billion just in 2021 [61]. However, this unprecedented type of asset is still in its adolescence, potentially somewhat hyped phase, and it is thus naturally prone to significant volatility. While a clear value proposition still needs to consolidate, it is commonly accepted that NFTs well align with the massively increasing digitization and virtualization of our professional and private lives, and the rapidly evolving metaverse (which, in the context of blockchain technology, is occasionally also referred to as "cryptoverse").

From a historic perspective, the advent of the internet of blockchains with its disruptive concepts of decentralization and tokenization for an internet of value ("IoV") [62, 63], sometimes referred to as Web3 or Web3.0 [64, 65], might be viewed in the context of the multi-stage industrial revolution; commencing in the years 1760 to 1820 / 1840, the first industrial revolution saw the transition from hand production methods to machines, new chemical manufacturing and iron production processes, the increasing use of steam and water power, the development of machine tools and the rise of the mechanized factory system [66]. The second industrial revolution saw rapid standardization and industrialization from the late 19th century into the early 20th century [67].

The following "Digital Revolution" coined the second half of the 20th century, characterized by a shift from mechanical and analogue electronic technology to computing, digital record-keeping and communication [68]. Hallmarks of this third revolution are the mass adoption of the internet / world wide web ("WWW"), online shopping, smartphones and apps, social media, and the merger of artificial intelligence (AI), big data, the internet of things (IoT), and various scientific disciplines. The ongoing automation of conventional manufacturing and industrial practices, using modern smart technology is often termed "Industry 4.0" [69].

It seems that these technological "revolutions" launch at increasing speed, narrowing their succession from centuries at the start to, nowadays, only a few decades. In the eyes of many futurists, a strong candidate for the next, or fifth, still somewhat silent industrial revolution, might pivot around "decentralization" and "virtualization".

Also, the century-old scientific culture has notably evolved over the recent decades; there is an increasing institutional pressure on academics to optimize their publication

outputs towards sometimes disputable metrics, which tend to favor quantity for quality. In addition, while originating from good intentions, funder-driven open-access initiatives have produced a plethora of new journals and conferences, which often display a "predator" mindset towards maximizing the collection of fees from authors, while grossly deprioritizing scientific integrity.

As an unquestionably detrimental fallout, researchers are implicitly pushed to artificially spread out their findings over several publications, so that an abundance of manuscripts hits the finite bandwidth of readers, leaving even possibly valuable efforts broadly unnoticed. Moreover, a limited number of qualified referees tend to increasingly opt out of an exuberant number of requests for review, so the delicate assessment process is exhaustively delayed, or delegated down the ranks to less experienced experts.

The interplay of the rather manic hunt for metrics and unhealthy proliferation of subprime publication outlets is accompanied by an insufficient methodological and experimental verification by independent peers, and, occasionally, even by the very authors. Common malpractices intervening with sound replication by other groups are rooted, for instance, in improper experimental design, insufficient documentation of methods, incomplete provision of (raw) data [70, 71], inappropriate statistical analysis [72-75] and deceptive researcher bias [76-78]. Such highly undesirable trends are associated with the infamous "reproducibility crisis" [79-84], which, depending on the field, leads to unfair academic competition, significant economic losses, and even fatal damage to patients.

Furthermore, rising economic pressures on research institutions to raise external funding entangle their researchers in very time-consuming grant preparation. It is an open secret that these statistically overwhelmingly unsuccessful efforts are usually supported by contracting costly ghost writers that tend to be largely unfamiliar with the core research topic, but draw down a considerable share from the already tight research budgets in many academic environments. Consequently, steadily increasing numbers of high-caliber proposal submissions meet severely limited and rather static budgets through publicly funded programs, causing counterproductive frustration by researchers, and a perceived poor, or even objectively negative return on investment [85].

This paper outlines a new avenue to substantially improve research endeavors, encompassing aspects of funding, dissemination, accessibility, management, governance and exploitation, by the blockchain technology stack that has swiftly emerged since its vastly unnoticed origins in the later 2000s. The proposed concept builds on its foundational, decentralized setup, trust generation, tokenization, combined with the swiftly expanding simulation capability in science and RTD through digital twins [86-88]; these are virtual representations which serve as the real-time digital equivalents of physical objects or processes. At the present state of the art, such digital twins may be mostly available in engineering and physical sciences, with rapidly accelerating progress to be anticipated in the life sciences. Note that a few promising and similar minded initiatives have already formed, focusing on the publication aspects [89-92], data exchange [93], and broader topics such as funding, replication, NFT-tokenomics, and DAOs also covered in this work [94-98].

The next section covers relevant aspects of blockchain technology, specifically tokenization, oracles, prediction markets, automated market makers (AMMs), curation and decentralized finance ("DeFi"), which the traditional research might not be very familiar with. Based on these ingredients, the novel concept of decentralized science ("DeSci") [99, 100] is developed, including the toolbox comprising NFTs, reward and reputation systems, crowdsourcing of research, community involvement by voting, arbitration and governance schemes. (Note that the term "DeSci" is not uniquely defined, yet, and has been used in somewhat different contexts [101-104]). Owing to the highly interdisciplinary character of DeSci, terminology that may not be familiar for the general reader, but which would be too complex to intersperse in the text and thus compromise readability, has been amended with online links.

2. Blockchain

By virtue of its immutable, fully algorithmically controlled consensus mechanisms, the distributed ledger technology (DLT) blockchain provides solid, battle-tested trust between mutually unknown parties in a decentralized online environment without the need for middlemen. The integrity of the blockchain is secured by demanding "skin in the game", i.e., the staking or personal investment from participants, and rewarding good behavior, typically via its native digital assets and tokens; with a slight ironic touch, this self-sustaining mechanism may arguably be viewed as the largest-scale behavioral incentivization program in human history.

In conventional consensus architectures like proof-of-work (PoW) [105] in Bitcoin and a few others [106-108] which are mainly focusing on payment function, the staked asset are mined and awarded for investment in (specialized) computing infrastructure and (electric) energy needed for solving cryptographic puzzles; many latest-generation smart-contract blockchains, like Ethereum (after its next major upgrade expected in the course of 2022) [109], Cardano [34], Polkadot [35], Solana [36], Terra [110], Avalanche [111], Algorand [112], Stellar [113], Cosmos [114], Near [115] or Fantom [116] employ sophisticated and extended (delegated / nominated) proof-of-stake (PoS) [117, 118] methods that are secured by recruiting the collective of their users to amass a critically sized asset pool. In either case, gaining a 51% majority is commonly required for being able to deliberately manipulate decision making; gaining such ruling power on these blockchains would involve massive financial means, rendering such nefarious tampering harshly loss-making, and thus pointless, at least for economically motivated actors (other than rogue nations).

2.1. Tokenization

The possibility to immutably register and time stamp ownership of assets on a tamper-proof distributed ledger has opened up the paradigm of tokenization   [24, 65, 119]. Modalities of such tokens are transparently encoded in smart contracts and deterministically executed on the blockchain's virtual machine. A token economy directly enables access to crowdfunding projects, and for the general public to take part in potentially highly profitable investment tools, that were traditionally exclusive to the financial elites.

Fractional ownership through tokenized economies is slated to blur the lines between owner and customer; for instance, social media giants like Facebook [120] (now "Meta", not to be confused with "Metamask" [121], the long-established cryptocurrency wallet [122] for Ethereum) presently offer a value by connecting to the general or shared-interest communities of account holders, while financially siphoning off profits arising from huge network effects. In a tokenized, decentralized world, (social) network business models could be run by code and community governance, thus letting the crowd, that epitomizes the basis of value creation, reap the commercial fruit from its own inputs.

2.2. Oracles

The ability of blockchain technologies to interact with the world outside its own ledger requires credible external data feeds, called oracles [123-129]. Such external information might be provided from different types of sources and trust mechanisms. For instance, exchange rates for currency trading pairs or stock values are intrinsically available in digital form, while natively analog information, such as weather, traffic statistics or time, needs to be converted for onboarding. Due to the finality of smart contracts that are triggered by data inputs procured by these oracles, consensus needs to be fortified by trust-endowing mechanisms, e.g., by sourcing data providers and validators from a sufficiently large community of independent actors, and asking them for staking, and possibly also time-locking, their crypto- or reputation tokens, to bestow credibility to their data contributions to the oracles.

2.3. Prediction Markets

It has been shown in various contexts that the wisdom of the crowd can predict the outcome future events with astonishing accuracy [130-140]. Community engagement can thus generate tremendous value for economic decision making depending on, e.g., election outcomes, sport results, or societal trends. This work investigates how similar staking mechanisms, that are already applied for bestowing trust to PoS blockchains, can also be harnessed to incentivize the sourcing of expertise and crowd intelligence.

2.4. DeFi

Leveraging collective wisdom in combination with liquidity from the crowd thus orchestrates the price finding in spot and futures markets for trading physical or digital commodities and assets through order books at the backbone of traditional finance ("TradFi"); they inform decision making on investments or issuing loans in banking, for putting a price tag on insurance policies, or for bookmaking in the betting industry.

Similarly, automated market makers (AMMs) are at the hub of decentralized finance ("DeFi") [141]. The widescale, sometimes rather turbulent success story of DeFi over the recent years underpins the potential for value creation through blockchain technologies. Nowadays many established financial institutions take a more positive stance on the crypto space [142-144]. Decentralized exchanges ("DEXes") [145, 146] and decentralized applications ("Dapps") [147] are blossoming, providing barrier-free global access to investment vehicles, that historically have been a privilege of the wealthy few, while the vast majority of the global population that either unbanked or exposed to high inflation of their domestic currencies.

3. Decentralized Science (DeSci)

The objective of this paper is to scope viable avenues for fundamental science as well as more commercially focused research and technology development (RTD) how to capitalize on the continuing "blockchain revolution". For the following considerations, it is important to factor in the strong trends towards augmented (AR) and virtual reality (VR) in the "metaverse" [42, 46], which represents a strong candidate for progressively influencing science and RTD; this movement will be substantially fostered by the rapidly increasing public availability of massive computing resources and data sets, e.g., through cloud-based resources [148-152], of fab labs [153] for making "things", of open accelerator biochemical laboratories, and the proliferation of participatory research models [154-157]. Furthermore, decentralization through blockchain innovation dovetails with other exponential technologies, such as artificial intelligence (AI), the internet of things (IoT) [158, 159], big data [160], digital manufacturing [161, 162], robotics, and the life sciences.

3.1. NFTs

Similar to the ownership of virtual assets, crowd engagement involves systematic record keeping of the diverse contributions that are, in their entirety, crucial for the success of research projects. Similar to creative art, such as paintings or music, scientific work delivered by individuals or entities to the project should be captured by NFTs. These intellectual artefacts may capture ideas, inventions, methods, materials, processes, modelling, program code, and, last but not least, experimental and simulation results, and their characterization, validation and optimization through new parameter sets. In addition, accompanying activities, e.g., documentation, reporting, publication, communication, education, promotion, as well as commercial and public engagement, should be recorded on the ledger.

In the event where data is to be gathered for clinical research, patients may provide their own samples; similar to current practices in the domain of genomics [163], patients may then be entitled to a share of potential commercial revenues according to the value of the data that can be attributed to them. Evidently, as for traditional science, e.g., involving animal experiments or clinical trials, such studies must also be carried out under the highest ethical, regulatory and privacy-preserving practices possible.

3.1.1. Content and Structure

The foundational idea behind DeSci is that, in a similar way to creative art or property, different types of research outcomes are represented by NFTs; these contain a set of basic elements outlined in **Error! Reference source not found.**: creator and owner, terms and conditions for use, distribution algorithm of rewards and potential slashing. These contributions are documented, e.g., in the form of a report that details methods and parameters for proper reproduction of the posted experimental or simulation results, a knowledge-graph [164] providing semantic context for facilitating machine reading, and a link to an off-chain depository for relevant data; various decentralized storage platforms [165-170] distinguish by their persistence mechanism,   incentive structure, data retention enforcement, level of decentrality, and consensus finding scheme [171].
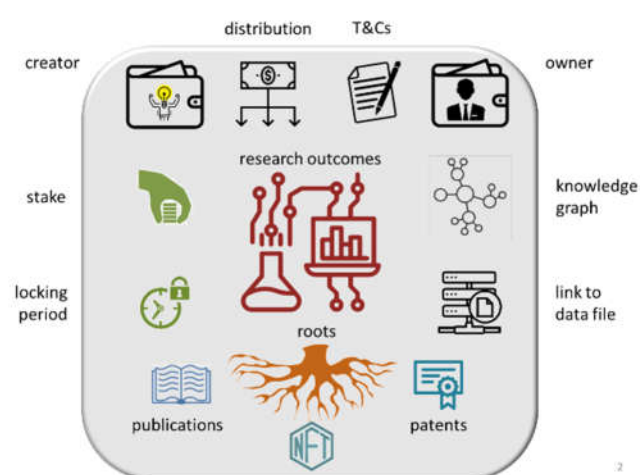

Figure 1. Proposed structure of NFTs representing research outcomes. A standard should be defined for a project or DeSci as a whole, which systematically captures information related to the research outcomes, its embedding into the state-of-the art and tokenomics.

In the same way as scientific publications and patents, NFTs should point to relevant state-of-the-art, including other NFTs; this structured NFT content will also support manual or (semi-)automated linking to other preceding and upcoming NFTs. This way, NFTs may be viewed as an advanced version of IP [172] rights where underlying, intangible creations of the human intellect may not only be claimed, but also be executed, e.g., in terms of automated payments triggered by oracles connected to smart contracts. Further NFT fields also keep a dynamic record of the mandatory (minimum) stake and locking period of the creator and / or owner, as well as tokens locked to the NFT by the crowd to be utilized in reward or slashing algorithms, as stipulated in the project descriptor and encoded in the blockchain executing transactions.

Scientific or commercial RTD projects are commonly organized in work packages (WPs). With their features compiled in **Error! Reference source not found.**, the outcomes of WPs may be represented by NFTs, and the project itself as a collection of interconnected NFTs. So-called "IP-NFT" constructs have been elaborated, with current emphasis on managing data ownership and access in the biomedical space, specifically for development of therapeutic drugs [173-175].

However, each project might have its own requirements and preferences on how to handle its IP, such as methods, program code, data or designs. There are various open-source license constructs available [176]. Blockchain may also preserve privacy, e.g., of data sets, and also to robustly time-stamp IP to safely document prior art, essentially playing the role of a tamper-proof electronic lab book for recording proof-of-knowledge or freedom-to-operate for an invention. Eventually, the NFTs may set the foundation of a patent application, which would mainly make sense in case competition ought to be mitigated or royalties generated in more commercially focused projects. For initiatives pursuing public Commons [177, 178] under open-source / open-access policies for outcomes,

seeking patent protection might not necessarily be required. The underlying blockchain technology would also facilitate time-locking or restricting access to IP-relevant project information, for instance, by deploying privacy preserving techniques like multiparty computation ("MPC") [179] or homomorphic encryption [180]; these cryptographic techniques would still allow its use for computation without disclosure of such private or proprietary data.

3.1.2. Crowdsourcing Research Work on NFTs

Error! Reference source not found. sketches how NFTs are generated in a community-based, participatory research approach. The project owner defines quantitative key performance indicators ("qKPIs") to accurately define the technical objectives of a WP / NFT, a possibly multi-stage scheme for pre-selection and eventual ranking of multiple submission, and delineates the formal framework, e.g., on the required stake, timelines for delivery, and the reward and slashing procedure. Governance and arbitration panels (see designated section further below) may be part of the decision-making structure.
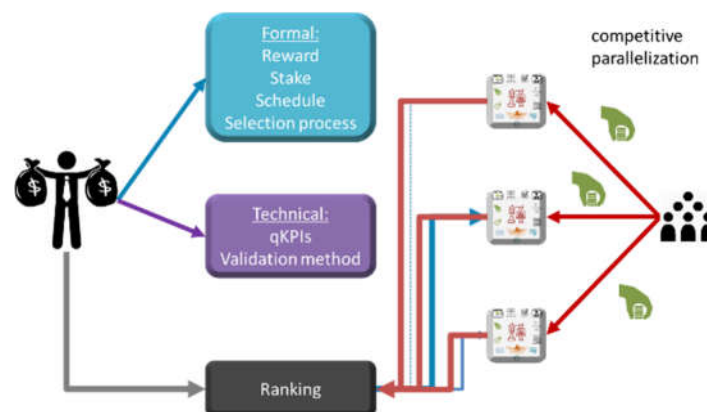

Figure 2. Project as a collection of work packages (WPs) with their research outcomes represented by NFTs. Crowdsourcing of quality outcomes is incentivized by bounties that are posted with reward schedules and technical specification on KPIs and their validation. Reviewers are reworded for ordering the submissions from the crowd in a competitive parallelization process.

Error! Reference source not found. schematizes the idea of crowdsourcing WPs by expressing its outcomes via NFTs. The project owner initiates the process by posting technical requirements in terms of quantitative key performance criteria (qKPIs), selection process, staking and reward schedule. In response, the crowd submits proposals that they need to stake for bestowing credibility, and to discourage spamming; the proposals received are then ranked, either directly through the owner, or by a predetermined mechanism, e.g., involving a committee or public vote. A single or a cohort of proposals are then charged to carry out the WP and achieve the targets expressed as qKPIs, e.g., in a competitive process.

3.1.3. Onboarding of NFTs to Projects

The selected initiatives then present their outcomes in form of a preliminary NFT that is to be evaluated for its ranking amongst competing submissions, and its introduction to the project (**Error! Reference source not found.**). The creator and / or owner of the pre-NFTs are obliged to support the credibility of their research outcome by a time-locked stake. The crowd, ideally comprising of independent experts, is then invited to thoroughly validate the NFT, and strengthen the impact of their assessment by their own "skin-in-the game".
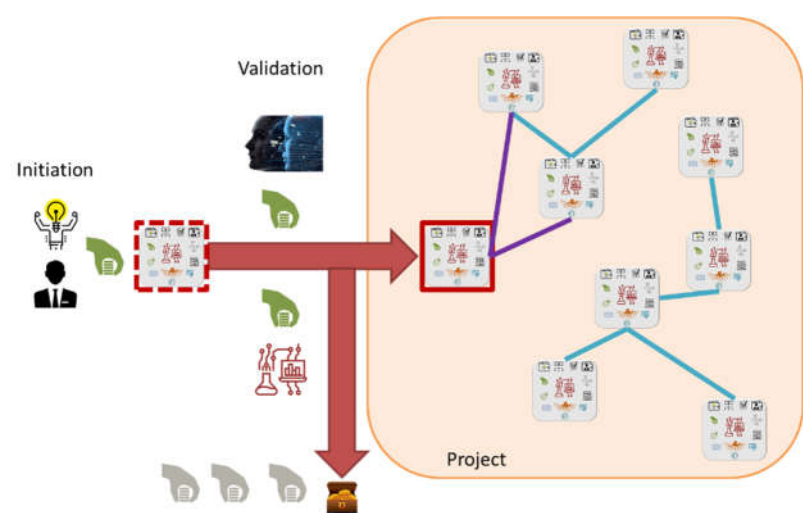
Figure 3. Introduction of new research NFT into science or RTD project. Any member of the crowd can submit an NFT solving the challenge of a work package specified by the project. Other members of the crowd independently validate the results. All these stakeholders put down a potentially time-locked stake to bolster the credibility of their inputs. A consensus process then dismisses or accepts the new NFT into the project results, represented by a network of NFTs.

A consensus mechanism that is specified within the project descriptor then decides on the quality and credibility of the new NFT, e.g., by a stake- and time-lock-weighted majority vote; the process may be based on decentralized identification (DID) [181, 182] for assigning crypto-wallets to individuals, and (optionally) on quadratic funding / voting principles [183, 184] to somewhat lower the influence of economic heavyweights ("whales"). The stakes are then either multiplied and issued, or (partially) lost to the project treasury, depending on a positive or negative outcome of this stage.

3.1.4. Connecting and Appreciation of NFTs

Once onboarded to the project, a new, community-approved NFT is embedded into the network of existing NFTs (**Error! Reference source not found.**). Starting with the root information provided in each NFT (**Error! Reference source not found.**), links can be added by their owners, or the crowd, through time-locked stakes at both ends of the connection. The general idea is that the product of committed, time-locked stakes enter the algorithm for issuing (one-off or periodic) rewards of an NFT (**Error! Reference source not found.**).
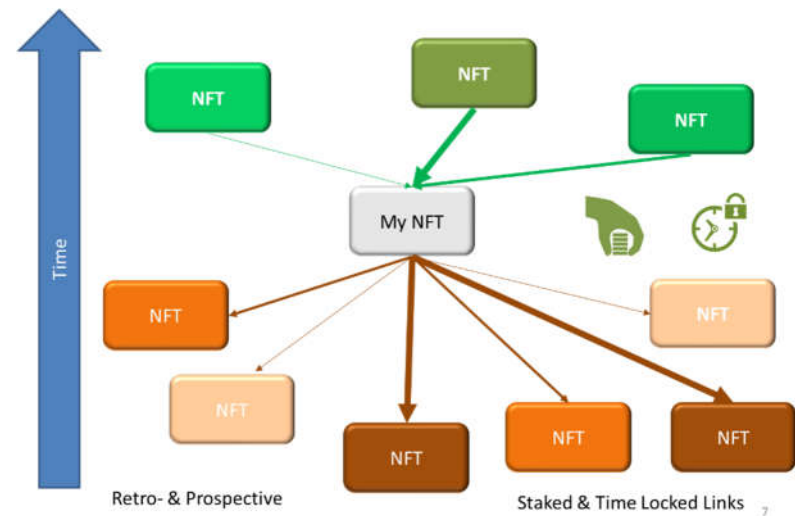

Figure 4. Anchoring of research NFT in existing project network and connection to future NFTs through staked and time-locked links.

In the suggested model, the overall staking value at the ends of each link are pairwise multiplied, and then aggregated over each NFT (**Error! Reference source not found.**), possibly modulated by non-linear factors that saturate towards high values [184].
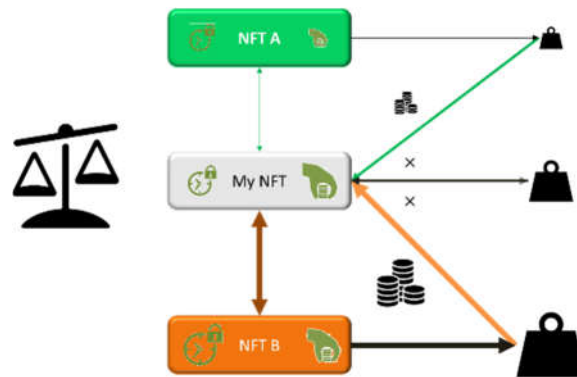

Figure 5. Rewarding of NFTs to stakeholders after their acceptance to the project. In its most basic implementation, each link from a given "My NFT" to other members in the project's NFT network is rewarded in proportion to the total amount staked on the NFTs at its ends.

So, for instance, all N NFTs of the project possess a total stake of S_i may be indexed by $i, j \in \{1,2,3, \dots, N\}$. A (symmetrical) binary matrix $\Theta_{i,j}$ is filled displays a 1 at the position (i,j) for a connection between i and $j \neq i$, otherwise zero. In the most basic implementation, the value of each NFT i

$$V_i = \frac{S_i \cdot \sum_{j=1}^{N} \gamma \cdot \Theta_{i,j} \cdot S_j}{\sum_{i=1}^{N} S_i \cdot \sum_{j=1}^{N} \gamma \cdot \Theta_{i,j} \cdot S_j} \cdot T \qquad (1)$$

is then derived from relative impact and the value of the entire project treasury T while setting γ to unity. In a more refined approach, this factor $\gamma = \gamma(N, S_i, \Theta_{i,j})$ may be a function, which, for instance, similar to quadratic funding [183, 184], may be configured for suppressing monopolization by a dominant player, in favor of decentralized decision making in a diverse community. Furthermore, the parameters $N, S_i, \Theta_{i,j}$ and T, and thus V_i, might depend on the point in time, e.g., through the epochs introduced in the following.

3.2. Reward System

3.2.1. Treasury

The project maintains a reserve of tokens that are initially filled by the project owner, which may be a commercial venture, private investor, funding agency, foundation, or by a crowdfunding [185-187] campaign (**Error! Reference source not found.**). Tokens are awarded according to a predefined rule set. Especially in research   projects, it is typically necessary to split the total pay-out for WPs and their NFTs into a guaranteed, upfront payment after their selection, e.g., in order to pay salaries and bills, and a premium for successful delivery after community assessment.
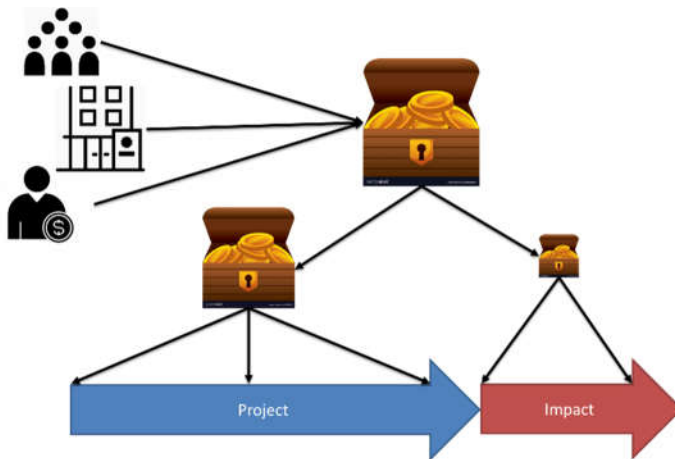
Figure 6. Project treasury. To assure its economic sustainability, a project needs to strategically distribute its initial (one-off start-up) funds and any follow-up income across the project execution and exploitation phase, see also **Error! Reference source not found.**.

Importantly, this treasury ought to stay open beyond the end with the delivery of the final WP (**Error! Reference source not found.**), e.g., for funding upgrades, and for entertaining promotional and commercialization activities; also, similar to royalties in intellectual property (IP) [172] contributions, the owners and stakers may be rewarded according to the sustainability of their NFT's impact. Revenues may continue trickling into the treasury, for instance, through trading profits, seigniorage [188] and arbitrage gains [189] on project-associated cryptocurrencies.

3.2.2. Epochs

The time of project execution and its follow-up may then be partitioned into a sequence of epochs, similar to the procedure for staking rewards in various PoS-type blockchains (**Error! Reference source not found.**) [34, 35]. As already indicated in the context of equation (1) on the valuation of NFTs, a fraction of the treasury, e.g., proportional to its total stake, is allocated to each epoch, and distributed to the NFTs according to their relative, token-weighted stake in the project.
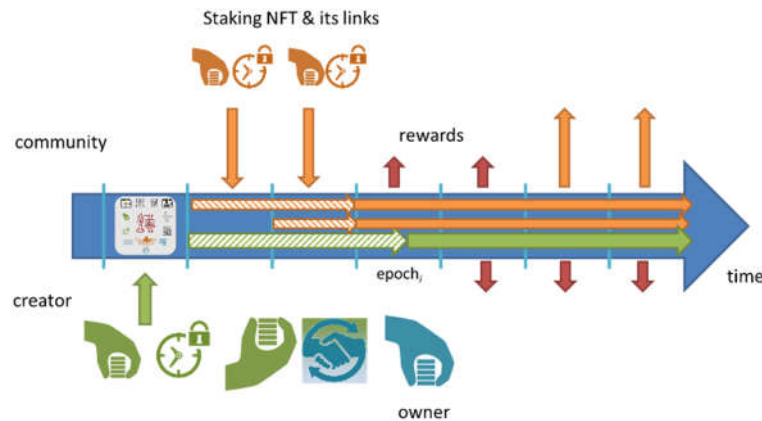

Figure 7. Staking, trading, rewarding from project treasury through epochs representing a finite time interval within the development and exploitation phase of a project (**Error! Reference source not found.**). In each epoch, project tokens are spent, and income is collected to the project treasury. A formula relating the balance on the treasury to rewards issued as a function of trusted parameters accessible on the blockchain needs to be encoded in a smart contract.

3.3. Crowdsourcing of Research

The fundamental challenge in collaborating on research projects with possibly anonymous or pseudonymous community members is trust; for this, the traditional scientific community has established a culture where results are published with proper documentation of data and sources to either support or dismiss the pitched scientific hypothesis. Importantly, the research methods applied need to be adequately described for allowing independent validation by peers.

3.3.1. On-Chaining of Research Outcomes

By its intrinsically digital nature, verification of submitted research outcomes in the context of blockchain technology always needs to be carried out through computation, ideally on decentralized networks. So, similar to multimedia recordings, trustful analog-to-digital (A/D) converters assuming the function of oracles are needed for on-chaining results obtained from research carried out in the physical world.

The concept for on-chaining research outcomes to a blockchain elaborated in this work predicates on the already very advanced, and swiftly emerging capability to virtualize the actual world through simulation by means of the fast proliferation of unprecedently powerful computing resources available to the public.
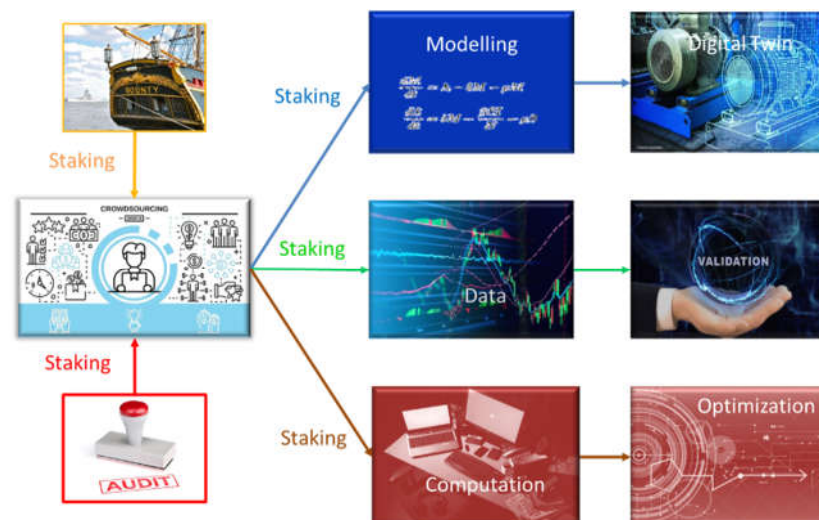

Figure 8. Trust in crowdsourcing of NFTs by staking. The blockchain implementation of a request for a project contribution (eventually leading to a new NFT) requires a staked reward bounty to be issued for successful delivery of the technical objectives, and a staked audit for assuring the integrity of the smart contract. For a request that can be addressed by a purely virtual approach by a digital twin, three basic levels of contributions can be crowdsourced, also by demanding stakes from contributors: for refinement of the digital twin model, for generating and validating data submitted, and for providing the usually comprehensive computing resources that is essential for performing algorithmic   design optimization in a highly multidimensional parameter space.

Error! Reference source not found. illustrates the concept of crowdsourcing research through blockchain. Each step requires staking and time locking of tokens by the contributors to underpin their credibility. A research goal is formulated in terms of objectively verifiable parameters, e.g., qKPIs, and the crowd is incentivized by a clearly defined reward schedule. An auditor certifies the integrity of the processes underlying evaluation and remuneration from the project treasury. Also bug bounty [190, 191] programs can be implemented, e.g., to fortify the soundness of the underlying smart contracts. Monetary driven incentive schemes might be replaced or complemented by "meritocratic" reputation systems [192, 193] that are already common in academic research, e.g., the (disputable) Hirsch or h-factor [194], which is widely employed for quantifying research impact, or global university rankings [195, 196].

The members of the crowd, possibly pre-selected via competitive tendering (**Error! Reference source not found.**) or randomized selection, then measure and confirm the validity of submitted research data. To construct an A/D interface for trustful on-chaining, the project also sources realistic modelling and simulation to create a digital twin [86-88] that can accurately virtualize experimental scenarios, including the statistical spread of results due to tolerances of input parameters. For data validation, the recruitment of computational resources is incentivized for decentralized validation of findings; the same computational capabilities may then also be employed for numerical parameter optimization.

3.3.2. Digital Twins

Trustful onboarding of research outcomes to a blockchain primarily hinges on producing a digital twin capable of realistic simulation of experiments. As, for instance, observed in the massively expanding computer gaming arena, the interplay of computational power and simulation methods already manages to produce an increasingly immersive, 3-dimensional user experience (UX); the notion "realistic" technically means that the laws governing nature, combined with initial and boundary conditions, are accurately reflected. While numerous projects, particularly in the domain of physical sciences and classical engineering, already possess a solid track record on this itinerary towards virtualization, other disciplines slated to follow along an exponential path. For the specific example of microfluidic "Lab-on-a-Disc" systems for bioassay automation at the point-of-care, we published several implementations of digital twin technology, including methods for their algorithmic performance optimization [197-202].

3.3.3. Compute-Enabled Oracles

While at its very foundation, blockchain, especially those implementing PoW like Bitcoin, may be deemed a sophisticated incentivization scheme for computing resources. However, in the interest of bandwidth and security, it is wise to devote this infrastructure to transactions. Pricing structures, e.g., on the EVM, thus deter users from running comprehensive, time- and memory consuming calculations on-chain.

In case a state change of the blockchain is to be induced by complex simulation of a digital twin model, complex computation can be offloaded to decentralized oracle networks ("DONs") composed of nodes. Confidence in the validity of outcomes from these compute-enabled oracles may, for instance, be established by open market solutions including reputation scores derived from performance history, or network trusted nodes [203].

3.3.4. Experimental Results

Many scientific fields, such as clinical research, the life and social sciences still mainly rely on often extensive experimental campaigns on biosamples, animals or humans. In the event where data is to be gathered for life science projects, patients may provide their own data and the value of that data may be attributable to those patients if the data results in products that make it to a marketplace. This is already happening within the genomics domain [204].

In the context of sourcing data, it is worthwhile pointing out the composability of financial instruments and processes within the smart contract domain in DeFi. In DeSci, this compelling opportunity may be fostered through streamlined formats for data files and their exchange, e.g., on the analogy of Ethereum's ERC-20 [205], ERC-721 [206, 207] or EIP [208] standards.

In these cases, a hybrid approach needs to be implemented: as previously, submission of empirical, real-world data sets needs to be supported by a time-locked stake from a number of independently acquired data sets to endow optimum credibility and protection, e.g., against fabrication of data or collusion of nefarious actors; data submissions are then filtered through a digital twin in the form of data analytical algorithms which take

into account factors like stake and reputation of its producers and voters from the crowd, as well as plausibility between data sets as a prerequisite for on-boarding them as NFTs.

3.3.5. International Data Spaces

The International Data Spaces (IDS) reference architecture [209, 210] deals with data sovereignty, secure data exchange and sharing using the IDS Connector concept. Some of the features, such as decentralization and distribution of trust, are compatible in both, blockchain and IDS systems. Blockchain technology can therefore act as a key enabler for maintaining shared data assets in an IDS environment. Here, large datasets are made available through its IDS connector, where the shared data asset might encompass a hash code or NFT to verify a larger file (e.g., a complex federated model).

When a business community decides to store shared data assets on a blockchain and make this data accessible to the IDS ecosystem. 1) The blockchain acting as a data consumer registers certain data from the IDS ecosystem on the cryptographically secured, distributed ledger. For instance, a measurement, which has taken place, or certain sensor data. 2) The blockchain acting as a data provider makes data accessible to other parties in the IDS ecosystem, for instance, by recording certain transaction data.

3.4. Community Involvement

3.4.1. Participatory Models

On top of the benefits in quality, efficiency and costs through eliminating the need for middlemen, crowdsourcing in DeSci bears the opportunity of running science and RTD projects in a more inclusive and democratic approach. Following this game-changing paradigm shift takes research out of its many silos into a global community, thus triggering crucial network effects to enhance its value in a non-linear manner (Metcalfe's law,) [211]; sourcing the wisdom of the crowd is broadly recognized for improving the quality and credibility of research outcomes. The active involvement of a community also tends to substantially increase their commitment to deliver on the technical objectives, as well as bolstering the long-term impact of a research project. Participatory models also facilitate the adoption of (quasi) standards and platform strategies [212] that are crucial to tap into important economy-of-scale effects [213, 214].

3.4.2. Governance

While a "code is law" mantra is feverishly nurtured among crypto purists, it is also widely acknowledged that governance structures need to be established for decision-making and conflict resolution in community-led projects. Particularly in the process of on-chaining research outcomes, decisions, e.g., on quality, selections and rankings for issuing rewards by smart contracts, may be challenged; there is always a chance that an originally scoped algorithm might not fully echo the actual situation, conceivably leading to unfair or even random outcomes, and thus undermining the vital community spirit and discouraging contributors.

Moreover, community-agreed improvements of the ledger-encoded rule set should be permitted. In this regard, DeSci can be well guided by existing mechanisms, like community-appointed judges, arbitration panels and technical councils wielding distinct veto privileges; such, at times, token-weighted governance structures have already been successfully introduced in various blockchain ecosystems [215-222], in these cases mainly to be able to upgrade their own ecosystem; they have, after some painful lessons were learnt [223, 224], led to the formation of a rapidly growing number of chiefless, entirely community governed decentralized autonomous organizations (DAOs) [225-230]. Several top-notch universities, including Harvard, MIT, UC Berkeley and Oxford, have launched Education DAO ("EduDAO") [231, 232] with the objective of tackling the prevalent "funding crisis and skills gap". Rather convenient development kits and exemplary application cases for composing and customizing the (Science / RTD) DAOs conceived in this work

from its constituent elements, e.g., for minting designated crypto-tokens and voting on a treasury,   are publicly available [233-235].

4. Summary and Outlook

4.1. Summary

The swiftly growing Web3 technology blockchain ecosystem provides a highly potent toolset for seminally upgrading the legacy organization of academic research. For the proposed concept of decentralized science (DeSci), research projects are interpreted as networks of non-fungible tokens (NFTs) representing the outcome of its work packages and a set of attributes, such as its creator(s), ownership, stakes, scientific roots and semantics; each crowdsourced contribution to these NFTs, such as the original idea, conceptualization, improvements, scientific methodology, experimentation, simulation, analysis, validation, verification, documentation, forecasting and promotion, is recorded and timestamped in conjunction with metadata, on a distributed, tamper-free, and immutable public ledger. Adapting mechanisms already established in other blockchains, the underlying tokenomics, governance and arbitration schemes can be geared to incentivize broad participation of competent experts and their good behavior in the very spirit of the project objectives.

With the presented, crypto-enabled mechanisms, the quality, credibility, efficiency, transparency,   inclusiveness, impact, and sustainability of scientific projects can be distinctly improved, hence offering a much-needed resolution to the progressively endemic funding, credibility and sustainability crisis of science. Due to the intrinsically digital nature of the distributed ledger technology, disciplines that lend themselves to virtualization enabled by digital twins, such as engineering or physical sciences, are deemed easier to onchain than fields like the life or social sciences, which may need to pursue an empirical or hybrid approach, such as the life sciences.

Proper cross-checking, especially of experimental data or real-world sensors, by independent, even pseudonymous peers can be decidedly improved through tokenization mechanisms known from decentralized finance (DeFi). By incorporating commercially critical mechanisms for confidentiality and intellectual property (IP), e.g., through introduction of privacy elements, digital identity, curation services and access-restricted blockchain setups, the above-described instruments enabling DeSci may readily be extended to application-focused research and technology development (RTD).

The combined action of NFTs, competitive validation and virtualization through digital twins on trusted nodes forms the ideal link to connect science and RTD to blockchain, unleashing it from its academic and institutional siloes, and laying the groundwork for effective self-administration of the entire research stack in decentralized autonomous organization (RTD or Science DAOs); similar to the coding scene, a new class of freelance scientist may emerge. Other mechanisms, that are already used on DeFi, may well be incorporated into DeSci, e.g., crowdfunding.

4.2. Opportunity, Risks and Barriers

Blockchain constitutes a still comparatively young technology, the maturity of its technological backbone, application space and application space may somewhat compare with the internet in the mid-1990s: a space marked by rather poor user experience mainly populated by tech-savvy experts, still lacking smartphones and killer apps like online shopping or social media. On the one hand, this early stage of development offers great opportunity. New applications that are not even on the radar, yet may disrupt entire businesses. For instance, if only a small fraction of present global gold reserves were invested in cryptoassets, such as Bitcoin, the valuation of its tokens would inevitably have to increase by orders of magnitude. On the other hand, the still budding ecosystem has suffered from serious vulnerabilities and major exploits; occasionally, downward-incompatible upgrades were infuriating developers, even leading to community-splitting hardforks.

In an effort to solve the so-called "trilemma" [236], certain blockchains opted to sacrifice one of its cornerstones of decentralization, speed and security for another to optimize their performance towards their main applications. Various second layer solutions have been suggested [236-245]. Bridges between blockchains, and side or parachains have been constructed to promote interoperability [246-248]. (Decentralized) digital identity (DID) and privacy solutions, e.g., via conventional or even decentralized mechanisms, such as, zero-knowledge proofs [249], have been elaborated to combat monopolization, as well as to conform with legally compulsory know-your-customer (KYC) and anti-money-laundering (AML) practices, or nationally often starkly diverging legislation on securities. The futuristic Internet Computer [250, 251] initiative describes a decentralized alternative to currently dominating corporate cloud services that, in practice, also still play a role in many blockchains [148, 149].

There are further risks, such as the still rather elevated short-term volatility of cryptocurrencies, which is often closely tied to poorly understood behavioral economics of market participants, and the competition of central bank digital currencies (CBDCs) that are expected to be launched in the near future. Imminent regulatory pressures may force cryptocurrencies to truly decentralize, and to revisit the risk strategy of system-critical stablecoins. Blockchains may also lose the entire value of their tokens after token rug-pulls, along a rapidly emerging innovation, and only projects having a profound loyalty and size of their user base, high utility and speed may survive.

Other threats are cyberattacks, e.g., of (distributed) denial of service (DDoS) [252], on blockchains, especially by non-economical players, e.g., nation states, or the power games and collective, nefarious usage of coins by economically dominant "whales". While the frequently practiced open-source character of code gives transparency, it might induce vulnerabilities to blockchains and smart contracts. As cryptographically secured systems, blockchains may also be exposed to future quantum computing capabilities; note that various strategies for post-quantum cryptography have been elaborated [253]. So far, history has taught that the blockchain economy may take substantial blows on the chin from such setbacks, but emerges even stronger in the aftermath.

For on-chaining real world inputs, significant opportunity for collusion and or fabrication of data inputs exists. Careful design of crypto-economic incentives will be required but it seems possible to, at the very least, increase the reliability and auditability of sensor outputs that may be inserted into the scientific literature and records.

Extra ethical and privacy requirements are at play when patient related data is involved in scientific and medical processes; as such, it will be critical to ensure that decentralized science and medicine abides by the highest regulatory standards possible. Deviation from such rigorous regulatory processes for acquiring such data may prompt authorities to block approval of resultant therapeutic and diagnostic products.

To disperse these quite valid concerns, which often revolve in the context of compliance with ESG (environment, social, governance), major blockchains, with the most notable exception of Bitcoin, already run, or are planned to transition to Proof-of-Stake (PoS) or similar consensus mechanisms that are radically lowering their often-quoted carbon footprint [254]. Some blockchain initiatives even, immediately or indirectly, incentivize the protection of global commons, such as poverty, education, charity, climate, and biodiversity [255-258]. Overall, the tremendous potential of blockchain is recognized across an increasing number of traditional industries. Even in recent years, several key stakeholders have shifted from blanket dismissal of blockchain's utility to adamant supporters.

From a scientific perspective, it is difficult to keep track of the far-reaching spectrum of the technology, and distinguish facts from interest-driven announcements, as much of the communication is channeled by frequently pseudonymous sources through social media, websites, and non-peer reviewed whitepapers. Certainly, there will be massive inertia in the scientific community to migrate to an unprecedented alternative. The disruptive model for DeSci (version 0.1) proposed here will, quite expectedly, be encountered by some frequently valid skepticism; such critical reception will necessarily raise the awareness of present issues, and trigger fruitful discussions leading to widely backed

advancements and refinements. Nevertheless, the giant benefits of integrating the 21st century Web3 technology blockchain to seminally improve the legacy culture of science and RTD in terms of the quality, credibility, transparency, efficiency, sustainability, community engagement and adoption will hopefully be increasingly recognized over time.

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