The Innovation Game

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Abstract

Open Source software provides the only known example of a public good that is produced commercially at scale, without requiring either government subsidies or charitable funding. In his famous analysis of the economics of Open Source, Eric Raymond suggested extending the Open Source model to a wider domain using monetary incentives, but noted a critical obstacle to any such extension: the market cannot price code contributions, resulting in a market failure.

The Innovation Game is a framework of incentives that aims to address this issue within the area of computational science by introducing a market pricing mechanism for code contributions, based on a novel variant of proof of work. This mechanism enables a ground breaking approach to research funding. In this approach, investors fund the production of public research through The Innovation Game and share in the revenue generated from tokens rewarded to participating researchers. Not only can this approach permit the transformation of otherwise proprietary research findings into public knowledge, it can also render fundamental research investable by the private sector for the first time.

1 Introduction, Overview, and Background

For hundreds of years, it has been recognised that certain essential infrastructure, such as roads, bridges, and public parks, is not effectively provided if left to the market alone. These are examples of public goods. The absence of such infrastructure leads to reduced economic output and quality-of-life. Accordingly, public goods are typically provided by governments and funded through general taxation.

Funding is necessary for the creation and maintenance of most public goods. The free rider problem, which allows individuals to benefit from a good without contributing to its cost, is the primary reason why public goods are not normally provided by the market, despite their clear economic and social benefits. This problem occurs when individuals can benefit from a good without contributing to its cost, leading to underfunding and insufficient provision.[1] The ability to levy taxes has historically meant that governments are uniquely able to overcome the free rider problem by ensuring that everyone contributes to the funding of public goods. However, the Open Source movement has emerged as an exception to this rule.

Open Source software, a privately produced public good, is the single most impactful driver of technological innovation today [1]. The transformative potential of Open Source development is indisputable, as projects like Linux, Apache, and countless others now power the world's technological infrastructure. The largest technology companies, including Apple, Google, and Facebook, regularly contribute to, and benefit from, Open Source projects, creating a public goods infrastructure upon which countless innovations are built.

There are several reasons why the first example of privately produced public goods at scale occurred in the domain of software: The raw material costs for software are negligible. With the emergence of the internet, individuals with the required interest, time, and skills were able to form communities to collaborate on software projects. However, to be most effective, Open Source requires a code base with certain properties that are often absent in data-processing algorithm implementations like those used in computational science and machine learning. This results in a market failure meaning that traditional Open Source development models are less effective.

The Innovation Game (TIG) proposes to solve this problem for data-processing algorithms by incentivising contributors with token rewards. The value of each contribution is determined through a market mechanism that employs a variant of Proof of Work. Similarly to Open Source, the knowledge generated through TIG is a public good. Furthermore, extending an open and collaborative model to computational science enables TIG to incentivise Open Data by linking data availability to the processing method. In sum, TIG aims to unlock the full potential of computational science by incentivising open collaboration in the development of data-processing algorithms.

[1] Charitable organisations, funded by voluntary donations, occasionally provide public goods. However, compared to governments, charities tend to be limited in the extent to which they can provide public goods due to factors such as funding constraints and a narrower scope of influence.

1.1 Overview of The Innovation Game

Markets operate according to the principles of supply and demand, acting as a decentralised system for allocating resources [2]. Functioning markets establish prices efficiently and are intrinsically resistant to censorship and manipulation. However, for certain goods and services, there is a "market failure" meaning that the market cannot price these goods or services, and the benefits of the market mechanism are lost [3]. A market failure exists with respect to code contributions for certain collaborative software projects, including open development of algorithms for most scientific applications. This market failure was highlighted by Raymond [4]. A separate market failure concerns fundamental and early-stage science, and affects the development of algorithms in this domain [5].

The Innovation Game (TIG) seeks to address these market failures by introducing a class of participants called Benchmarkers that generate demand for optimised algorithm implementations. This creates a "synthetic" market for algorithms that solve significant problems in science, technology, and mathematics. Benchmarkers perform proof of work in exchange for token rewards. This proof of work is of a particular type, which is performed using algorithms that have scope for optimisation. This "optimisable proof of work" (OPOW) creates a demand for efficient algorithms to solve the proof of work problems.

Agents called Innovators satisfy Benchmarkers' demand for improved algorithms. Innovators are rewarded with tokens based on their algorithm's performance, measured by the degree of its adoption by the Benchmarkers. The overall effect is that TIG incentivises the development of improved algorithms for solving important scientific problems, as well as optimised hardware to run these algorithms. The market mechanism in TIG, enabled by the Benchmarkers, has several important properties. It offers extraordinary resistance to manipulation, while inherently accounting for the economic viability of producing specialised hardware for executing the algorithms. This mechanism also provides a market signal that serves to determine which of the IP embodied in the algorithm implementations TIG seeks to capture through patent filings.

In TIG, all intellectual property is available under a novel licence called the TIG Open Data Licence. This copyleft licence features the Open Data Requirement: If output data generated by running an algorithm (which is covered by TIGs IP) is distributed, the distributor must make the corresponding input data available. For anyone wanting to use TIG IP under more permissive terms, a commercial licence is available for purchase. The fees derived from commercial licenses generate demand for the TIG token. This creates an incentive for commercial entities to make their data available in exchange for free use of IP held by TIG.

In addition to promoting Open Data, TIG has the potential to convert what would otherwise be proprietary research findings into public knowledge, because investors can fund computational science research in return for ownership of any tokens earned by the research output (the algorithm), rather than ownership of the IP embodied in the algorithm itself. TIG can also make fundamental research investable by the private sector: In TIG, challenges in fundamental research areas are rewarded in the same way as for applied areas. With challenges covering a broad spectrum of research disciplines, value "spills over" into research for the more applied challenges, even when property rights cannot be secured on the research outputs. In this way, TIG aims to capture value from fundamental research, something which, historically, only governments have been able to achieve.

Given the prominent themes of decentralisation and proof of work, the reader might wonder how The Innovation Game relates to proof of work based public blockchain networks, such as Bitcoin. In Bitcoin, the primary function of proof of work is to provide protection against double spending, however, a remarkable secondary effect of proof of work in Bitcoin (which has received much less attention) is that it creates a market for optimised mining hardware [6]. In The Innovation Game, the primary role of optimisable proof of work is to create a market for optimised hardware *and* algorithms.[2]

1.2 Open Collaboration, Open Source, Open Data

Research and development are considered *open and collaborative* (OC) when contributions are freely accepted, and the resulting knowledge becomes a public good. In the realm of complex scientific and technological projects, where outcomes are inherently uncertain, an OC approach can offer numerous advantages. When there is sufficient participation, crowdsourced peer review enables early identification of issues and ensures adherence to standards, while access to a diverse pool of skilled contributors results in higher-quality outputs, delivered more quickly and at reduced cost [7]. Open collaboration can lead to a tipping point where, with sufficient participation, the project begins to accelerate away from closed alternatives. However, maximising the potential benefits of an OC approach requires adequate incentives for participation.

[2] We note that this market is "decentralised" in the same sense as (for example) a stock market: participation is crowdsourced through voluntary exchange, and driven by supply and demand. This holds true irrespective of whether the market infrastructure is hosted on one server or many. In particular, this form of decentralisation is quite distinct from the decentralisation of hosting infrastructure, as exemplified by public blockchain technology.

The power of the OC approach is exemplified by the Open Source software movement. By promoting the sharing of source code while mitigating the free rider problem, Open Source has succeeded in providing world-class public goods in the form of software, without the need for government or charitable funding. Open Source development is best suited to codebases with certain properties:

Property 1 (*Large codebase*): Copyright is fundamental to open source licensing as it grants the original creators of the software the exclusive right to reproduce, distribute, and modify their work. However, copyright can be circumvented by reimplementing the code, which is easier for smaller codebases [4]

Property 2 (*Near term utility*): Contributors are incentivised to help create an output they find useful (commercially or otherwise) in the short term [8]. In Open Source, access to the resulting software typically forms a major part of the incentive to contribute.

Property 3 (*Modularity*): A modular project permits multiple contributions to be made simultaneously with minimal coordination. Modularity also enables individuals to contribute usefully without needing to understand the entire project, making it more accessible. As a result, a highly modular project can thrive without full-time contributors who would normally require monetary compensation [9].

These properties are often absent in implementations of data-processing algorithms, such as those employed in computational science and machine learning. Absence of these Properties can be compensated for by introducing monetary incentives (at least in principle), but this is contingent on a significant degree of value capture being achievable.

1.3 Value Capture in Open Source: Dual Licensing and Data

One strategy for capturing value while remaining Open Source is *dual licensing*[3] which aims to balance Openness with monetisation by offering both a free licence and a (paid) commercial licence. In traditional dual licensing the Open Source licence is typically of the copyleft variety: requiring that any derivatives of the software be released under the same licensing terms. For developers who don't want to release their modifications under these terms, there is the option to pay for a commercial licence. Under certain circumstances, such as when Property 1 is absent, copyleft can be difficult to enforce by use of copyright. In this scenario, patents can be used.[4]

In the context of algorithm for science, dual licensing has various limitations. Effective value capture requires that some property rights be secured. This is notoriously difficult when the software may not have near term utility (Property 2), which will tend to be the case for software embodying experimental algorithms, or algorithms with applications to fundamental or early stage scientific research.[5] Furthermore, value capture alone is not sufficient. We also need a method of returning value to contributors, however, until now there has been no such method.[6]

Fortunately, our application has some features which make it more tractable than the general case. If we assume that each contribution is a functional implementation of an algorithm for solving a specified problem, the performance of the algorithm can be assessed by running a series of benchmarks. But even with this favourable structure, a multitude of questions remain, including: How much reward is appropriate for what level of improvement? Which hardware should be used for assessment of performance? What if the algorithm is optimised to run on a particular type of hardware, and what if this type of hardware that is not widely available or is very expensive? The Innovation Game is designed to provide an answer to these questions for computational problems such that the solution is difficult to compute but efficient to verify.

For our application, there are also significant challenges related to data. The Open Source model focuses on source code dissemination, not data sharing. In computational science, while source code accessibility is critical, data availability has grown equally crucial, especially given the surge in machine learning. Data sets, often viewed as factual lists, elude traditional property rights in major jurisdictions, including the U.S., making a copyleft effect unattainable [12]. Thus, open projects sharing data risk free riding, as closed projects can utilise the shared data without reciprocal sharing. It follows that, in certain domains (notably machine learning) the absence of corresponding data diminishes the intrinsic value of algorithms.

[3] In recent years, dual licensing has fallen out of favour, partly due to the perception that it exploits the work of voluntary contributors who do not receive any direct financial compensation for their contributions [10]. The market created by TIG addresses this issue of contributor compensation.

[4] The developer receives a patent licence if and only if the licensing terms are honoured. One example of a project with this licensing approach is MySQL [11].

[5] Indeed, that is why this type of research must usually be government funded. See for example [5].

[6] This is the subject of Eric Raymond's seminal essay "The Magic Cauldron". He concludes that offering monetary rewards for code contributions would greatly extend the range of situations to which open collaboration could apply. He also notes that the general problem of valuing individual code contributions in Open Source constitutes a formidable challenge [4].

Another issue in the case of data-processing algorithms is that additions or improvements to these algorithms might not be distributed in the course of commercial use—instead— it is the *output data* which is distributed. However, in copyleft licences such as GPL, the requirement to make additions or improvements to the code available (under the same licensing terms) is triggered only by the distribution of the source code. It follows that, for such algorithms, copyleft may be neutralised, making it harder to capture value through dual licensing because there is no clear incentive to pay for a commercial licence.

2 Proof of Work, Optimisation, and The Innovation Game

Proof of work was originally conceptualised as a pricing function to apply a cost to sending a message, in order to deter email spam and denial-of-service attacks. [13]. More generally, proof of work is a method of imposing a cost during task execution by requiring the computation of a solution to an 'asymmetric' problem—one that is difficult to solve but easy to verify. There are a vast number of important computational problems in science and technology that feature this property. These include scientific inverse problems,[7] which require determining initial conditions given the conditions at a later time.[8] TIG employs proof of work in order to create a market for optimisations that enhance the efficiency of computational methods. These optimisations could result from a new algorithmic strategy, code improvements, or hardware enhancements, and could range from a minor refinement to an entirely new approach.

Consider a market for proofs of work, such as is created by the Bitcoin network. We know from the example of Bitcoin mining that hardware optimisations that increase the efficiency of miners tend to be widely disseminated. This is due to the profitability arising from mass-producing hardware incorporating the optimisations; to remain competitive Bitcoin miners frequently update their equipment, which has the effect of minimising disparities in efficiency.

We would like to allow proof of work with scope for algorithmic optimisation, however, algorithmic optimisations have the potential to be far larger than code or hardware optimisations. This is understood to be problematic in the context of proof of work mining, because, if an optimisation were to result in a very large improvement in mining efficiency, the miner with access to the optimisation would be incentivised to keep it to themselves. If this were to occur, rival miners would be driven out-of-business, leading to centralisation of the network. This is why digital currency mining networks have been constrained to use only a narrow class of proof of work problems for which there are no algorithmic shortcuts [16].

The Innovation Game employs a novel POW method that we call *optimisable proof of work* (OPOW), comprising n component proof of work problems. OPOW is designed to remain stable even if a very large algorithmic optimisation is developed with respect a minority $p \ll n$ of the component problems.

The advantage that such an optimisation would provide to a miner who keeps the optimisation private, would be limited. As a result, algorithmic optimisations for the component problems in OPOW behave more like a code or hardware optimisation insomuch as it is preferable to 'sell' the optimisation, rather than keep it private. This promotes the dissemination of optimisation.[9]

The core mechanism behind OPOW can be illustrated with an analogy: Consider a rowing boat with multiple rowers. In the boat, one rower, who is a hundred times stronger and faster than any other rower in the boat, can only provide a limited boost to the boat because the oars must remain reasonably synchronised.

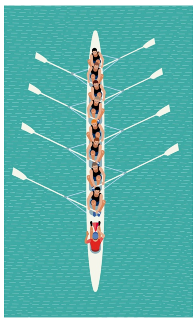

Figure 1: Rowers

2.1 The Innovation Game in a Nutshell

The Innovation Game uses OPOW to provide a pricing mechanism for contributions to open and collaborative projects in computational science, incentivising research by rewarding contributors with tokens. Specifically, these contributions take the form of implementations of data-processing algorithms (which we call "implementations"), that can be used to solve random instances of asymmetric problems in fundamental and applied areas of computational science, that are featured in TIG. Our medium term goal is to onboard somewhere in the range of 100-200 of these problems. TIG offers rewards, in the form of tokens, in return for code contributions (implementations) that are able to solve instances of these problems more efficiently.

There are three types of Player in TIG:

[7] This is a consequence of the second law of thermodynamics [14, 15].

[8] Another class of problems with this asymmetric character are NP-complete problems, such as neural network training, Boolean satisfiability, and decisional traveling salesman.

[9] A technical account of OPOW will be presented separately. See also Appendix A. Please note that OPOW is the subject of a patent application [17].

Commercial Enterprise (Entities that sell products based on the IP captured by TIG). Commercial enterprises must pay a fee to use the IP captured by TIG in their products, *unless they are willing to make their code and/or data available* (see below). The fee permits use of all IP in TIG, is rate-card based, and is payable in TIG tokens. This generates demand for the token.

Innovators (Coders; academic scientists; entities conducting commercial research). Innovators develop and submit more efficient implementations to TIG for solving the featured challenges. As long as the implementation reaches a threshold of adoption by Benchmarkers, the Innovator receives a reward of tokens.

Benchmarkers (Token miners; enthusiastic supporters of TIG; anyone with a computer). Benchmarkers perform proof of work (OPOW) by solving randomly instances of the challenges featured in TIG using implementations that have been published to TIG by Innovators. Benchmakers earn token rewards, and gain a competitive advantage by solving challenge instances more efficiently.[10]

An implementation can be used by Benchmarkers on TIG if and only if it is published to TIG (publishing to TIG requires making the source code available to all). Should a published implementation be an improvement on the previous best, then it should see significant adoption by the Benchmarkers, in which case, the Innovator that contributed the implementation earns a reward of tokens whenever their implementation is used by a Benchmarker to solve an instance of a problem. In this way, OPOW provides a method of equitably returning a share of the value captured to contributors (the Innovators) by providing token rewards. Accordingly, TIG solves a special case of the problem highlighted by Eric Raymond in The Magic Cauldron, specifically, the difficulty in pricing contributions to open and collaborative software projects, and this enables payments to contributors.This results in a clear incentive to find a more efficient implementation for performing work, because a more efficient implementation enables a Benchmarker to reduce their operating costs.

Our objective is for the rewards in TIG to be commensurate with the expected value of the contribution. The more widely an implementation is adopted, and the longer it remains widely adopted, the more token rewards the Innovator receives.[11] Every problem in TIG offers identical token incentives for both Benchmarkers and Innovators. In general, an Innovator receives a different reward for an implementation embodying an optimisation to the *algorithm*, than if the optimisation is with respect to the *code*.[12]

Value Capture

There are three distinct licences in TIG.[13]

- **The TIG Game licence**: This licence governs The Innovation Game (The TIG Game) participation and secures the Intellectual Property rights of the ensuing innovation. The licence allows for the use of submitted algorithm implementations by Benchmarkers, and use of any IP captured by TIG by Innovators for playing TIG Game only. For someone that wishes to participate in the TIG Game as an Innovator or Benchmarker and earn TIG tokens, this must be the chosen licence.
- **The TIG Open Data licence**: This licence is allows for TIG IP to be used free of charge and includes a share alike provision. If data generated from the code execution (output data) is shared with third parties, the input data must also be made available *to the extent necessary to allow a reproduction of that output data*. This is the licence of choice for those who wish to make commercial or non-commercial use of all and any implementations and IP captured by TIG, and do not want to pay for a licence, and are willing to share their data.
- **The TIG Commercial licence**: This licence allows for closed use of all implementations and IP captured by TIG in return for the payment of a fee. Unlike the TIG Open Data licence, the TIG Commercial licence is a paid license does not include a share alike provision or impose an obligation to make data available. This licence is anticipated to be chosen by those preferring to keep their algorithm optimisations and/or data private and who are prepared to pay for a licence.

Having been assigned by the Innovators when the implementation is submitted, all captured IP will be managed and licensed by the TIG Foundation.

The Foundation is mandated to make contributed IP available under the TIG licences, as described above.[14] Benchmarkers play a crucial role in the process, as they provide a measure of performance which serves as a market signal.[15]

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[10] In this sense, Benchmarkers are analogous to Bitcoin miners.

[11] We note that, in the context of TIG, Benchmarkers provide *demand* for optimised implementations for solving the problems featured in TIG, and are *supplied* with implementations by Innovators. Thus, Innovators' rewards are allocated through a *market mechanism*—see also Section B.

[12] The details of the rewards mechanism, including the method by which the type of optimisation (algorithm or code) is established within TIG, and the division of rewards between optimisation types, will be presented in our forthcoming technical paper.

[13] See the *TIG IP Policy Rationale* for details [18].

[14] Contributed implementations also generate spill over in IP later captured by TIG. See *Internal Value capture*, Section 4.

[15] See Section 3 for more on the utility of the market signal provided by Benchmarkers.

The demand for tokens correlates with the need for TIG Commercial Licences, which require a fee payable in tokens. The TIG licensing strategy, combined with the TIG protocol, provides a framework of incentives for development of more efficient implementations of algorithms for solving many of the most important problems in computational science. See Figure 2.

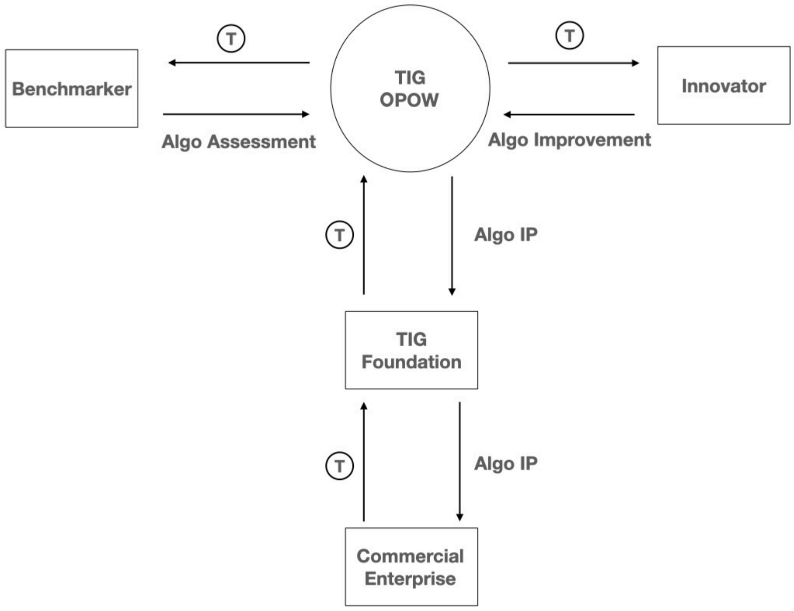

Figure 2: The economic model of The Innovation Game. Arrows represent asset flows (goods, services, tokens). The circled 'T' denotes TIG tokens.

Selecting Challenges

For a challenge to be added to The TIG Game, there should be a high degree of consensus among experts as to its significance. To facilitate the process of adding challenges, a committee of experts will nominate problems for consideration. Upon nomination by the committee, token holders vote on whether the problem will be added to TIG.[16] The vote serves as a check on the committee's power to decide which problems to add to The TIG Game and when. Token holders have a vested interest in the timing and frequency of problem additions to The TIG Game because of impact this has on captured IP value and, consequently, TIG token value.[17]

The incentive for adding problems is to increase the potential capture of licensable IP by The TIG Game. However, because all problems in The TIG Game share the same reward pools, adding too many problems would dilute the reward available for each problem, and reduce the incentive for Innovators to contribute. Achieving a balance between the total number of problems and individual problem rewards is vital for maximising valuable innovation and token value. Consequently, token holders are incentivised to vote to maintain the optimal balance. Challenges can also be retired from TIG via a similar mechanism: Proposal by the committee followed by a ratifying vote.

2.2 How TIG Drives Open Collaboration and Open Data

TIG aims to establish a platform that fosters open collaboration in computational science. To achieve this, we must account for the differences between the types of codebases that tend to feature in scientific algorithms and those have more traditionally been subject to open collaboration, such as open-source software projects. TIG's approach is to use token payments, combined with a novel method of pricing code contributions based on OPOW. TIG also deploys a multi-licensing strategy that leverages IP capture (copyright and patents), and a data availability requirement. In particular, TIG incorporates a direct mechanism for internal value capture in the form of copyright and patents on contributed algorithm implementations and associated inventions. External value capture comes via licence fees paid for use IP under the TIG Commercial licence. See Section 4 for further discussion.

With regard to the issues raised in Section 2, the increased possibility of reimplementation which results from a smaller codebase (Property 1) is overcome by use of patents. As noted in Section 2.1, this is not a new strategy. More novel is the combination of potentially thousands of patents pertaining to a diverse array of problems and strategies for solving these problems. This will tend to de-risk the investment in patent coverage. Further de risking results from obtaining a market signal in the form of adoption by the Benchmarkers, on the basis of which a decision on whether to patent a given invention can be based.[18]

The network of Benchmarkers generate demand for efficient algorithms for solving the problems featured in TIG. This demand exists irrespective of the demand for such algorithms in wider industry,[19] incentivising contributions, even for fundamental or early-stage areas of research which might not be useful (outside of TIG)

[16]Token holders may delegate their voting power to another user if they do not fee equipped to make an informed decision.

[17]For example, if the committee were to nominate a problem that is clearly not sufficiently important to justify inclusion in TIG, then its inclusion can be vetoed by the token holders—the incentive to do this is clear: Less important problems imply less valuable IP in TIG, lower demand for the token (from licence fee payments).

[18]Having first filed a provisional patent application.

[19]Thus "near term utility" (Property 2), if not already present, is brought about by the Benchmarkers.

in the near term. We say that this demand, generated by Benchmarkers performing OPOW, creates a "synthetic market" for the algorithm implementations that are supplied by the Innovators. This market distributes rewards to Innovators in the form of tokens, enabling the possibility of full-time engagement.[20]

TIG provides an incentive to make data open: The opportunity to use IP captured by TIG *free-of-charge*, under the terms of the TIG Open Data licence. Furthermore, because the share-alike provision in the TIG Open Data licence is activated by the dissemination of output data as well as the source code of the implementation used to generate that output data, the incentive to take a commercial licence remains intact.[21]

Given sufficient participation, an OC approach can have tremendous advantages. The power of an OC approach is exemplified by the Open Source software movement. Nonetheless, as we transition into an era where we process vast amounts of data using algorithms, a problem arises. Data-intensive fields like computational science and machine learning often feature codebases ill-suited for open-source development. This was discussed in Section 1 with reference to properties 1-3 (Large codebase, Near-term utility, Modularity).

For projects lacking any of Properties 1-3, benefit derived from open sourcing is limited due to potential low participation, resulting in a diminished incentive to Open Source the project in the first place. This is the situation for computational science. Absence of Property 1 (Large codebase) means that the ability of an Open Source licence to discourage free riding is diminished; this reduces the motivation to contribute.[22]

Consider, for instance, a late-stage applied (LSA) research project in computational science. For LSA research, it is expected that there will be a useful result in the near term, therefore, because of the absence of Property 2 (Near-term utility), the incentive to participate *in order to obtain a useful output* is present. However, projects in computational science do not in general have Properties 2 and 3. Lack of Property 3 (Modularity) means that the project is more likely to struggle to attract contributors unless monetary compensation is available. These factors explain why LSA research projects in computational science (those which are privately funded) tend to be conducted on a proprietary basis, where funding is given in return for ownership of the resulting IP. With TIG, commercial funding can be provided in return for tokens earned by an implementation submitted by an Innovator, while the IP embodied by the implementation becomes a public good.

For early-stage applied and fundamental (EAF) research in computational science, the incentives are different to those of LSA. This is because, for EAF, Property 2 is also absent: The outcomes from EAF research tend to be so uncertain that the incentive to participate *in order to use the output* is significantly diminished. This means that private research funding is not normally available, and so EAF research must be *publicly* funded. For EAF, public funding eliminates the commercial case against Open Sourcing, but absence of Properties 1-3 tends to reduce engagement, limiting the potential benefits of OC development. By offering token rewards, TIG aims to increase engagement in OC fundamental research in computational science, and also improve efficiency of resource allocation by utilising a 'synthetic' market mechanism tied to OPOW. See Appendix A.

3 Value Creation in The Innovation Game

EAF research typically faces challenges in attracting private funding due to the high uncertainty regarding when the output will be monetisable. The Innovation Game introduces a novel class of market participants called Benchmarkers. For Benchmarkers, a more efficient implementation has immediate economic value as it enables them to perform more proof of work at a reduced cost. This creates a market[23] for the implementations provided by Innovators. We term this a *synthetic market*, as it is brought about, somewhat artificially, by introducing a new consumer class (Benchmarkers) for the specific purpose of facilitating an efficient allocation of resources to the Innovators, thereby incentivising development of implementations for solving the problems featured in TIG.

In TIG, the allocation of rewards aims to be viewed as equitable. The reward an Innovator receives for contributing an implementation to TIG depends on the extent to which the implementation (or at least the

[20]See Appendix A for more on the allocation of rewards by the synthetic market.

[21]We wish to emphasise that, despite superficial similarities, the TIG licensing model is fundamentally different from traditional dual licensing. For example, dual licensing is synonymous with *single vendor licensing*, which required assignment of copyright by contributors. TIG licensing does not require such an assignment.

[22]Patents are occasionally used in open-source realms to safeguard the inventions that the code embodies. Since patents are expensive, however, this can prove challenging in the absence of a clear near-term method for generating revenue (which Open Source projects do not normally have). Furthermore, it is often hard to know if a patent is worth filing, and, if it is, it must be filed immediately, before it has been established whether or not the project will gain traction. TIG addresses this issue by using the market signal provided by the Benchmarkers. See *Internal Value Capture*, Section 4.

[23]We would like to emphasise the distinction between a "market" and a "marketplace." A "marketplace" refers to a venue for the trading of goods and will inevitably emerge in some form, as long as there is a "market" (i.e., supply and demand) for the goods. Although TIG does constitute a marketplace for scientific inverse methods, this aspect is relatively incidental. The primary focus of TIG is the creation of a market for these inverse methods. It is worth noting that TIG differs significantly from various projects aiming to create a marketplace for tokenised intellectual property, as those do not address the core issue: the absence of a functioning market for such IP. See also Appendix A.

algorithm it embodies) is used by Benchmarkers. A core assumption in TIG is that the extent of implementation usage reflects the implementations performance, which in turn serves as a proxy for the expected value provided by the implementation in terms licence fees.[24] We now describe how each of the Players creates value in The Innovation Game.

Value Creation by Commercial Enterprise. By incentivising Commercial Enterprise to make valuable data sets and algorithm implementations available, and by ensuring that the knowledge generated by TIG is non-proprietary, TIG is designed to boost the productivity of businesses. Non-proprietary scientific research outputs and data, contribute to a stock of technical knowledge, a public good, from which businesses can draw when creating new products. The existence of this knowledge promotes competition within the commercial technology sector by limiting the extent to which established firms can build IP and data moats. This creates opportunity for fast-moving innovative companies.

Innovators, who are coders and computational scientists, develop and implement the algorithms underpinning computational science. TIG seeks to accelerate development by incentivising Innovators to contribute to OC research concerning the problems featured in TIG, enabling OC research (including fundamental research) to be conducted on a commercial basis. Furthermore, the TIG Open Data licence is designed to motivate Commercial Enterprises to make their data and algorithm implementations available, as compliance with the requirement for open data (See Section 2) entitles the business to a free licence to use TIGs IP. The aggregate effect is an increase in research process efficiency and an expansion of the stock of non-proprietary scientific knowledge, both of which contribute to enhancing the output and profitability of commercial enterprises.

Value Creation by Innovators. TIG aims to boost the efficiency of resource allocation for EAF research in computational science by offering a market-based allocation based on an objective measure of the performance of the contributed implementations. Besides facilitating an efficient allocation of rewards to Innovators, the availability of a transparent and objective performance metric can be a powerful force in promoting competition. By setting a common standard to assess the performance of contributions, a transparent metric enables people to compare their outputs with others, and assess their relative standing. Accordingly, such a metric can serve as a goal to strive towards, while promoting a sense of fairness and impartiality in the competition. This boosts motivation.

The traditional model for privately funded LSA research provides funding in the form of investment, in exchange for ownership of the resulting IP. However, studies by sociologists have repeatedly confirmed that a majority of scientists find this model demotivating, as it does not align with established community norms.[25] TIG offers an alternative model where investment is made in exchange for the investor receiving a share of any TIG tokens rewarded to the Innovator. This allows privately funded LSA research in computational science to be OC, thereby increasing motivation and productivity. TIG treats EAF research similarly, but, the benefit is different: TIG's market allocation can be more efficient, compared to the traditional funding model (public funding, allocated by committee), because rewards are received only if significant progress is made, according to an objective assessment (provided by the Benchmarkers), and the risk is borne by private investors who are subject to market forces.

Additionally, incentives are increased compared to the traditional Open Source model, resulting in higher participation and a greater likelihood of realising the full benefits of the OC approach. As noted in Section 4.1, the research enabled by TIG will be the first example of non-proprietary commercial scientific research.

Value Creation by Benchmarkers. The performance metric provided by the Benchmarkers is used to price the contributed implementations and decide which of the associated IP is worth capturing. Recall that Eric Raymond identified pricing as a core challenge in extending an open and collaborative development model beyond the current scope of Open Source. Specifically, Raymond recognised that the pricing issue as an instance of F.A. Hayek's renowned 'calculation problem' that can only be resolved via a market pricing mechanism [2]. In TIG, Benchmarkers create a market for implementations of algorithms for solving featured challenges, providing a market signal through which resource allocation to Innovators is determined, and by which the relative value of IP captured by TIG can be estimated. The Benchmarkers generate demand for both optimised implementations and the hardware on which the implementations are run, incentivising innovation in hardware development. Hardware optimisation is intrinsically linked to algorithm and code optimisation, with factors such as economies-of-scale in manufacturing playing a crucial role.

Use of the proof of work mechanism in benchmarking means the economic feasibility of manufacturing specialised hardware for running the implementations can naturally emerge. A further justification for employing proof of work is the extraordinary resistance to manipulation that proof of work can provide. Although performance tests

[24] As well as other less tangible benefits. See, *External Value Capture*, Section 4.

[25] In particular, the Mertonian norm of *communalism* which states that the output of academic science should be non-proprietary.

conducted by one or more parties with minimal energy expenditure might be sufficient at small-scale, growing the network to a globally significant scale necessitates addressing issues such as "*who assesses the implementations' performance, according to which assessment criteria, and on which hardware?*". The market-based approach using proof of work enables TIG to circumvent these challenges and achieve practically unlimited scale.

We further note that using OPOW to create a market for optimised algorithms naturally mitigates Goodharts law: "*when a measure becomes a target, it ceases to be a good measure.*" Traditionally, algorithm performance is established by using the algorithm to run one or more standardised test calculations. This often leads to the creation of algorithms optimised for the test environment rather than real-world applications. For the TIG, the "measure is derived from use by Benchmarkers for performing proof of work, which requires continuous heavy use to solve a wide array of problems of ever-increasing difficulty. This mimics real-world usage far more closely than traditional methods of assessing algorithm performance.

Summary

The Innovation Game creates value by (i) allowing LSA research in computational science to be conducted on an OC basis, while retaining the potential for investment, (ii) boosting incentives to participate in EAF research, leading to greater efficiency, (iii) motivating researchers by providing an objective measure of performance, and enabling research output to be declared a public good, without the need to turn down commercial funding opportunities, (iv) incentivising a new class of market participants (Benchmarkers) to develop optimised hardware for scientific computation, (v) accelerating the development of, and adding to, the stock of non-proprietary knowledge from which businesses (particularly smaller, challenger businesses) can draw to create new products and processes.

4 Value Capture in The Innovation Game

Value capture in TIG relies on the ability to secure at least some IP rights for the innovations embodied in the submitted implementations. In Section 2, we outlined how The Innovation Game achieves internal and external value capture. We now discuss TIG's value capture mechanisms in greater detail.

Internal Value Capture. We anticipate that many Innovators will be academic scientists. Scientists' behaviour tends to follow a particular set of norms. This means that scientists do not typically prioritise monetary reward over all else. Instead, scientists tend be motivated by the desire to act according to what is 'best for science', for its own sake, and also because being 'seen' to behave in this fashion can bolster their standing within the scientific community.

Contributors to Open Source projects are motivated by the desire for a better product and by reputation building within the Open Source movement, which they consider to be a positive force in society. We intend for TIG 'movement' to be perceived similarly, and for the motivations of Innovators in TIG to parallel those of contributors in Open Source. Capturing IP rights in TIG enhances the expected value of all token rewards and furthers the objectives of the TIG project in general. Accordingly, by enabling the capture of IP,[26] Innovators' can build their reputation within the TIG community. Conversely, failure to enable the capture of IP in cases where this is feasible and desirable, would be frowned upon. Benchmarkers offer a market signal as to which implementations represent improvements over previous bests. This signal is used to decide which IP to protect, which patents to prosecute, and so on. Although there may not be patentable output for some fundamental research problems, TIG can still capture value generated by fundamental research through spill overs into applied problems featured in TIG, for which IP rights *can* be secured.[27]

External Value Capture. TIG captures external value through licence fees paid under the TIG Commercial licence. This licence allows the use of all TIG IP while exempting the licensee from the obligations (under the TIG Open Data licence) to make input data and algorithm implementations available. Although the TIG Open Data licence does not entail a fee, it can enable value capture of a different variety: To the extent that TIG succeeds in incentivising open data, it will be perceived as making a significant contribution to the 'open' movement. A positive perception of TIG is important for IP rights to be enforceable in practice.[28]

[26] For instance, Innovators may send a written account of their innovation to the TIG Foundation on a confidential basis, prior to general publication. The TIG Foundation will then file a *provisional* patent application. A provisional patent application can be filed on the basis of a manuscript describing the result. The process is short, and secures a priority date. A full patent application should then be filed within some defined time period (typically 12 months) in order to continue the application process. Alternatively, Innovators may prefer to file a patent application themselves, which they then assign to the TIG Foundation.

[27] Note that this is analogous to the way that many governments seek to capture value generated from fundamental research, as spill over value is captured by the domestic technology industry.

[28] Given that the source code for all implementations submitted to TIG is openly accessible, there exists a potential risk for non-compliance with the specified licensing terms, which could result in a free rider problem. This risk is also present in the context of traditional Open Source software.

4.1 Discussion

TIG aims to emulate the Open Source software movement by establishing a reputation as a public good, such that the fee for the Commercial licence is widely accepted as reasonable, and any avoidance of the fee becomes a social taboo. Innovators are encouraged to facilitate TIG's capture of IP by submitting a description of their invention (embodied in their implementation) to the TIG Foundation, which can then file a provisional patent application. See Section 4 for more detail. There can be different rates of Innovator rewards for code optimisations and algorithmic optimisations. This reflects the fact that algorithmic optimisations tend to be harder to achieve and result in larger increases in performance. Also, implementations incorporating algorithmic optimisations inherently include code optimisations, but not vice versa.

The Innovation Game enables both applied and fundamental research in computational science to occur on commercial terms which do not require that the output is proprietary, rather, the output is a public good. Please refer to Section 2.2 for more detail.

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A Rewards for Benchmarkers

We denote by f_x^i the number of qualifying solutions for the x^{th} challenge submitted by Benchmarker i. The normalised $\hat{f}_x^i$ is defined $\hat{f}_x^i := f_x^i / \sum_j f_x^j$ where the sum ranges over $1, 2, ..., N_m$, and N_m is the number of Benchmarkers. For n challenges, the condition $\hat{f}_1^i = \hat{f}_2^i = ... = \hat{f}_n^i$ is called $\hat{f}^i$-parity. A Benchmarker i's rewards are proportional to their influence $\mathcal{I}^i$ which is defined as

$$\mathcal{I}^i \equiv \hat{\beta}^i := \frac{\beta^i}{\sum_j \beta^j}, \quad \beta^i \equiv \frac{\langle \hat{f} \rangle^i}{1 + k\, C_V^i / \sqrt{n-1}}, \quad \langle \hat{f} \rangle^i \equiv \frac{1}{n} \sum_y \hat{f}_y^i, \quad C_V^i \equiv \frac{\sigma^i}{\langle \hat{f} \rangle^i} \quad \text{and} \quad \sigma^i \equiv \left\langle (\langle \hat{f} \rangle^i - \hat{f}^i)^2 \right\rangle^{1/2}.$$

In the above, C_V^i is the coefficient of variation and σ^i is the standard deviation of the $\hat{f}_{x=1,2,..,n}^i$, and $k = 2$ (at the time of writing) parameterises the penalty for deviation from parity.

Nevertheless, empirical evidence suggests a high degree of self-regulation within the Open Source community. For example, it is known that engineers employed in commercial entities will typically refuse to engage in activities that they perceive as violating Open Source licensing terms. This behaviour primarily stems from their positive regard for the Open Source movement's ethos. TIG aspires to achieve a similar level of positive regard within its community.

B The Synthetic Market: Pricing Contributions to TIG

We introduce the concept of a *synthetic market*, which we define as a market that is artificially contrived, rather than emerging spontaneously. An example of a synthetic market is the market for SHA-256 hash pre-images, created by Bitcoin, which provides protection against double spends by establishing consensus of time ordering of Bitcoin transactions [1]. One method of creating a synthetic market involves introducing a new class of market participants. In our case, these new market participants are the Benchmarkers, who generate demand for efficient implementations to solve the problems featured in TIG. The use of a given implementation by Benchmarkers determines that implementations performance, which we assume to be a proxy for the eventual value that the contributed implementation will provide to TIG.

Figure 3(a), (left hand side). Depicts the current method of academic research funding in the sciences: government subsidy, with non-market allocation. Box ① represents the functioning market for goods produced by commercial enterprise. Box ② represents the market for EAF research, with respect to which there is market failure. Governments attempt to correct for this market failure by providing a subsidy for EAF research.

Figure 3(b), (right hand side). TIG creates a new class of market participants called Benchmarkers. Benchmarkers can be viewed as analogues to those "real world" commercial entities that (eventually) derive enormous value from scientific research outputs. In this way, TIG creates a synthetic market ③, for implementations (embodiments of algorithms) for solving important problems in computational science. The result is allocation of Innovator rewards according to relative performance of submitted implementations.

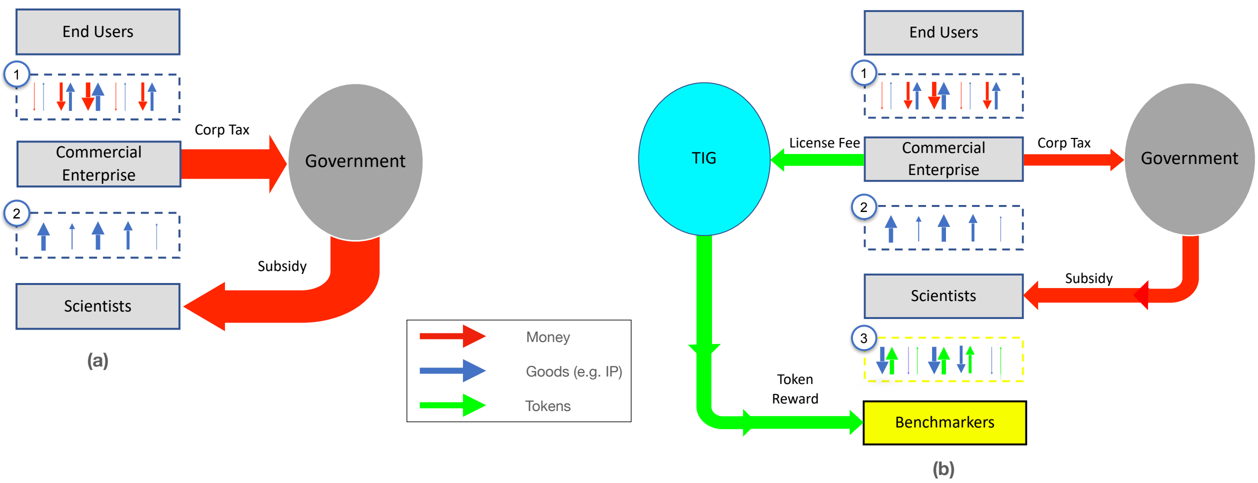

Figure 3: (a) represents the way that EAF research is currently funded: Through government subsidy, with non-market allocation. (b) represents the situation for TIG with respect to methods in computational science such as inverse methods: The Benchmarkers establish a synthetic market for these methods.

We note that the Innovator rewards may permit a reduction in government subsidies (as illustrated by the narrower red arrow on the right).