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RESEARCH ARTICLE

Uncertainty and dispute resolution for blockchain and smart contract institutions

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Abstract

Smart contracts have been proposed as a means of revolutionizing transacting between human actors and contributing to blockchain platforms substituting for many current institutions. However, the technical nature of blockchain platforms and smart contracts requires levels of certainty and foresight sufficient for contracts to be complete. We examine the technical and economic characteristics of blockchains and smart contracts to identify sources of uncertainty that may pose challenges to the ability of these technologies to displace existing institutional arrangements, in particular, the courts and other arbitration arrangements. Despite the development of alternative automated blockchain institutions such as the Kleros dispute resolution system, the case for smart contracts and blockchain applications to supplant real-world institutions remains weak. Inherent incompleteness due to limits to information availability, human cognition, and communication means that traditional contract governance institutions will continue to complement blockchain smart contract governance arrangements. The more complex and unique the transaction, the higher the value at risk, the harder to anticipate and precisely specify contingencies and measure and observe outcomes. Furthermore, the longer the time frame between agreement and execution, the less likely it is that smart contracting will be more efficient than traditional contracting.

Keywords: Blockchain; distributed autonomous organizations; distributed ledger technology; Kleros; smart contracts

1. Introduction

Blockchain technology is frequently cited as a disruptive game-changing innovation with potential long-term influence in commercial and social spheres. It has been portrayed as the 'next-generation Internet' (Shermin, 2017), a new 'foundational technology' (Iansiti and Lakhani, 2017) offering alternatives to firms and markets as a means of organizing transactions (Davidson *et al*., 2017; Wright and de Filippi, 2015). It is said to have the potential to influence how people interact and thereby change society (Zachariadis *et al*., 2019) – that is, applications may function as constitutional catallaxies governing interactions by numerous disparate 'citizens' in a democratic community of activity (Berg *et al*., 2020). However, it has also attracted concerns, particularly in regard to its potential to support illegal activities (e.g. 'Ponzi' schemes) and fuel the rise of new forms of authoritarianism (Werbach, 2018). Zachariadis *et al*. (2019: 106) observe: 'while opinions about blockchain's efficacy and legitimacy vary dramatically, even the firmest supporters of the "blockchain revolution" have conceded that the biggest challenge for the growth of distributed ledgers is and will be governance'.

One of the purported benefits of the burgeoning blockchain technology is its potential to act as an infrastructure supporting 'smart contracts'. Some proponents imagine a future where commerce will take place exclusively using smart contracts, thereby avoiding current activities such as contract drafting, judicial intervention, opportunistic behavior, and the inherent ambiguities of written language (Berg *et al*., 2020; Lesaege and Ast, 2018). Others highlight the elimination of reliance upon trust-based intermediaries made possible by hosting self-executing contract code on distributed systems, and the potential for commercial activity to take place between digital decentralized autonomous organizations (DAOs) without any need for human interaction or intervention (Tjong Tjin Tai, 2018). In these conceptions, blockchain technology facilitating smart contracts is heralded as not just a new means of transacting, but an entirely new paradigm of management potentially capable of disrupting traditional forms of governance (Pilkington, 2016).

Smart contracts are undeniably a technologically sophisticated innovation. The highest-profile popular example to date is offered by the blockchain platform Ethereum. It enables an entire panoply of applications – including smart contracts – to be written using its proprietary programming language Solidity and hosted on its distributed node network. Essentially, this is centralized and publicly verifiable computing where suitable encoded and digitally signed instructions (or their absence) trigger algorithmically determined events.

Significant advantages claimed for smart contract use include guaranteed performance due to the impossibility of legal intervention, the ability to bypass the need for costly legal advice, and other transaction cost savings (Tjong Tjin Tai, 2018). If smart contracts can reduce the costs of performance verification and enforcement – especially across international borders, where court jurisdiction is limited, or where one or both parties lack access to reasonably well-functioning courts or other arbitration processes – then they may feasibly lead to more efficient institutional arrangements (Gans, 2019; Reinsberg, 2019, 2020; Varian, 2010).

Yet, smart contracts and blockchain applications operate within a wider transactional framework where both physical and digital goods are exchanged (Gans, 2019). The digitization of transactions has led to new organizational and institutional forms (e.g. multi-sided platforms), motivating the design of new governance processes (Parker and Van Alstyne, 2018). If blockchain applications are more efficient substitutes for existing institutional forms (e.g. firms, markets, nation states, and their institutions such as courts) as a means of organizing transactions, hence in normal competitive interaction will replace them, then their governance arrangements must be capable of addressing all possible eventualities arising at least as efficiently as those existing institutions. If this strong test cannot be met, then it might be expected that smart contracts will be adopted within institutions where existing governance arrangements evolve to accommodate them (Sklaroff, 2017; Werbach, 2018) rather than leading to the creation of entirely new constitutional catallaxies.

As few sustained commercial activities to date have employed smart contracts, empirical evidence of alternative institutional forms emerging is sparse. This leaves theoretical and limited case study analysis of the small number of trials and pilots observed to date, as the inquiry methods best-suited currently to gain insights into the potential for blockchain applications and smart contracts to bring about the efficiency gains and institutional transformations anticipated.

In this paper, we employ an institutional economics analysis of the characteristics of smart contracts as they relate to both physical and digital transactions. The analysis is supported by one practical and one theoretical case study, to assess the effectiveness of the governance arrangements of the blockchain environments in which smart contracts will operate. We find that the requirement to code precise executable steps *ex ante* and effectively irreversibly (or unstoppably) using blockchain technologies necessitates a degree of precision and foresight about potential future eventualities that are unrealizable in all but the simplest of interactions. The rules-based approach necessitated when pre-programming transactions anticipate a state where complete contracting is feasible, so is not well-suited to an environment where unexpected outcomes can arise, leading to dissatisfaction and costly disputes. The ability to automate predetermined arbitration and dispute resolution processes to address the consequences of these unexpected outcomes is also constrained by limitations to complete contracting, notably bounded rationality, imperfect information, and information asymmetries when an agreement is struck and translated into code. This stands in direct contrast to principles-based governance frameworks offered under contract law and the courts which have developed

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ways to specifically address dissatisfaction and disputes arising as a consequence of contractual incompleteness. We conclude that for efficiency-raising objectives to be attained, a role will continue to exist for traditional contract governance institutions (notably contract law and the courts) as complements to blockchain governance arrangements.

The paper proceeds as follows. Section 2 defines smart contracts. Section 3 examines the economics of contracts focusing on their inherent incompleteness. It considers whether the technological features of smart contracts mean they are capable of addressing, or are constrained by, any of these limitations, relative to the current transactions for which they may substitute. In section 4, the institutional mechanisms developed to cope with contractual incompleteness are discussed, and the limitations of smart contracts in replicating these features are explored. Section 5 discusses the implications for the future of smart contracting. It includes an analysis of two proposed 'solutions'. First, a quasi-judicial application operating on the Ethereum blockchain (Kleros) intended to supplant traditional courts. Second, the proposed use of artificial intelligence (AI) to utilize learnings from real-world judicial processes to continuously improve the quality of computer-mediated contracts (self-driving contracts), where traditional and smart contract-based institutions exist as complements to each other. Section 6 concludes.

2. What are 'smart contracts'?

'Smart contracts' (in their current popular manifestation) operate within the context of blockchain technology. A blockchain is a form of distributed ledger which uses consensus algorithms to ensure that information placed on it has not been altered (Zachariadis *et al*., 2019), and transparency of ledger content, to assist in instilling trust in otherwise weakly institutionalized environments (Reinsberg, 2020). They were designed initially to settle the transfer of property rights in an underlying digital token (e.g. bitcoin) by combining a shared ledger with a cryptographically-based incentive system designed to securely maintain it, without involving a central clearing house or market-maker (Nakamoto, 2008). However, a blockchain ledger can also be used to record the fact of an agreement between the parties and the contractual terms agreed. It thereby provides an essentially immutable (or more accurately, tamper-resistant) record which can be referred to in the event of a dispute arising between the parties. The blockchain record is thus an improvement over paper records or simple digital renderings of them, which can be (relatively) easily altered (Catalini and Gans, 2020).

However, some blockchain platforms enable more sophisticated applications. For example, the Ethereum platform uses its token (ether) to enable the purchase and use of computing resources on its attendant Ethereum Virtual Machine (EVM) runtime environment to operate a wide array of applications. Drawing on the Turing-complete features of its proprietary programming language Solidity, 'smart contract' code – instructions that will self-execute at a future date when specified preconditions are met – can be written to operate on the EVM (Davidson *et al.*, 2017). This feature enables potentially very complex 'nests' of smart contracts to be created. In the sense that a firm is a nexus of contracts, this allows (theoretically, at least) the creation of completely autonomous organizational entities (DAOs) operating with little or no human intervention (O'Kelley, 2012). In the Coasian conception articulated in transaction cost economics by Oliver Williamson, Oliver Hart, John Moore, and others, firms and other institutions as aggregations of transactions exist precisely because of the inability to capture all relevant elements perfectly within the individual transactions themselves. Those institutions aggregating these imperfect transactions at lower costs will prevail over those with higher aggregation costs.

In essence, 'smart contracts' are not 'contracts' in the economic sense of being legally-enforceable promises with binding obligations on two parties seeking to broker a mutually-beneficial exchange in the 'physical' world (even though the properties being transacted may be in digital form). Neither do they capture the dynamic processes of search for partners, negotiation of terms, reaching (and in some cases recording) the agreement, and monitoring and enforcement of performance of the agreed terms that constitute the economic activity of real-world 'contracting' between human actors (as per

Williamson, 1979). Rather, they can be best described as static, one-time automating of some parts of a contractual agreement or agreements reached independently between human actors. Algorithmic rules that run on a distributed blockchain automatically respond to inputs according to pre-programmed rules. Inputs can be varied in type, including fully autonomous sensors (e.g. a digital thermometer), online inputs (e.g. a change in stock price), or external decisions by human agents in a physical world. Based on these inputs, the pre-programmed logic stored on a distributed blockchain automatically initiates the action irreversibly as all changes are written into an (effectively) immutable distributed ledger. Potential actions include distributing cryptocurrency or making a computation and issuing an output, such as triggering software or electromechanical (IoT) devices. Among the many useful and interesting features of smart contracts is the ability to embody multi-signature arrangements (including the N-of-M type) that are automatically verified for digital signatures.

Smart contracts form a subset of computer-mediated transactions (Varian, 2010). Their purported economic advantages are twofold. First, the immutability of the mechanism to activate the pre-agreed terms stands as a check on the potential for any of the parties to the agreement to opportunistically deviate at the cost of others, leading to a potentially more efficient outcome. Second, they benefit from the ability of the blockchain on which they are based, to enhance trust between parties that contractual undertakings will be performed where neither the social nor institutional mechanisms developed over time to support non-digital transacting are present (Gans, 2019), for example, in developing economies (Reinsberg, 2019). However, the interconnectedness between smart contracts and blockchain platforms can result in consequences not just for the parties to the contract but to the wider blockchain platform.

Blockchains dispense with centralized intermediaries (e.g. market-makers, banks, governments) by enabling the secure transfer of property rights associated with system tokens (coins) directly between participants. At the same time, they dispense with the (formerly valuable) role of intermediaries as means of ensuring that payments are made or clear title to the goods (or at least to the goods represented by the token) is transferred. For cryptocurrency transactions, these are one and the same. As Werbach (2018) articulates, blockchains allow trust in intermediaries to be replaced by trust in the code that ensures transactions are transparent, indelible, and in the case of smart contracts, unalterable after the terms have been agreed and coded. Smart contracts have also been proposed as substitutes for other institutional mechanisms such as reliance on reputation built up over time as parties directly observe behaviors (if the pre-agreed terms are automatically executed, the parties cannot act opportunistically – Gans, 2019; Nakamoto, 2008), contract law (smart contract code enacted on the blockchain in effect replaces non-digital laws – Sklaroff, 2017), and even the courts (if the code executes the pre-agreed terms perfectly, then disputes will not arise so courts will be unnecessary – Casey and Niblett, 2017; Lesaege and Ast, 2018).

These presumptions, however, appear to overlook some of the potentially efficiency-reducing complexities inherent in transacting. Smart contracts do not, of themselves, address issues to do with the incentives of humans to perform obligations that cannot be easily measured either digitally or by a third party, thereby limiting the circumstances in which they may be feasible (Gans, 2019). Furthermore, drawing on Williamson (1979), their indelibility necessitates a high degree of certainty that what is coded is what was agreed and intended, that the intentions of the parties will not change between the time of agreement and the time of execution, and that there are no weaknesses in the contract and blockchain code (which is visible to all who are interested) that render it liable to exploitation by unknown individuals, if blockchain institutions are going to improve on alternative arrangements. The expected costs of new risks must be considered. For example, unanticipated exploitation of the unintended behavior of the logic of the 900 lines of code governing the operation of The DAO (a decentralized autonomous company established on the Ethereum network) ultimately led to a significant loss of credibility (for both Ethereum and the blockchain/smart contract nexus) and a very costly hard fork of the Ethereum platform in 2016 (Dupont, 2017; Zachariadis *et al.*, 2019).

Thus, while smart contracts may hold some advantages for simple transactions involving purely digital properties such as cryptocurrency tokens, when transactions involve tokens representing

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non-digital assets, the performance (or non-performance) of obligations in the non-digital world, and/or complex interactions of many different obligations, the situation is likely far more nuanced.

3. Traditional *versus* smart contracts: the problem of incompleteness

The core problem facing smart contracts is the same as that for all contracts – they are incomplete. For a contract to be complete, prior to entering into the contract, the parties must be able to (Williamson, 1979):

- foresee all relevant contingencies that might arise;
- describe all the contingencies accurately;
- identify, after the fact, which contingency has occurred; and
- willingly agree upon an efficient course of action for each possible contingency.

Once they have entered the contract, the parties must abide by its terms.

In practice, all contracts are incomplete because the mapping from possible contingencies to rights, responsibilities, and actions cannot be fully specified, for a variety of reasons. These include but are not limited to: asymmetric or imperfect information; bounded rationality; opportunistic behavior; difficulties specifying or measuring performance; difficulties enforcing performance; and the presence of transaction costs (negotiation, information acquisition, etc.) (Milgrom and Roberts, 1992). Smart contracts may be able to address some elements of opportunistic behavior and enforcing performance by removing human discretion, and by clever use of incentives identified in stylized game theory models. They offer lower-cost and more secure means of transacting across national borders, and within jurisdictions where recourse to unbiased courts and well-established dispute resolution processes is limited. They may also, in some instances, lead to lower transaction costs by removing intermediaries with market power (Gans, 2019). However, they offer no special means of addressing many other reasons for incomplete contracts arising in the first place. Indeed, injudicious application may introduce new forms of incompleteness potentially leading to worse outcomes than in non-smart alternatives.

First, no human or digital actor can realistically foresee all contingencies that might arise. The actual outcome is therefore always uncertain, to a greater or lesser degree. Uncertainty can arise from two sources: opportunistic behavior controlled by human actors, which is to some extent predictable and therefore amenable to management via contractual incentives; and random events outside of human or digital control and, frequently even, any knowledge or foresight (Laffont, 1989). While algorithms utilizing game-theoretic principles can potentially align participants' incentives where the likely opportunism can be reasonably anticipated, it cannot where the relevant behaviors are not taken into account in the first place. For example, the opportunistic behavior leading to the DAO collapse was not foreseen, with very costly consequences.

Furthermore, a perfect prediction of what will occur in the future is impossible for either human or digital actors (a form of imperfect information). The more volatile is the environment in which the contracting is taking place, and the further away is the time at which the outcomes of the contract will be delivered (leading to the potential for more unexpected events to occur), generally the less likely it is that either party can make accurate predictions about what might actually occur. As most prediction models rely upon historic data, if the event is due to factors not anticipated by or correlated to the historic data, then even the best models (including AI algorithms) based on historic data (which may not always be available) will be unable to predict the outcome (Kay and King, 2020). In many instances even if data are available, the exact causal factors are unknown, so forecasts made using the data are inherently error-prone.

Because the parties have different information bases to begin with, and neither necessarily knows what the other party does or does not know (asymmetric information – Akerlof, 1970) they may form different views of what may or may not occur. This includes the likelihood that either may engage in opportunistic behavior that harms the other party or prevents the contract from delivering the

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expected returns or identifying what form that opportunism might take. Even if future events could be foreseen, the parties may not be able to rationally interpret what the outcome might mean for them or how it might affect their approach to negotiating the contract terms (bounded rationality – Simon, 1955). Moreover, the transaction costs of writing (or coding) a contract capable of taking into account all of these potential contingencies will be vast (Williamson, 1979). Even if it is possible to identify and code terms once, this does not reduce the costs of having to analyze each situation on its own merits and making a selection from a vast array of pre-coded scenarios. These will increase in number each time a new eventuality is either theoretically conceived or observed in practice.

Second, the limits of human cognition, linguistic precision, and differences in interpretation make it impossible for all the relevant contingencies to be described accurately and unambiguously. Some concepts defy precise linguistic expression in the first instance, leading to potentially many different ways of describing the same phenomenon, each of which may be interpreted differently by third parties. This poses particular difficulties when contingencies (variously described) must subsequently be reinterpreted as computer code (assuming the contingencies are amenable to coding in the first place). The more complex is the contingency, and the more difficult it is to describe what is required, the more likely it is that 'errors' will occur in translation. This is particularly likely when there are many interdependent steps in the contingency which rely on feedback from other steps and the order of their performance matters for the outcome.

As Sklaroff (2017) observes in relation to earlier computerized contracting technology Electronic Data Interchange (EDI), the precision of computer code is of no greater benefit than imprecise verbal or written human language if the underlying concept cannot be accurately expressed in the first instance. Coding potentially adds further distortions. While rigorous testing involving coder and contracting parties may eliminate some errors and misunderstandings, it is extremely costly in complex cases to test the code for all possible anticipated contingencies. And such testing itself is also subject to communication and interpretation limitations.

Third, it is not always possible after the fact to observe the contingencies that have actually occurred. Even if the outcome is visible (i.e. it is not deliberately concealed or unable to be observed in the first place), its detection and interpretation suffer from the same limitations of description and interpretation identified above, at least for human actors. To the extent that digitized detection is feasible, this may reduce some of the consequences of attending human detection for contingencies that were anticipated. However, if the outcome was a contingency not anticipated originally, so was not captured in the relevant code, it will not be 'observed' for the purposes of the smart contract. The code will therefore respond as anticipated by another contingency (e.g. non-performance) when this is not the optimal response. A human responder with more flexible observation criteria has more options available, but again may not be able to identify and observe the outcome (or may also trigger an inappropriate action).

Fourth, the ability to agree on courses of action for every possible contingency is infeasible for many reasons. The ability to agree on what should occur for even a small number of contingencies is transaction-cost intensive, meaning most contracts typically specify only those contingencies the actors perceive are most likely to occur. But limited predictive ability means these will not necessarily include the contingency that does eventuate (see above), especially if the environment is volatile or the outcome occurs a significant time after the contract terms are agreed. The parties' ability to agree to terms that will be optimal in the future is also constrained by their limits of foresight. The parties can make the best projection they can about what their preferred outcome will be, but by the time the outcome is delivered, their situation and preferences may have changed. The outcome – albeit exactly what was agreed – may no longer be the best outcome for them given other (unanticipated) changes that have occurred. While the agreed terms are performed, with the greater knowledge that comes from time passing, one or other of the parties may have preferred a different set of terms to prevail.

Finally, contracts are incomplete if the parties do not abide by the terms. To the extent that non-compliant actions can be anticipated, contract terms can be designed to include incentives for the parties not to act in this manner. However, these cannot always be anticipated, especially if novel circumstances occur that make non-compliance more attractive than the agreed terms. It may be that circumstances have changed so much that neither party wishes the current terms to prevail, in which case renegotiation is the preferred outcome. Yet the immutable performance of pre-agreed terms in smart contracts precludes such efficiency-raising renegotiation.

An illustrative example is furnished by the Percent Finance cryptocurrency money market which in early November 2020 published incorrect contracts that led to over 1 million dollars in cryptocurrency (at the current valuations) being locked in contracts and becoming unusable (Medium, 2020). In principle, the problem could in part be solved by the communities governing the cryptocurrencies involved but as there are no explicit (real-world) contractual relationships between Percent Finance and these parties, no resolution was apparent at the time of writing. The smart contracts concerned run on the Ethereum blockchain using the Solidity programming language. From a strictly technical point of view, these smart contracts worked as published, but because of a problem of interpretation and coding, the code did not function as intended, resulting in material losses for individuals concerned.

4. Institutional responses to uncertainty

The realities of contractual incompleteness have resulted in the development and evolution of various institutional mechanisms that assist the parties to enter into contractual agreements, that otherwise might be eschewed due to the uncertainties arising (Cooter and Ulen, 2016). These include contract renegotiation; reliance on reputations; relational contracting; reliance on the provisions of contract law; and arbitration processes (including recourse to the courts). However, smart contracts have limited recourse to these remedies, which poses a real challenge to the assertion that autonomous entities comprised solely of smart contracts can offer credible and feasible substitutes for these institutions.

4.1 Renegotiation

As the parties to contracts enter into them of their own free will, they can also by mutual agreement cancel them or renegotiate the terms in the event that changes in circumstances make this desirable. The very existence of the option for renegotiation, even if it is not utilized, addresses a real risk of contracting, especially for events far into the future where the effects of uncertainty are likely to be greatest. Thus, costs that may have been incurred and otherwise-undesirable outcomes avoided, and transactions that might otherwise be eschewed because of the presence of uncertainty can go ahead.

Smart contracts, however, by design and intent cannot be cancelled or renegotiated (unless this is included explicitly as a condition of the contract, which if they would defeat the purpose of certain performance of the agreed terms). Thus, if circumstances change in a manner that has not been anticipated and coded, the parties have no option other than to let the contract run its course and then negotiate another contract in order to get to the same outcome that could have been achieved by cancelling or renegotiating. However, it might be more costly to get there than under the non-automated alternative because the undesired original outcome – that would have been averted under cancellation or renegotiation – must necessarily occur before the preferred outcome can be obtained. Indeed, the end result may be a negotiation to a third outcome – one less preferred than the one that could have been achieved had cancellation and renegotiation been feasible, but a better outcome given that the contract has in fact been executed and costs of getting to the otherwise-preferred outcome have changed. The consequences for Ethereum following The DAO expropriation illustrate how the inability to renegotiate left no other alternative than a hard fork to remedy the consequences of an unexpected event.

This suggests that smart contracts will be less likely to be suitable in situations when the time between striking the deal and contract performance is large and/or the environment is volatile, as these are the circumstances when a renegotiation is most likely to arise in traditional contracts. They would also appear to be unsuited to high-value contracts where losses in the event of things not going to plan are large. Indeed, they appear to be best suited to contracts with a near-

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instantaneous performance where the costs and risks of unexpected changes are low and where the terms (including those for potential dispute resolution) are simple, unambiguous, and amenable to rule-based coding. That is, for fully digital assets where the delivery processes themselves are digital (e.g. payments in cryptocurrencies) and where the transaction costs of having to recontract are low. To the extent that the contracts involve digital assets representing physical assets (e.g. a physical good in transit for which payment in cryptocurrency is tied), the costs of performance and correction are unlikely to be insubstantial (e.g. supplying the requested item when an incorrect one has been supplied).

It has been proposed that smart contracts can be designed to include a degree of flexibility. For example, automated processes can be paused awaiting a quorum of affirmative votes before proceeding with a predetermined action. Furthermore, it has been proposed that AI can be applied to learn from past decisions to develop principles to apply in future decisions. However, neither of these options satisfactorily address the event of a truly unanticipated event occurring. In the first case, if the event is truly unanticipated, then *ipso facto* the coding cannot include detection of the state as a contingency requiring the automated action to be paused. In the second case, AI requires *ex ante* specification of models and variables of interest to be applied in the learning. If the unexpected event concerns unspecified variables not correlated to the variables actually observed, then it is not clear that an AI system will be capable of even detecting the situation, let alone learning or proposing new principles from it. This further supports the contention that smart contracts are less well-suited to complex situations or long time frames where the likelihood of unexpected events occurring is greater.

4.2 Reputations

Werbach (2018) identifies that blockchain technology allows participants to trust the outcome of the system without having to trust any individual participant. However, trusting the code to deliver a predictable outcome is not the same thing as trusting the integrity of those transacting on the blockchain.

When parties trade frequently and observably, they can develop reputations for abiding by a given set of also clearly-observable rules. Parties with good reputations can be identified during the search stage of a contract process. The counter-party may rely to some extent on the selected party acting within the rules for the transaction in question for fear of losing the good reputation and future trading opportunities. Reputation scores are frequently used in online transacting.

However, as reputation scores are based on historic data, they provide no specific guarantees about how the specific contract in question will play out. Even a party with an exemplary historic record may act unpredictably, opportunistically, or contrary to expectations in any given future transaction. Such an outcome may be more likely if the circumstances in which the contract duties are performed differ from those in which the reputation was developed. For example, if unknown to the counter-party, the position of the relevant party changes (say, this is the last trade the party intends to make, so reputation is no longer relevant). Thus, reputations cannot be relied upon as substitutes for contract terms specifying what will occur in the event of behavior outside the rules. While smart contracts can ensure the performance of the agreed terms of a specific transaction, they offer no special means of addressing the broader issues of trust and reputation underpinning long-term commercial relationships.

4.3 Relational contracts

Relational contract theory is characterized by a view of contracts as relationships rather than discrete transactions (Macneil, 1969). Relational contracts avoid the high transaction costs of agreeing and specifying a vast range of contingencies and terms. Instead, they specify a narrower set of principles under which the parties agree to interact, with a mutually-agreed arbitration process that can be invoked if either party believes the other has acted outside of them (Williamson, 1985). They differ from 'spot contracts' where the parties interact once only and have no expectation that they will interact with each other in the future. Spot contracts, therefore, rely very strongly on adherence to specified terms.

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Relational contracts are especially useful when the terms and outputs are very difficult to define, and when it is expected that as the parties interact with each other frequently over an extended period of time, changes will occur (in both the state of the world and participant knowledge and understanding) that are not necessarily easy to anticipate or describe. Employment contracts are one example. Principles-based regulation is another example (Black, 2008). Provisions within the constitutions of firms specifying how important governance and operational relationships are to be managed are frequently specified in relational terms, because (in Coasian terms) firms form precisely because the requisite transactions cannot be executed efficiently using spot contracts. In relational contracts, the parties learn more about each other (reducing initial information imperfections and asymmetries), and reputations for operating within the agreed principles can be developed. While these reputations may be valuable, they may not be easily transferable outside of the relationship. Hence, the strongest incentive for abiding by the principles comes from the desire to avoid a costly arbitration process and the attendant risk that arbitration may lead to a worse outcome.

The inherent transactional basis of smart contracts precludes the use of a relational approach to the management of uncertainties. This appears to rule out an entire class of interactions from consideration for smart contracts, as well as raising significant questions about the plausibility of DAOs. As firms are long-lived entities formed (at least partly) because of the costs of incomplete contracting for which relational contracts are a remedy, then they cannot be efficiently constituted within a technological environment requiring complete contracting as a necessary precondition.

4.4 Contract law

Contract law (consisting of both statutes and the body of precedents from historic cases) provides the rules by which (unless otherwise specified) contracts are governed. It assists with addressing the precision and interpretation of some contractual terms by providing explicit definitions to be applied in contracts within a given jurisdiction. To the extent that room still exists for interpretation, or that terms and meanings in both the law itself and contracts governed by it may take on different meanings in different contexts, access to the courts to seek a judicial ruling is available as a default arbitration process. Indeed, contract law itself provides a mixture of both rules to be applied in contracts and principles to guide judges when called upon to make rulings on matters of interpretation that could not be foreseen when the laws were drafted but will inevitably arise because of the inherent 'contractual incompleteness' of the law itself.

While smart contracts may take place within a set of overarching rules approaching those within contract law, the inability to capture and apply principles in code is a significant limitation. The use of principles in applying contract law is important, as even though all contingencies cannot be specified in advance, a process exists for finding a resolution in the event of disputes or unexpected outcomes arising. Contract law thus serves to substantially reduce transaction costs. If smart contracts dispense with the ability for principles-based arbitration, then there appears to be no alternative to the parties bearing the risks and costs of unexpected events as they fall, other than resorting to transaction-costly specific inclusion of courses of action for all anticipated contingencies. However, this still fails to account for those cases where the outcomes were not anticipated. If the costs and risks of smart contracting are too great for the parties to bear (e.g. for high-value one-off transactions with unique characteristics), then smart contracting may be more costly than relying on the established traditional institutional mechanisms.

4.5 Courts and arbitration

The courts and other arbitration processes provide the ultimate recourse to the resolution of contractual arrangements that do not play out as expected. Their precise benefit is their ability to apply principles and evidence to reach decisions on matters that are not easily resolved using prescriptive rules-based processes. An important consideration is that courts and arbiters are not bound to

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consider only the states and expectations when the contract was agreed. They are thus well-suited to making decisions when a myriad of contract-specific factors may have changed after the contract was initially agreed but were not anticipated by the parties at the time of entering into the agreement. In doing so, courts and arbiters may be guided by precedents of what has occurred when past decisions of a similar nature were decided, but ultimately every case is considered taking account of its own unique facts and context.

An *ex post* principles-based court or other adjudication and arbitration process (e.g. alternative dispute resolution processes) taking account of unanticipated changes that occur after a contract is agreed appears to be diametrically opposed to rules-based smart contracting where it is presumed that all possible contingencies can be anticipated *ex ante* and programmed into code, and be enacted without a change in the future. This appears similar to the tension between *ex ante* rules-based regulation. The only activities possible are those approved in advance by the regulator and competition law, where all activities are possible except a few high-profile exceptions, parties are free to experiment and any potential breaches are addressed *ex post* by the courts on a case-by-case basis (Black, 2008). In smart contracting, only those scenarios anticipated *ex ante* can be programmed into code and will be executed with certainty regardless of whether this is ultimately what the parties themselves might desire as time passes and they become better informed.

Welfare-enhancing innovative responses to these changes are precluded just as surely as innovative behavior outside the rules is precluded in tightly-regulated markets. While smart contracting allows certainty to be obtained that some anticipated welfare-harming eventualities are excluded, this is at the cost of welfare-enhancing (or at least loss-limiting) actions that are available in more flexible (less prescriptive) traditional institutional systems. We note this characterization differs from the continuum in Allen *et al.* (2019) between a centralized dictatorial regulatory state and decentralized private orderings. It addresses only the static efficiency costs and benefits of different dispute resolution processes themselves, and not the whole contracting process or wider economic and social environment in which the transactions take place.

5. Implications

While smart contracts may be capable of automating the performance and enforcement components of a contracting process, they are not well-suited to the development of institutional arrangements governing contracts between human actors who are boundedly rational and imperfectly informed. Uncertainty and risk are not abstracted away by smart contracts, and indeed new risks may be introduced. As long as humans must translate the intentions of contracting parties into computer code (including the coding of complex contractual nexuses such as those required for DAOs), the limit of human cognition and communication constrain the potential uses of blockchain and smart contract technology. While some transactions may be well-suited to these instruments, it appears that at best they offer a complement to rather than a substitute for traditional contracting institutional environments. The broad formal and informal governance arrangements that have evolved to facilitate traditional contracting offer an institutional framework for dealing with both complexity and uncertainty that appears incapable of being fully replaced by blockchain and smart contract institutions. These arrangements include but are not limited to reputations, relational contracting, contract law, the courts, and other arbitration processes and ultimately the state itself.

However, this has not dissuaded some blockchain and smart contract advocates from proposing the development of institutional arrangements performing similar roles, being pre-programmed into blockchain applications, in order to support completely separate and alternative institutional environments to firms, markets, courts, and even the nation state.

5.1 Kleros

One area of interest is the provision of automated dispute resolution systems as an alternative to court and other arbitration processes. Kleros proposes offering a decentralized third-party arbitration and

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dispute resolution process on the Ethereum blockchain (Lesaege and Ast, 2018). Other dispute resolution processes (Mattereum, LTO Network, Sagewise, Blockchain Arbitration Forum, Jury Online, and Enigma) are discussed in Allen (2019). We focus here on Kleros because, if effective, it may enable Ethereum to become a completely stand-alone alternative contracting environment (or constitutional catallaxy as envisioned by Berg *et al*., 2020) rather than merely a complement to existing traditional institutional arrangements.

Kleros proposes Crowdsourced Online Dispute Resolution (CODR) as a judicial mechanism based on the Athenian kleroterian, which used a form of randomized crowdsourcing to select 'jurors' to hear disputes and make rulings. It claims 'smart contracts are smart enough to automatically execute as programmed, but not to render subjective judgments or to include elements from outside the blockchain. Existing dispute resolution technologies are too slow, too expensive and too unreliable for a decentralized global economy operating in real time. A fast, inexpensive, transparent, reliable and decentralized dispute resolution mechanism that renders ultimate judgments about the enforceability of smart contracts is a key institution for the blockchain era'.

Kleros proposes to address this with 'a multipurpose court system able to solve every kind of dispute'. It 'works as a decentralized third party to arbitrate disputes in every kind of contract, from very simple to highly complex ones. Every step of the arbitration process (securing evidence, selecting jurors, etc.) is fully automated. Kleros does not rely on the honesty of a few individuals but on game-theoretical economic incentives'. Payments made in the Kleros coin pinakion using Schelling Point game theory concepts are used to promote jurors unknown to each other to 'tell the truth' in their decision-making. Kleros expects agents to vote for the true answer because they expect others to vote for the true answer.

The system is an opt-in one where smart contracts can designate Kleros as the arbitrator in case of a dispute. This reflects the ability for non-digital contractors to nominate an arbitration service or specify the legal jurisdiction in which disputes will be heard. Kleros anticipates developing a number of specialist 'courts' over time, to hear cases in different areas (e.g. e-commerce, transport, insurance) and sub-areas (e.g. air transport, sea transport, air transport within transport) where specialist knowledge is required of the jurors. When these are available, the contract can specify which of these the dispute will be heard in, or whether a general court is sufficient.

When a dispute arises, the aggrieved party can trigger a Kleros process by completing a form identifying the nature of the dispute (in effect, selecting from a predetermined checklist what the nature of the 'problem' is). Evidence in free-form English to be used by the jurors is encrypted and securely uploaded, but not posted on the blockchain (in order to preserve privacy). Each complaint leads to the automatic generation of a new 'contract' (process) specifying computer-generated options for resolution (these are being developed using standard contracts and standard dispute resolution mechanisms) and the number of jurors required. The contract is 'broadcast' on the blockchain, and potential jurors can signal their interest by depositing tokens. The system then selects jurors, with those depositing more tokens having a greater chance of being selected. After assessing the evidence, the jurors 'vote' for one of the options (the decision cannot be changed) and provide a reason why they chose that option. Kleros documentation indicates no process to deal with a dispute with a check in the 'none of the above' box.

Jurors do not see each other's votes, but they can still declare they voted in a certain way, although offering no reason why they thought this was true (required for Schelling Point to be effective). Votes are aggregated and the smart contract is executed based on the most popular decision. Jurors are rewarded with a fee determined by the relevant sub-court; jurors who vote 'incoherently' with other jurors will lose some of their tokens which are distributed to the 'coherent' jurors (the majority). Kleros jurors thus face a clear incentive to select easy and uncontroversial cases where there is a high likelihood of all jurors agreeing. The smart contract will determine, based on the decision, which original contract party pays the arbitration fee. For the process to be fully automated, it may be necessary for the parties to the original contract to deposit the arbitration fee in a smart contract escrow, which is divided and paid to Kleros and the non-liable party when the disputed contract is decided or refunded to the depositor after a given period of time assuming no dispute has been lodged. An appeals system is also included.

While the Kleros system exhibits many external features reminiscent of real-world court and arbitration systems, its *ex ante* automation relies on pre-determined options and outcomes. Tractability relies upon a limited number of options chosen from what, over time, may build up to be a very large number of possible candidates. These factors render it unsuitable for all but the simplest and most straightforward agreements with a very limited number of expected outcomes and potential disputes, which must be capable of rendering into bright-line 'yes/no', 'right/wrong', or other formulaic checklists. That is, the disputes most suited to Kleros are ones that arise frequently and already have tailor-made remedies available to be executed after jurors viewing the evidence respond to predetermined choices of assignment of liability.

It begs the question therefore of what form of hearing is possible for a novel dispute arising from circumstances unexpected by either the contracting parties or the Kleros personnel coding the 'off the shelf' smart contracts available for selection as remedies by the jurors. A traditional court is capable of arbitrating such a case, and potentially coming to a novel (precedent-forming) decision and/or remedy. However, the Kleros system appears to leave the aggrieved party bearing both the unexpected outcome from the execution of the original smart contract and with apparently no recourse to 'justice' (at least within the originally-selected arbitration process). Furthermore, Kleros also fails to replicate traditional judicial system incentives. Kleros jurors are rewarded for conformity, not skillful application of the law and fact interpretation to novel situations. Cases which are the most uncertain, because there are not good coded precedents to populate the solution options 'on the table', are the most likely to lead to disagreement between jurors and therefore a higher likelihood of jurors losing the coins deposited when bidding for the case. The 'popular' non-controversial cases will lead to the highest bids, while difficult and novel cases will struggle to recruit a panel. This is the opposite of the traditional legal system where judges 'compete' for appointment to the most difficult or controversial cases in order to employ and enhance their large stocks of human capital and to build up their reputations for insightful or precedent-setting decisions.

Given these conditions, it seems most unlikely that smart contracting on the Ethereum blockchain with Kleros adjudication will be desirable for novel transactions with uncertain outcomes. Although Kleros may promise quicker and less-costly resolutions than a traditional process, it is not providing the same service. Indeed, it is arguably worse than the traditional arrangement, as there appears to be no way for the system to automatically identify cases that do not fit the check-box or 'smartly' update itself over time with better or different decisions or alternatives (precedents) generated from its own system. A human-mediated traditional court or arbitration process running alongside (i.e. complementary to) the automated system thus appears necessary if disputes arising from novel or unexpected outcomes are to be satisfactorily resolved. Indeed, if such an option is not available, it is likely that the transition of those transactions that are well-suited to an automated smart contracting environment (simple, frequent, low-value, low-risk, short time frame) will be delayed. As a result, the time at which the transaction cost savings that can be anticipated from such a change will accrue.

5.2 Self-driving contracts

By contrast, Casey and Niblett (2017) conceive of 'self-driving contracts' as a potential alternative to blockchain-based smart contracts. It offers an example of how complementary institutional arrangements can evolve over time, albeit that it may go one step too far in proposing the eventual replacement of traditional arbitration processes.

The authors acknowledge as a starting point the reality of the incompleteness of contracts. They do not propose, as for smart contracts, that computer-mediated transactions will specify the full details and contingencies of the contract. Rather, they imagine a future where the parties could specify intentions or goals. Then an AI would be able to 'fill in the gaps' in line with these goals as more is learned about the environment in which the parties are operating. In their conception, artificial agents will fill in contractual gaps in the way a mediator or court might do today.

This approach appears to have promise, as it acknowledges both the reality of information asymmetries and the dynamic nature in which knowledge is acquired over a longer period of time. It also builds upon principles-based contract law; therefore, the arrangement appears more consistent with long-term and relational contracts. This suggests the ability for automation of more complex contracts than appears feasible with blockchain-based smart contracts. However, it stops short of providing an automated disputes resolution process, at least in the short run. At least until sufficient information is acquired, a human judicial system will still be required to adjudicate cases and provide precedents to inform the AI system. However, the intention is that eventually, the AI will have sufficient information to 'fill the gaps' in ways that will reduce reliance upon more costly human-mediated systems.

A self-driving contract system thus may be able to create contracts that take account of iterative changes in a particular environment – for example, new ways of engaging in opportunistic behavior that emerge as parties respond to contracts with new and different terms. It may also address the problems arising from human actors being imperfectly and asymmetrically informed, and boundedly rational. However, it begs the question of whether any AI taking as its base historic information can adequately prepare contracts that can cope with totally unexpected situations unable to be predicted by a fully-informed and perfectly rational human actor. Also, how will it cope in the case of unique new environments totally unprecedented in human experience? While the number of cases of this type may be small, it is not impossible that they can occur. Thus, a system aware of the incompleteness of real-world contracts must, for the sake of completeness, have arrangements in place that 'expect the unexpected'. It is difficult to imagine any better instrument than the current human court or arbitration systems (albeit that in an AI-enabled world, they may have access to a different range of information to make their decisions than is available to the courts currently).

6. Conclusions

A smart contract requires all actions to be amenable to pre-determined coding. The greater the number of variables to be monitored and the degrees of uncertainty that those variables might communicate, the greater is the likelihood that the order in which the events will occur is uncertain. The likelihood is higher that something totally unexpected might occur, making it harder to satisfactorily capture the requisite interactions in a 'smart contract' to be executed (in one or more stages) *ex post*. These are exactly the characteristics that render even standard digital renderings of real-life transactions problematic. Unless all possible eventualities can be anticipated and coded unambiguously *ex ante*, it must be expected that unanticipated outcomes will render the contract unsuitable for its originally-intended purposes. Predicting these eventualities is impossible given the boundedly rational nature of humans and their interactions, let alone environmental uncertainties which can be neither predicted nor controlled by human actors. Laws, incidentally, are also extremely difficult to code as experiments by Shay *et al.* (2016) have shown for relatively simple tasks such as automating traffic speed limits.

This suggests smart contracts may be suitable for a number of highly-standardized spot transactions with predetermined outcomes undertaken between strangers. However, they are unlikely to be useful for governing highly-complex transactions or novel transacting environments, or any better than existing computerized applications for governing interdependent relational-based commercial interactions between parties who are known to each other and interact frequently. A risk exists that over-use of smart contracts will result in a reduction in contractual flexibility to suit algorithmic processing that will crowd out the ability for future contractual experimentation and attendant welfare increases if they are the only way in which parties can interact in a given market. This tension is akin to the use of *ex ante* regulation (centralized control) to impose the use of only a small number of approved standardized contracts, as compared to competition law (distributed) governance, where all forms of interaction are permitted except for a limited number of violations whose use is detected and prosecuted *ex post*. As uncertainty is inherent in almost all interactions, smart contracts are unlikely to become ubiquitous unless imposed unilaterally. Ironically, a technology (blockchain and smart contracts) purported to support the development of new forms of distributed societal interaction can succeed only by sacrificing *ex post* distributed flexibility for *ex ante* centralized rigid control.

Furthermore, the blockchain institutional environments in which smart contracts are utilized are not well-suited to providing mechanisms to resolve disputes arising from the consequences of imperfect contracts because the solutions themselves are imperfect. For example, applications such as Kleros are constrained by the self-same limitations as the contracts they oversee. This suggests that, despite hopes held for blockchains to become complete stand-alone institutional environments where all commercial interactions can take place, the reality is far more nuanced. Traditional institutions such as contract law, the courts, and arbitration processes are better-suited to addressing the consequences of unexpected and unpredicted outcomes than blockchain institutions, simply because they take account of the limited foresight and cognition of human actors. This suggests that enabling contracting parties to choose between the environments on a contract-by-contract basis, based on the characteristics of the transactions in question, is both a pragmatic and efficiency-raising solution. Future research might examine how the court system interacts with smart contracts. Also, how the issue of identity is used and develops in this context as a blockchain identity amounts to nothing more or less than the possession of a private key corresponding to a given public one. This prompts to know the solution to a particularly difficult mathematical problem.

However, in order to facilitate greater experimentation and use of smart contracts, it may be preferred by smart contracting parties to 'hedge their bets' by not forgoing the benefits of having smart contract-related disputes resolved using real-world mechanisms, especially if the costs and risks of the contract are substantial. In this way, both systems can benefit from learning about the different challenges arising from the consequences of contractual incompleteness in the two environments. This will support the development and improvement over time of algorithms for use in computer-mediated contracting environments, such as those indicated in the 'self-driving contracts' model. Without a doubt this will require adaptations to the substance and expectations of both contract law and blockchain design, but this is not new for contract law, at least.

In conclusion, therefore, it appears that the 'entirely new paradigm of management potentially capable of disrupting traditional forms of governance and management' –anticipated by blockchain and smart contract advocates – will still rely to a very great extent on the institutions that have been developed and evolved over thousands of years to support human interactions.

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