Block Chain Technologies & The Semantic Web: A Framework for Symbiotic Development

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Abstract. The concept of peer-to-peer applications is not new, nor is the concept of distributed hash tables. What emerged in 2008 with the publication of the Bitcoin white paper was an incentive structure that unified these two software paradigms with a set of economic stimuli to motivate the creation of a dedicated computing network orders of magnitude more powerful than the world's fastest supercomputers. The purpose of which is the maintenance of a massive distributed database known as the Bitcoin "*block chain*". Apart from the digital currency it enables, block chain technology is a fascinating new computing paradigm with broad implications for the future development of the World Wide Web, and by extension, the further growth of Linked Data and the Semantic Web. This work is divided into two main sections, we first demonstrate how block chain technologies can contribute toward the realization of a more robust Semantic Web, and subsequently we provide a framework wherein the Semantic Web is utilized to ameliorate block chain technology itself.

Keywords: Block Chain, Smart Contracts, Linked Data, Semantic Web

1 Introduction

With the rise of the Bitcoin crypto-currency the concept of distributed block chain databases received wider attention. Based on the distributed block chain infrastructure a wide range of distributed applications can be built. The most recent and innovative approach in that regard is Etherum platform, which includes a Turing-complete programming framework aiming to realize smart contracts. Similarly as block chain technology can facilitate distributed currency, trust and contracts application, Linked Data facilitated distributed data management without central authorities. In this article, we investigate how the block chain and Linked Data concepts can be fruitfully combined to realize novel applications.

One of the problems with the block chain as a technology is the negative association it has inherited due to the illicit nature of some early applications of Bitcoin as a currency. Moreover the polarization of it's advocates, who often regard it as a panacea, i.e. "*the most important invention in the history of the world*"[3], and vehemence or apathy of its detractors, e.g. Jamie Dimon the chief executive officer of JPMorgan Chase, quick to write it off completely as a "*waste of time*"[4], has contributed toward an environment wherein it is difficult to isolate the novel contributions of block chain technology, of which there are some, and how they might be harnessed to improve the infrastructure of the Web, a development we regard as both desirable and actionable.

This work proceeds with a two-pronged demonstration, first we provide an objective analysis of block chain technology in the context of its relevance to the Semantic Web. With our framework firmly established we go on to describe a methodology for the implementation of several applications made possible through the integration of well known Semantic Web concepts within the computational architecture of the block chain and set forth a benchmark for evaluating the validity of our approach.

In Section 2 we provide a high level description of the functional underpinnings of the Bitcoin block chain and examine two technologies that extend the current block chain in ways applicable to the contribution we describe above. Section 3 is comprised of two component analyses, we first demonstrate our model of a block chain based URI naming scheme that positions the RDF data model in closer alignment with the concept of Cool URIs [2]. Section 4 describes the composition of an extensible ontology for block chains and the resultant Linked Data ecosystem in the context of exploring the exchange of value within a network as well as the unification of the disparate technical nomenclature, towards creating a common understanding of analogous components existing in silos of the development landscape this open-source community continues to foster. Subsequently we examine the case for novel semantic applications of decentralized Industry 4.0 platforms from online education to supply chain management.

2 Background

The block chain facilitates a resilient and highly distributed ledger for recording transactions, attributing them to a specific node in a network, and ordering them in time. This is the functionality that undergirds the cryptocurrency Bitcoin (BTC), among others. This phenomenon is made possible through a process known as "*mining*" whereby a large number of dedicated high-powered computers running application-specific integrated circuits (ASICs) [8] process the transactions of the Bitcoin network in real time, competing with each other for a small fee associated with a new transfer in BTC in addition to a "*subsidy*" in the form of a fixed amount of newly minted Bitcoins.

Data is permanently recorded in the Bitcoin network through files called blocks. A block is a record of some or all of the most recent Bitcoin transactions that have yet to be recorded in prior blocks. Mining is the process of adding transaction records to Bitcoin's public ledger of past transactions. This ledger

[3] http://rogerver.com
[4] http://fortune.com/2015/11/04/jamie-dimon-virtual-currency-bitcoin

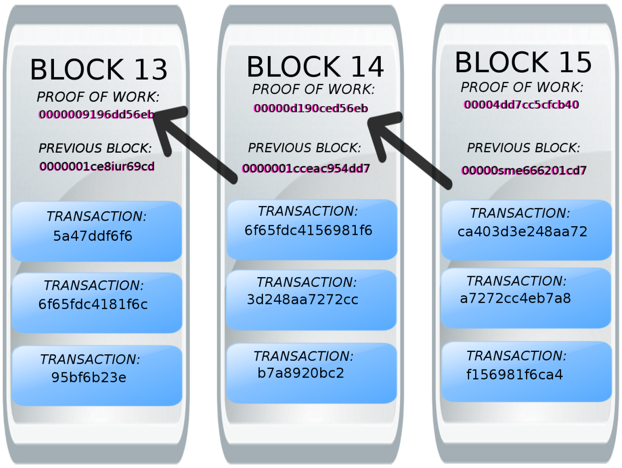

Fig. 1. Illustration of a Block Chain

of past transactions is called the block chain as it is a chain of blocks. The block chain serves to confirm transactions to the rest of the network as having been executed.

Block Chain. A useful analogy for conceptualizing block chain technology is peer-to-peer (P2P) computing, wherein a distributed application architecture partitions work loads among equally privileged participants in an application, forming a peer-to-peer network of nodes. A block chain is a globally shared, transactional database, similar to the peer-to-peer file sharing system BitTorrent. All participants in a block chain network can read the database.

Where it diverges from P2P applications is in the "*consensus*" mechanism. Changes in the database are performed by means of transactions, which have to be accepted by the participants in the network. Transactions are atomic (i.e. executed in full), durable (i.e. can not be altered) and cryptographically signed by the creator (guarding access to modifications of the database). Figure 1 illustrates the block chain concept. Several transactions are bundled in a block and then executed and distributed among the nodes in the block chain network. In case of conflicting transactions, the first one is given precedence and subsequent conflicting ones are discarded.

Block Chain 2.0. The securing of a cryptocurrency network notwithstanding, there are a multitude of applications that can be run alongside, or in conjunction with the Bitcoin block chain, taking advantage of the large amount of computational effort generated by the dedicated mining machines and the open access afforded to this processing power available to all holders of even nominal amounts, i.e. 0.00000001 (known as 1 *Satoshi* after the author of the original white paper [4]), of BTC.

Furthermore there are numerous forks of the original open-source Bitcoin code, known as "*altcoins*", the majority of which implement negligible or generally uninteresting modifications. That said, in this paper we explore two of such forks that have extended the original block chain concept in ways which can be utilized to provide useful and unique services, extending the block chain concept in powerful ways.

Bitcoin's scripting language allows one to store small amounts of metadata on the block chain, which can be used to represent transactions more complex than simple exchange such as asset manipulation instructions, i.e. escrow services that cannot release a transaction without consent from multiple parties. These ancillary applications have come to be known collectively as "*Block Chain 2.0*".

Smart Contracts. The original block chain network can be regarded as a tool to execute a system of contracts focused on the application of value exchange. Altcoins such as Namecoin adapted this original "*currency application*" of the technology into other applications, in the case of Namecoin, to DNS registration.

Ethereum is another Altcoin project which attempts to build a more generalised block chain technology; on which all transaction-based state machine concepts can be built, to provide to the end-developer a tightly integrated end-to-end system for building software on a hitherto unexplored compute paradigm in the mainstream: a trustful object messaging compute framework, i.e. performing non-trivial computations within the block chain itself [14].

While the Bitcoin block chain does allow very simple transactions (i.e. the transfer of funds from one account to another), Ethereum expands the concept of transactions to arbitrary complex contracts dubbed "*smart contracts*". For this purpose, transactions contain an algorithmic description of the smart contract and Ethereum provides programming languages and APIs for devising the smart contract.

Ethereum Virtual Machine The Ethereum Virtual Machine (EVM) is the runtime environment for smart contracts in Ethereum. It is sandboxed and completely isolated (i.e. code running inside the EVM has no access to network, filesystem or other processes). Smart contracts even have limited access to other smart contracts.

In subsequent sections we explore how the extended functionality of "*smart contracts*" facilitates a series of novel methods for the symbiotic development of block chain technologies with the Semantic Web.

3 What can Block Chain do for Semantic Web?

In the preceding sections we examined the novel computational paradigm that block chain as a technology makes feasible. In this section we will demonstrate ways in which block chain technology can be applied in practice towards the actualization of a more resilient architecture for the Semantic Web.

3.1 Secure Resource Identifiers

On the Semantic Web, all information is expressed in statements about resources. Resources are identified by International or Uniform Resource Identifiers (IRI/URIs). While URIs are very beneficial, they also have some inherent weaknesses:

- *Centralization.* While individual URIs can be minted in a distributed fashion, the identifier generation relies on the centralized DNS system, which poses a single point of failure or attack.
- *Persistence.* In case of intentional (e.g. a merger or acquisition of a legal entity) or unintentional (e.g. bankruptcy) events, the persistence of identifiers can not be guaranteed.

There are three key requirements which an ideal identifier system should fulfill:

1. *Secure:* dereferencing identifiers should not be prone to attacks, i.e. when retrieving the content of a website or resource the authenticity of the content should be ensured.
2. *Human-readable:* it should be possible to give identifiers intuitive names, which can be easily remembered by humans.
3. *Decentralized:* no central authority should control identifier creation and pose a single point of failure or attack.

Zooko Wilcox-O'Hearn conjectured that no single kind of naming system can achieve more than two of these properties [3]. Aaron Swartz [6] described a naming system based on Bitcoin employing Bitcoins distributed block chain as a proof-of-work to establish consensus of domain name ownership. These systems remain vulnerable to an attack wherein the reputation system is subverted by forging identities in the peer-to-peer network but is secure under Byzantine fault tolerance.

Namecoin implements the concept. Namecoin is a decentralized open source information registration and transfer system based on the Bitcoin block chain itself. It enables users to dis-intermediate the Domain Name System (DNS) providers, one of the last bastions of centralization in the architecture of the modern web.

Practically speaking the issues identified above have afflicted the Semantic Web community in the past, e.g. the shuttering of Freebase by it's acquirer Google [16]. Consider the semantic machine learning system NELL (Never-Ending Language Learning) [5], which aims at remaining operational indefinitely. For such an ambition as this to be credible we must rely on a system that satisfies the aforementioned criteria, a system such as Namecoin. Consequently we have commenced the implementation of a fully functional mirror site to dbpedia.org under the top-level domain dbpedia.bit. To achieve success in this endeavour there are some technical hurdles to overcome, we detail these now.

On the protocol level, there are no constraints on URIs in Namecoin; names can be made up of arbitrary binary data with a length of 0 to 255 bytes. If we want a .bit DNS name, in Namecoin syntax the name should be structured as "d/example" where "example" must be a lower-case, valid domain name. New resources are assigned subdomains to dbpedia.bit. Listing 1.1 demonstrates a simple exemplary query on the de-referenceable block chain based naming scheme for DBpedia under the domain 'dbpedia.bit'.

```
PREFIX ex: <http://dbpedia.bit/exampleOntology#>
SELECT ?capital ?country WHERE {
  ?x ex:cityname       ?capital ;
     ex:isCapitalOf    ?y .
  ?y ex:countryname    ?country ;
     ex:isInContinent  ex:Europe .
}
```

Listing 1.1. SPARQL query on .bit TLD

In terms of long-term viability, names on this system can be transferred and thus also sold. It is even possible to sell names in a trust-less way in exchange for Namecoin currency, since the transaction sending the name and the transaction paying the seller can be made atomic. If a wallet owning a name disappears the name expires 36,000 blocks after the last update, so it will stay active for some time but then become available again for a new owner.

3.2 Namecoin Access

The Namecoin block chain stores the pertinent information for navigating the .bit top level namespace. However, since .bit domain names, are not yet part of the standard domain name system, these can not be de-referenced without additional support. For example, there are .bit web proxy servers that will correctly handle these DNS requests in a browser as well as extensions for Firefox, Chrome and online look up services[5]. To dereference or retrieve resources from dbpedia.bit run the core client, using the "name_show" RPC command, e.g. "name_show d/domob" on the debug console, or "namecoin-cli name_show d/domob" on the shell.

3.3 Storing data in the block chain.

There are multiple ways to store data directly within the Bitcoin block chain.

1. *Value:* Encode data in the number of *Satoshis* being sent to an address.
2. *Vanity address:* Brute force through keys until arriving at an address that encodes personalized data, i.e. encoding the pattern 1ESWC as in 1ESWCs3d48d3198863e75m7f9d1827cdfc6048e.

[5] http://namecha.in/name/d/domob

3. *MultisigAddress:* These are more complex Bitcoin addresses that require more than one signature from a private/public key to redeem the value.
4. *OP_RETURN:* Command in the Bitcoin scripting language that was specifically added to permit the inclusion of metadata (up to 40 bytes) on the block chain.

Moreover, units of real world value distinct from the block chain can be affixed to nominal amounts of BTC, as stock certificates were once printed on paper, the paper itself has some small value, but it represents (presumably) a greater value insofar as it is the physical manifestation of part ownership in some corporation. A so-called "*colored coin*" is used in conjunction with a wallet specially tailored to recognize such additional information, thereby conferring the benefits of the block chain's distributed trust mechanism to a multiplicity of novel applications [13]. We regard this as the most feasible medium of synthesis between block chain and representations of information in the Linked Data ecosystem.

4 What can Semantic Web do for Block Chain?

Through formal semantic knowledge representations we have created an ontology for capturing data within the block chain. The utility of such a shared conceptualization is twofold. Primarily it facilitates a shared understanding of block chain concepts between humans. Additionally, by exposing the block chain data according to an ontology, we enable interlinking with other Linked Data to conduct formal reasoning and inference.

Our work extends, in keeping with the principles of ontology reuse [18], an initial vocabulary created by Melvin Carvalho [9][6]. In so doing we formalize key concepts such as wallets, blocks and transactions. We render the vocabulary suitable for graphical analysis using Visual Notation for OWL Ontologies [12].

4.1 Exploring the Block Chain

One of the beneficent features of block chain technology is that it increases transparency through a completely open ledger (in order to establish trust) while simultaneously ensuring anonymity through preserving accounts behind their public keys. However, the transparency is currently only established on a technical level. For humans it is cumbersome to track transactions and accounts on the block chain. The vocabulary based representation of the block chain data increases transparency and analysis capabilities for human users.

We propose a model whereby transactions are represented in RDF, and thereby support the linking of wallets related by transactions to follow exchange activity around the network. The first generation of block chain explorers[7] are limited in efficacy by the aforementioned issue, as in Listing 1.2 transactions represented in JSON are notoriously difficult to follow throughout the network.

[6] `http://cc.rww.io/vocab`
[7] `http://blockchain.info/`

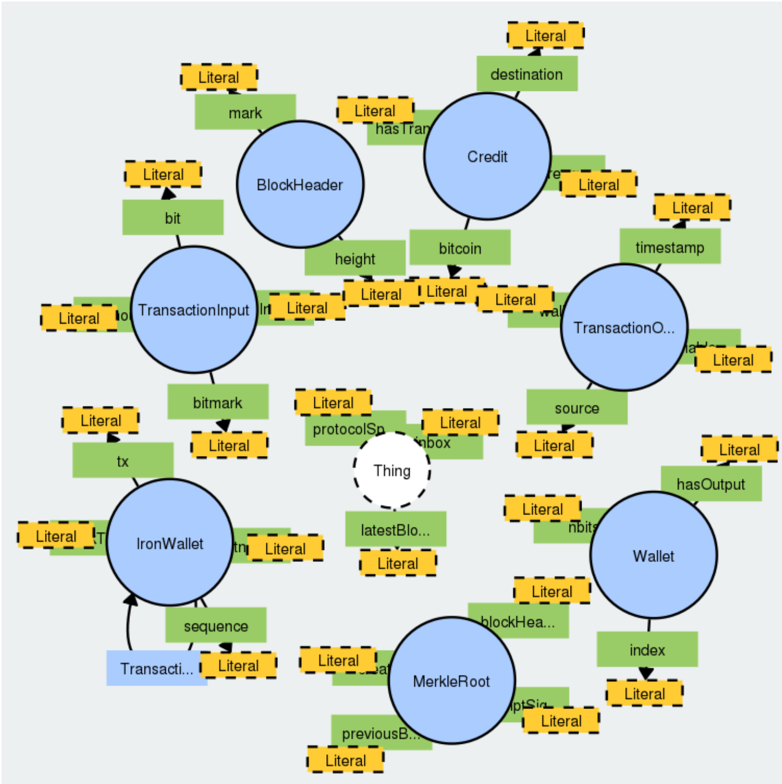

Fig. 2. Diagram Illustrating the Ontology


```
{
    "balance" : 43.50100000,
    "errors" : "",
    "paytxfee" : 0.005,
    "proxy" : "",
    "connected" : 0,
    "testnet" : false,
    "difficulty" : 1733207.51384839,
    "blocks" : 179602
}
```


Listing 1.2. JSON Exploration API Output

Our working ontology, implemented in OWL, melds the Carvalho vocabulary with the Bitcoin API calls list [8]. Furthermore we include functionality to actualize the working model of Ethereum smart contracts. However, since Ethereum is in an early stage of development, further changes are likely to be required in the future. Additions comprise in particular the ability to bind the validity of transactions to certain geospatial locations, to facilitate the generation of so-called

[8] `http://en.bitcoin.it/wiki/Original_Bitcoin_client/API_calls_list`

"*smart property*", property whose ownership is controlled via the block chain, with access contingent upon ownership of a public/private key pair [1].

4.2 Testnet Block Explorer

The term "*testnet*" is used to refer to a block chain created by forking the original Bitcoin code repository[9], configuring several nodes, and commencing the mining process on one's own machine or local network. This practice is the primary mechanism for block chain-based experimentation. Naturally testnet coins are distinct from Bitcoins "*in the wild*", they are not intended to denote monetary value, permitting iterative development without large capital outlays or adverse effects to the main Bitcoin block chain.

Transactions can be described using our working block chain vocabulary[10]. The supplementary information thereby created can be injected into the block chain by one of several methods:

- The coinbase field of a mined block allows for hexadecimal data which can hold 560 bytes.
- Use of a "*colored coin*" and corresponding specialized wallet.
- Multiple outputs can be used for a transaction such that each holds hexadecimal data. This would imply dust value outputs (outputs of $\leqslant$ 0.00005640 BTC) and in practice would contribute relatively "*large*" amounts of superfluous data to the block chain, a technique known as "*bloating*" and generally considered bad practice.
- Hexadecimal data from a multi-signature transaction can also be used to encode information.

The open-source *Block Explorer*[11] can be used to examine the contents of transaction blocks, i.e. recipient and sender addresses or code snippets delivered through counterparty exchanges and recorded in the testnet block chain as depicted in Listing 1.3.

```
{
  "sender": "1QBb5MpKUMiqc27wrD2QDRsC9gZYyy49",
  "recipient": "1AdCDBz2VmhUZDyDbibMo2QGGSjt93zbF",
  "size": 479,
  "merkleroot": "f5b3309272c5fcb3febb0f09986e77158",
  "time": 1440604813,
  "bits": "1814434",
  "difficulty": 54256630327.88996,
  "reward": 25,
}
```

Listing 1.3. Testnet Output Specifying Counterparties

Describing transactions in the context of Linked Data, as contrasted with a less expressive representation, facilitates a number of benefits. Binding transactions to individuals or organizations in furtherance of transparency, or to a

[9] http://github.com/bitcoin
[10] http://github.com/smenglish/block.chain.ontology
[11] http://testnet.blockexplorer.com

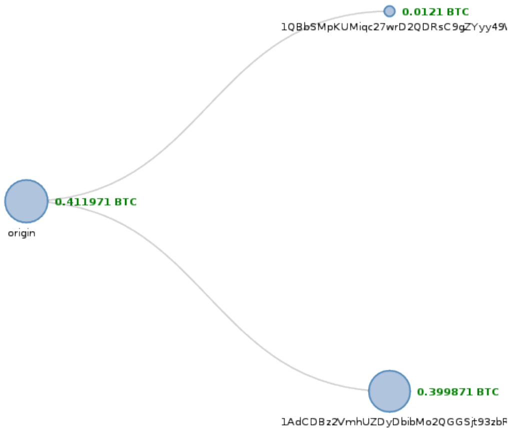

Fig. 3. Graphical Representation of Linked Transaction Counterparties

particular geographic location as in the execution of so called "*smart property*" arrangements. In Figure 3 we demonstrate how such a transaction propagates through our network, with many of such applications taking place there is an emergent linked data ecosystem of value transmission.

4.3 Standardization

At the time of writing, contributors to the core Bitcoin block chain code number less than four hundred individuals[12]. If block chain technology will become an integral component in the infrastructure of the modern Web it will necessitate its being thoroughly understood by a much greater community of developers. The lack of such a common understanding was cited as one of the premiere issues impeding this continued growth of block chain technology by Gavin Andreeson the successor to Satoshi Nakamoto as the principal maintainer of the bitcoin code base [7]. Accordingly we have contributed to a the creation of the first publicly-available[13] shared ontology to facilitate improved comprehension within this burgeoning development community.

5 Use Cases

In this section we outline a two prominent use cases of combining block chain and semantic technologies.

Industry 4.0 The fourth industrial revolution, Industry 4.0, is a collective term embracing a number of contemporary automation, data exchange and manufacturing technologies. It had been defined as "a collective term for technologies and

[12] `http://github.com/bitcoin/bitcoin/graphs/contributors`
[13] `http://github.com/smenglish/block.chain.ontology`

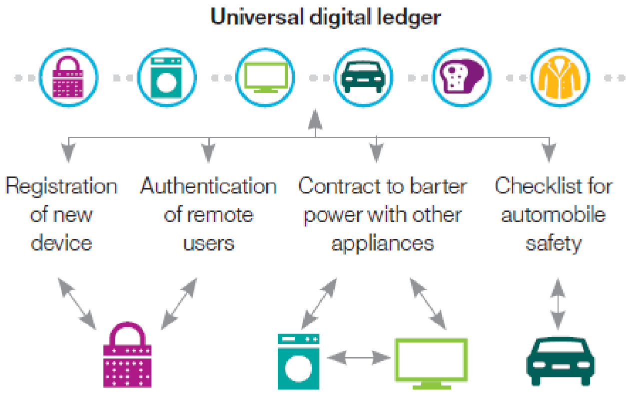

Fig. 4. Using the block chain as universal digital ledger for Industry 4.0 transactions [15].

concepts of value chain organization" [17] which draws together Cyber-Physical Systems, the Internet of Things and the Internet of Services, and critically Semantic Technologies. In this section we consider the ways the union of block chain technologies and the Semantic Web is shaping the continued development of this latest phase of industrialization.

Using block chain technology, a fully decentralized data marketplace for sensor data could be realized. Instead of establishing individual contracts with every data provider, the block chain could become a clearing house for sensor data exchange. In [15] IBM describes the vision of employing the block chain as universal digital ledger for Industry 4.0 transactions, such as registration of devices, authentication of users, bartering and supply chain transparency. For these applications, a comprehensive semantic description of the products and half-products exchanges in the value chain is essential. Finally, such descriptions should be linked with related information contained in other systems of the participating companies.

As a concrete example, Listing 1.4 shows the core logic of a Ethereum "*smart contract*", which represents an address on an Industry 4.0 [11] supply chain management platform. The `mortal` super-class defines the initialization and finalization of the smart contract. The contract `accountManager` itself comprises a potentially large array indexed by accounts with each entry comprising two pieces of information, an URI identifying a certain product type and possibly linking to further information about the product as well as a hash identifying a concrete product realization or production batch. The public key authentication of Ethereum ensures only a certified account owner can update information about the provenance of his products or semi-products. If other participants in the supply chain, refer to such a product or semi-product (e.g. in a way that it is incorporated/used within their product) the public ledger based on the

Etherum block chain ensures, the provenance of products and their incorporated half-products and ingredients can be traced back along the supply chain.

```
contract mortal {
    /* Define variable owner of the type address*/
    address owner;
    /* this function is executed at initialization and sets the owner of the contract */
    function mortal() owner = msg.sender;
    /* Function to recover the funds on the contract */
    function kill() if (msg.sender == owner) suicide(owner);
}
contract accountManager is mortal {
    /* data structure to hold accounts*/
    struct Account {
        string uri;
        bytes32 hash;
    }
    /* mapping of accounts to data*/
    mapping (address => Account) accounts;
    function setAccount(string uri, bytes32 hash) returns (bool)
        return setAccount(msg.sender, uri, hash);
    function setAccount(address account, string uri, bytes32 hash) returns (bool) {
        bool rv = msg.sender == owner || msg.sender == account;
        if (rv) accounts[account] = Account(uri, hash);
        return rv;
    }
    function readAccountUri(address account) constant returns (string)
        return accounts[account].uri;
    function readAccountHash(address account) constant returns (bytes32)
        return accounts[account].hash;
}
```

Listing 1.4. Simple Ethereum Contract on Industry 4.0 Platform `Provenance.org` [10]

Online Educational Credentials Figure 5 above shows a scenario of how a smart contract platform such as Ethereum could support micro and standard accreditation within a higher educational setting. Educational establishments including universities and MOOC companies such as FutureLearn develop and deploy courses and award recognition of student achievement through certificates, micro-certificates and badges. Students take courses and gain recognition after registering for and completing courses through certification. In an era of re-skilling and lifelong learning[14] students will increasingly take a variety of courses from a variety of providers over a longer period of time. There is a need in this context for students to be able to collect and store all their informal and formal qualifications in a fashion that makes these easily accessible to relevant parties such as potential employers and educational organisations. The above process can be supported by two decentralized block chain based applications (DApps) running on the Ethereum network. A Certificate Issuing and Validation DApp would handle the publication of signed certificates within a block chain. Secure signatures would tie all certificates to the specific issuing educational institution and the receiving student. Because of the nature of block chains the certificates

[14] No 21 year old on completion of a bachelors degree will have gained all the skills he or she requires for the rest of his/her life

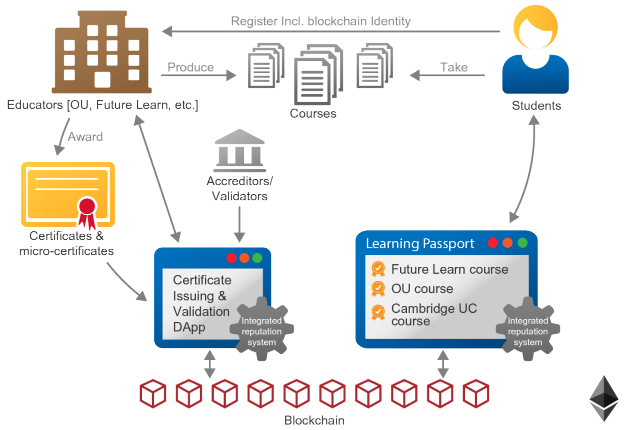

Fig. 5. A scenario of how block chains and smart contracts can support accreditation and certification in higher education

would remain valid even if the issuing organisation ceased to exist. Recently, the University of Nicosia has placed all the certificates for its free introductory MOOC "*An Introduction to Digital Currencies*" within the Bitcoin block chain.[15]

A Learning Passport DApp would enable learners to easily view and manage all recognition of their learning no matter if informal or formal. These might include badges collected for course completion from MOOCs and formal degree course certificates. Each of these two DApps would incorporate evaluation and reputation services. Certificates can be verified partly through reputation, but also be stored as credentials on the platform. For example, a verified credential proving certain prerequisites at one institution can allow a student to easily enroll in a higher level course at another. This allows the platform to operate with little overhead. Evaluation and reputation services would allow teachers and students to match their learning styles effectively. It will also set the stage for self-regulation of the system. Semantics can help in supporting interoperability issues in the above scenario. Namely:

– Mapping from university and educational establishment data structures into the data structures as required by block chain transactions and for the smart contracts.
– Semantically, indexing template smart contracts and transactions for re-use.
– Mapping between the Learning Passport data format into arbitrary certification and badging systems.

[15] `http://digitalcurrency.unic.ac.cy/certificates`

6 Conclusions and Future Work

In this work we have endeavoured to catalogue the results of a thorough analysis of block chain technology in terms of it's applicability as a computational paradigm to the Semantic Web and Linked Data community. Furthermore we have presented the results of our initial efforts to fuse these two constructs in mutually beneficial ways by extending the traditional Linked Data naming convention, providing an ontology for representation of elements and events in the block chain ecosystem, and building a procedure for Link Data representation of transactions in a block chain network. We have done a first step towards synergisticly integrating two promising decentralized data management technologies – Linked Data and block chains. It is the first step on a larger research agenda aiming to realize a truly distributed, democratic and domain-agnostic knowledge system.

At present we are undertaking efforts to apply our approach more generally to the Bitcoin block chain itself, we are interested in a comprehensive graphic analysis in RDF of the entire Bitcoin block chain, specifically one that is generalizable to *altcoins* as well. The dynamic nature of the Ethereum implementation codebase made it difficult to implement and test some of the ideas described in this article. We plan to create a comprehensive implementation and evaluation of integrating the Linked Data concepts into the Ethereum block chain.

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