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Review

REA, Triple-Entry Accounting and Blockchain: Converging Paths to Shared Ledger Systems

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Abstract: During the last half century, the concept of shared ledger systems that offer a single source of truth has challenged traditional bookkeeping, leading to innovations such as the resource-event-agent (REA) accounting framework, triple-entry accounting (TEA), and blockchain. Despite these advancements, the historical development of shared ledger systems remains under-researched and unclear, with the influence of REA on TEA particularly overlooked. This study aims to fill this gap by conducting a genealogical analysis of shared ledger systems, with a focus on tracing the development of TEA and its historical byproduct of the REA framework designed by McCarthy. Through a comprehensive literature review and interviews with pioneers in REA, TEA, and blockchain, we uncover the missing link between REA and TEA. Our findings suggest that the current explosion of shared ledger systems results from the convergence of three parallel research streams, occasionally interacting with each other. We correct common misconceptions, acknowledge the influence of key individuals, and map out the overlapping paths of REA, TEA, and blockchain. By elucidating the historical evolution of shared ledger systems, this study contributes to the academic debate and fosters further discourse among researchers in REA, TEA, and blockchain, thereby enhancing the potential applications within these fields.

Keywords: triple-entry accounting; REA accounting model; single source of truth; blockchain; distributed ledger technology

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1. Introduction

Scientific revolutions begin with extraordinary investigations that advance normal research (Kuhn 1996). According to (Kuhn 1996, p. 91), this is a very special stage in paradigm shifts, in which "scientists take a different attitude toward existing paradigms, and the nature of their research changes accordingly," with a "willingness to try *anything*...".

In the accounting profession, one such set of investigations were conducted between 1458 and 1494, with the works of Benedetto Cotrugli (1573), Marino de Raphaeli (1475 in Sangster 2015) and Luca Pacioli (1494). As a result of these investigations, double-entry accounting was applied for five centuries with widespread acceptance. However, a second revolution that took place between 1982 and 2008 has been rather overlooked.

Shared ledger systems emerged as a fruit of this revolution. One prime example of these systems is triple-entry accounting (TEA). Although this novel accounting concept does not change the fundamental philosophy underpinning accounting, it challenges the very role of the bookkeeper by addressing the possibility where the integrity of the bookkeeper is implicated.

In recent years, TEA has begun to catch the public attention from far-related fields such as computer science. Indeed, the computer science community has managed to materialize the fundamental principles of TEA through blockchain technology (Vijai et al. 2019)[1]. Meanwhile, TEA has inspired a number of works on real-time auditing and continuous assurance from the accounting community (Dai 2017; Dai and Vasarhelyi 2017; Alawadhi et al. 2015; Auditchain 2018).

These valuable and interrelated lines of investigation on TEA have not yet been duly pursued (Cai 2019, p. 3). The history of TEA is told in an incomplete manner, leaving the significance and implications of this scientific revolution poorly understood. Due to gaps in the tale, TEA has been widely believed to be the result of a cryptographic revolution with radical implications for accounting (Rao 2020; see also Cai 2019; Gröblacher and Mizdraković 2019; Inghirami 2019; Pacio 2018a).

However, the reverse is also true.

In this paper, we posit the existence of an opposite chain of causality, i.e., that a revolution in accounting broadened the applicability of cryptography. Specifically, we claim that the research of William E. McCarthy (1982), Todd Boyle (2000a, 2000b, 2000c), Ian Grigg (2005b) and, possibly, also Satoshi Nakamoto (2008), constitute an interrelated set of works telling the cohesive story of shared ledger systems.

Moreover, we show that TEA is, in part, a historical byproduct of the resource-event-agent (REA) accounting framework designed by McCarthy. While parallels between TEA and the REA framework have been noted (Gomaa et al. 2023; Grigg 2017a, 2017b, 2017c), the historical influence of the latter over the former remains overlooked as a result of an underappreciation of the stream of work revealing the 'missing link' between REA and TEA, primarily carried out by Todd Boyle (2000a, 2000b, 2000c).

With this in mind, we seek to fill in these gaps by conducting a genealogical analysis of shared ledger systems, correcting common misconceptions and investigating the largely unacknowledged influence of William E. McCarthy on TEA and today's blockchain technology.

In order to achieve this goal, we conduct a comprehensive literature review that covers the following: William E. McCarthy (1982), Robert Haugen (Haugen and McCarthy 2000), Todd Boyle (2000a, 2000b, 2000c), Ian Grigg (2005b), G. Ken Holman (2019), Yuji Ijiri (1975, 1982) and Chris Cook (2002). We place a particular emphasis on the works of Todd Boyle, the missing link between REA and TEA. We also spoke with pioneers in REA, TEA and blockchain to document the oral history of shared ledger systems. As shown by Figure 1, we find that the current explosion of shared ledger systems use cases has resulted from the convergence of three streams of research, developing in parallel and occasionally interacting with each other.

The contribution of this paper stems from the fact that, so far, historical ties between the REA framework and TEA have remained unexplored, possibly due to Todd Boyle's withdrawal from the field. This gap in the literature could obscure the potential of TEA and blockchain applications within REA initiatives. It may also limit an understanding of how blockchain and TEA systems could benefit from decades of accounting tools developed specifically for shared ledger systems within the REA framework. Additionally, there is significant confusion regarding the concept of TEA, including the relationships between concepts sharing this name. Our research aims to clarify and reveal these connections.

The rest of the paper is structured in the following manner. Firstly, we specify the terminology and elaborate on essential concepts of shared ledger systems. Second, we outline the methodology of this article. Next, we discuss the historical development of the aforementioned systems. Finally, we discuss and conclude with some general considerations.

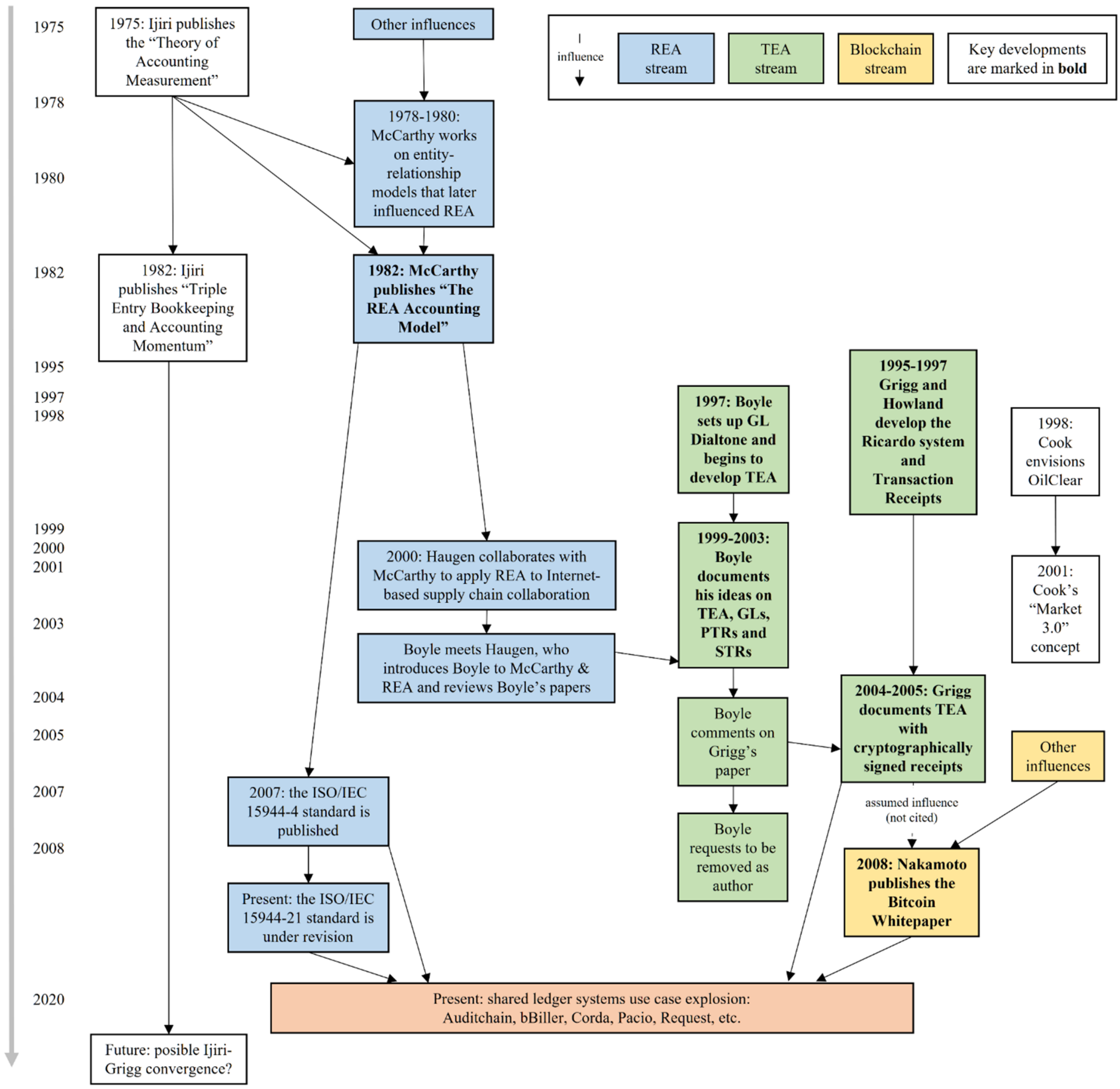

Figure 1. Essential history of TEA, showing the parallel development and confluence of three streams of research on shared ledger systems, namely REA, TEA and blockchain.

2. Concepts

2.1. Triple-Entry Bookkeeping

Our discussion of the historical development of TEA begs the question of what TEA is in the first place. We base our taxonomy on Grigg (2019a), who distinguished between triple-entry bookkeeping (TEB) and triple-entry accounting (TEA).

Triple-entry bookkeeping is defined as recordkeeping for two or more parties through a shared transaction repository (STR) with a "signature—signature—signature" structure (Grigg 2005a), i.e., a "triple-signed receipt" (Odom 2013, 2015). This means that in order to update the shared entry two parties need to be involved as follows: One party makes a unilateral transaction entry ("request," "offer" or "transaction draft") and the other approves this entry ("acceptance"). This can be seen as a signature-gathering process as follows: One party adds their signature to the transaction entry draft, the counterparty accepts by signing, the entry is validated and it is stored in the STR. The STR checks the validity of the signatures through a middleware server or distributed ledger technology network, and then itself signs off on the entry (Boyle 2001f, 2003e; Grigg 2005b). This generates a hashed triple-signed receipt such that all the parties hold the same data, and it guarantees that the data cannot be manipulated or lost via a single, shared entry, which is the single source of truth. In computer science terms, this is an implementation of the "what you see is what I see" (WYSIWIS) principle (Brown 2020).

In TEB, a local copy of the shared transaction repository may be integrated as a sub-ledger to the general ledger of transactional parties. This was termed a "stub—shared entry—stub"[2] structure by Boyle (2001b). However, because the shared entry is the sole reliable source of the transaction record, some have referred to this as "single-entry bookkeeping" (Pacio 2018a, 2020). Nevertheless, we discourage usage of this term. First, the term "single-entry bookkeeping" has already been reserved for simplified bookkeeping systems as opposed to double-entry bookkeeping. Single-entry bookkeeping systems only record stock accounts, i.e., assets and liabilities, without including flow accounts such as revenues and expenses (Ijiri 1986, p. 746) that double-entry bookkeeping systems do, and without two entries or sides (debits and credits) for each transaction (Grigg 2005b). Different from this type of simplified, single-entry bookkeeping, TEB is compatible with double-entry systems (Boyle 2000a, 2000b, 2000c). In effect, TEA represents pairs of double entries with each pair connected to a central receipt, resulting in three parties holding the triple-signed receipts (Grigg 2005b). This is another reason to call this concept triple-entry, rather than single-entry. Finally, even if there is a solid case for the usage the latter term, the former one is already an established category in the industry (Gröblacher and Mizdraković 2019; Ibañez 2022)

Note that the word "entry" is polysemic. In "historical" single-entry bookkeeping, the entry is the record of an asset or a liability without a counterpart to that record (Ijiri 1986, p. 746). In "modern" single-entry bookkeeping, it is the record of income or expenses, also without a counterpart (IRS 2015). In double-entry bookkeeping, an entry is a debit or a credit record (IRS 2015)[3]. In Boyle and Grigg's TEB, instead, the entries include three signature records, i.e., the three parties (Grigg 2005b). Furthermore, the single copy of the triple-signed record is in three places (ibid.). This means that TEB does not challenge double entry's bilateral recording of transactions.

2.2. Triple-Entry Accounting

Triple-entry accounting presupposes triple-entry bookkeeping, but also exceeds it. The difference between one and the other goes in parallel with the distinction between bookkeeping and accounting themselves. Bookkeeping is defined as recordkeeping, i.e., simply keeping a sequential (chronological) record of transactions, whereas accounting builds on bookkeeping to make that information flow into the decision-making areas of the firm, by means of systematizing, compiling, collating, synthesizing, processing, analyzing and/or auditing.

The position that bookkeeping and recordkeeping are synonymous (and to distinguish them from accounting in the above-mentioned manner) appears to be the majority position in the peer-reviewed literature (Rukhiran and Netinant 2018; Vollmer 2003, p. 357) and in many instruction manuals and handbooks (Chandler 1977, pp. 109–10; Ge 2005, p. 3; Ginigoada Foundation 2017, p. 3; Peters-Richardson 2011, p. 7; Wild et al. 2011, p. 4). This mainstream position will be followed in the remainder of this paper. However, it is worth noting that some authors believe that there is no difference between bookkeeping and accounting (Lomax 1918, p. 74) or they adopt different definitions (Edwards 1960, p. 447).

Additionally, we observe usage of both terms, i.e., double-entry bookkeeping and double-entry accounting. However, the two entries are fundamentally a trait of the bookkeeping system, not the accounting itself. It is nevertheless legitimate to speak of double-entry accounting, because the specific accounting edifice is determined by the bookkeeping technique. However, this nuance should be kept in mind. Similarly, there is nothing intrinsically "triple" about TEA, yet the underlying changes in TEB should impact the accounting method to an extent, thus justifying the term.

Thus, TEA is TEB with an accounting solution (Ibañez 2022; Ibañez et al. 2023). In other words, TEA includes a shared transaction repository with a "signature—signature—signature" structure, but it is not limited to just sequentially storing transactions. Rather, it also serves to classify and interpret them, facilitating decision-making, financial analysis and forecasting, tax planning and financial reporting.

As an example, let us imagine that Alice buys from Bob two bicycles in 2019 which are identical in every possible way: One bicycle is purchased in March for USD 70 and one bicycle is purchased in April for USD 80. In January 2020, Alice sells one bicycle to Charlie for USD 100. To record the transactions, Alice proposes transaction entries over a system managed by Ivan. Bob and Charlie accept, Ivan verifies the validity of the transactions, and the transactions are entered in a shared record. This is triple-entry bookkeeping. However, the following question arises: What was Alice's profit from the transaction with Charlie?

Alice can resort to a number of methods to calculate the profit from each transaction, such as last-in first-out (LIFO), first-in first-out (FIFO) and average cost (AVCO) (Peters-Richardson 2011, pp. 104–7; Wild et al. 2011, pp. 234–36). The choice between these methods will determine, for example, whether Alice made a profit of USD 20, 30 or 25 in her transaction with Charlie. Nevertheless, this choice is a matter of accounting, not one of bookkeeping. Thus, having a shared transaction repository (TEB) does not, by itself, answer this question.

Either the choice between methods of assigning costs is left to Alice, Bob and Charlie, or it is predetermined in the accounting software that they use. In any case, it is an accounting decision, with nothing specifically "triple" about its nature. However, Ivan may choose to integrate an accounting module[4] into the TEB system used by Alice, Bob and Charlie. In other words, Ivan may offer them to purchase a subscription to his online ERP system or webledger,[5] such that the TEB transaction records are automatically entered into each party's webledger. This may also allow Alice, Bob and Charlie to publish financial reports or to be audited, possibly in real time. This accounting module built on top of the TEB record is called triple-entry accounting (Ibañez 2022; Ibañez et al. 2023).

2.3. The REA Framework

Resource-event-agent (REA) is a model for an enterprise information system (Geerts and McCarthy 2006)[6] originally conceived by William E. McCarthy (1982). It proposes semantic abstractions generalizing business events (Boyle 2000c). This "computer software model of real-world (. . .) activities" is an "ontology" or "semantic model", i.e., a "set of classes, relationships, and functions in a universe of discourse" (Haugen and McCarthy 2000). The REA model purports to replace the classical double-entry accounting system with an information system integrated to all functional areas of an enterprise, i.e., not just limited to the accounting department. Nevertheless, REA can still be used to support the reporting artifacts of double-entry accounting, such as balance sheets and income statements (Gal and McCarthy 1986; McCarthy 2001).

William E. McCarthy (1982) conceived REA as a solution to the deficiencies in existing accounting models, including imperfect classification schemes, the lack of granularity in data and the lack of integration of the accounting system with non-accounting information systems in an enterprise. To solve this, he designed REA as a conceptual modeling tool for a centrally defined database containing atomic transaction records with all the relevant variables. At the core of this model lies the representation of transactions as business events, where the companies' agents exchange resources.

Originally, McCarthy and his followers were spelling out the conceptual framework for an integrated business information system for the various areas of a single company. Nonetheless, with the advent of the Internet, the REA model was extended to multiple business entities in a trading community, that is, to inter-company accounting[7].

Typically, accounting requires to record inter-company transactions from the perspective of one of the parties (ISO/IEC 2015, p. 3). For instance, "the mirror image of every sale recorded into receivables by a seller, is also recorded as a purchase, into accounts payable by a buyer" (Boyle 2000f). Therefore, accounting records are viewpoint dependent. McCarthy, however, proposed a representation of real-world business events from an independent, inter-enterprise view (ISO/IEC 2015, p. vii) that, simultaneously, was able to support different views of itself. This proposal was designed with the ANSI/X3/SPARC architecture for a database management system in mind (McCarthy 1982, p. 557; see also Tsichritzis and Klug 1978) and eventually resulted in the Open-edi Distributed Business Transaction Repository (OeDBTR) project led by the ISO/IEC JTC 1/SC 32/WG 1 eBusiness Working Group, which is discussed below.

2.4. Differences and Similarities between REA, Triple-Entry Systems and Blockchain

REA is a generalized framework establishing an ontology, whereas both TEA and TEB can be deemed implementations of REA (see above for a discussion of the differences between TEA and TEB). Nevertheless, when applied specifically to inter-entity transactions, REA offers a concept that is functionally equivalent to TEB, i.e., the Open-edi Distributed Business Transaction Repository (OeDBTR).

OeDBTR is the term assigned, within the REA ontology, to a single-entry system which tracks the immutable history of events triggering changes of state in multiple business entities, relying on the independent view of the transaction as a single source of truth and the open-edi standard for electronic data interchange described in ISO/IEC 15944-21 (McCarthy and Holman 2019; see also Holman 2019). TEB and the OeDBTR, thus, share the following fundamental characteristic: a viewpoint-independent record of transactions that is shared between two or more parties, and that can support different local "views" of the transactions.

How each transaction entry in a shared record manifests itself differently from the viewpoint of each party to the system is best represented as a three-dimensional bookkeeping grid, in which N sheets equal the N parties in the system, as depicted in Figure 2.

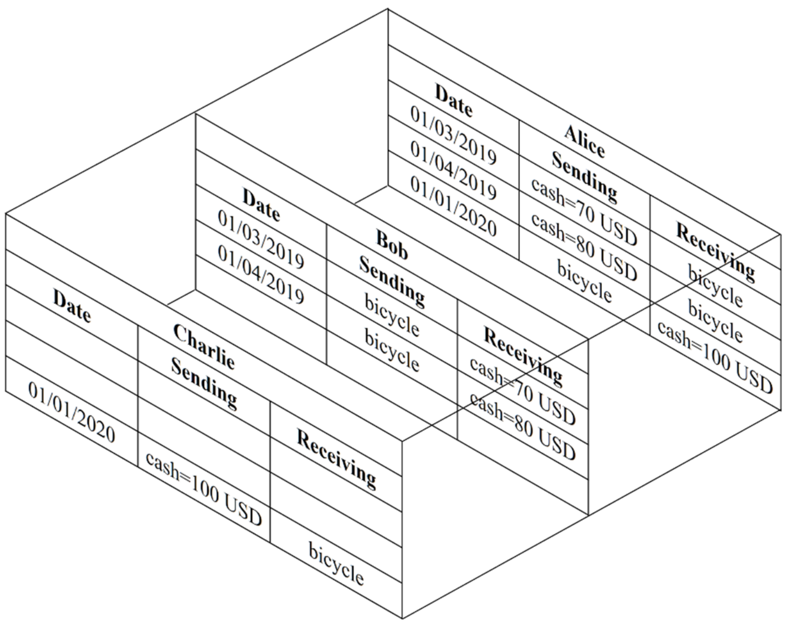

Figure 2. A simplified three-dimensional shared record of transactions. The same transaction record manifests differently from the viewpoint of each user, i.e., in each sheet[8]. Based on Boyle (2003a, 2003f).

Historically, shared transaction records and three-dimensional accounting were technically infeasible. Therefore, each party to a transaction had to make its own, duplicated, viewpoint-dependent record of the same transaction in its own, two-dimensional books. We call this "redundant bookkeeping". However, as Internet-based shared data environments such as triple-entry systems or OeDBTRs become possible, redundancy can be eliminated. In consequence, we posit that TEB and REA's OeDBTR are comparable.

Figure 3 presents a stylized comparison of the discussed accounting schemes. Triple-entry bookkeeping systems and REA both propose to eliminate redundancy through a shared transaction record constituting the single source of truth. REA provides for a shared "collaboration space" where the economic events in which agents participate are recorded (McCarthy 2016), but it does not specify the practical procedure necessary to agree on the single record. TEB introduces a signature-gathering process involving the two parties plus a trusted third party. In this context, TEB can be seen as a more concrete implementation, which takes this extra step at the cost of losing generalizability (Grigg 2020a).

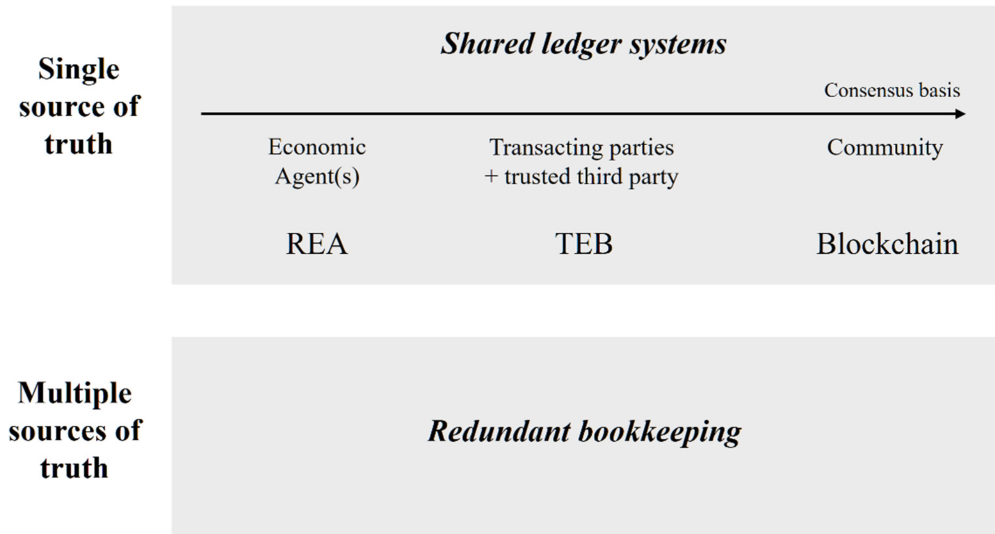

Figure 3. With traditional redundant bookkeeping, multiple sources that describe the same economic event exist and various versions can arise. This differs from shared ledger systems such as REA, triple-entry bookkeeping and blockchain, which incorporate designs for a single source of truth. The consensus basis on which the truth is determined depends on the specific shared ledger system.

Blockchain technology develops the TEB model even further. It is a form of distributed software architecture that allows untrusted actors to securely agree on a transaction record without a central point of supervision (Tasca and Tessone 2019; see also Liu et al. 2019). To do so, it replaces the trusted third party that characterized original TEB designs with community-based consensus. In this manner, blockchain shows that the collaboration spaces envisioned in REA are practicable with current computational possibilities (McCarthy 2016).

3. Methodology

To conduct a genealogical analysis of shared ledger systems, a multifaceted approach was employed, which combined both the literature review and the primary data collection through interviews. The research commenced with an exhaustive review of both the scientific and the grey literature on TEA, TEB and REA. The inclusion criteria for the literature were any articles mentioning or delving into triple-entry accounting. For REA, the literature that emerged from TEA literature was considered, followed by the literature emerging from saturation analysis, involving a recursive search process. This consisted of an iterative repetition process of examining the literature section of the bibliography consulted, until all the literature found referred internally, ensuring a comprehensive understanding of the subject and that the significant literature was not overlooked. In total, 150 articles, websites, industry reports, public statements, and white papers were reviewed.

Complementing the literature review, interviews were conducted with 15 key participants who played pivotal roles in the history of TEA, or who were currently working in systems combining REA and TEA, including notable figures such as McCarthy, Boyle, Grigg, Odom, Haugen, Holman and Hartley. These interviews were open-ended and allowed participants to share their insights and experiences freely. Out of the 15 interviews conducted, statements from 8 participants were incorporated into the final paper.

The genealogical analysis approach was chosen as it is best suited for understanding the historical and conceptual evolution of a topic. The combination of a comprehensive literature review, saturation analysis, and interviews with key figures ensured that the research captured the full breadth and depth of the subject and provided a holistic understanding of the historical ties between REA and TEA.

4. Results: A Genealogy of Shared Ledger Systems

As we described in the Introduction, the vox populi history of shared ledger systems has so many gaps that its development is not just incomplete, but also improperly understood.

The popular version of the story goes as follows: Pacioli invented double-entry accounting in 1494. The convention remained unchallenged until 1982, when Yuji Ijiri conceived TEA (Vijai et al. 2019). Ijiri's ideas were forgotten, however, until Ian Grigg brought them back to life in 2005, giving a series of twists to the concept (ibid.; Fullana and Ruiz 2020). In spite of this innovation, Grigg's idea was impracticable at the time because it was necessary to trust a third party with the shared ledger. Nevertheless, thanks to the fortunate exogenous appearance of Satoshi Nakamoto's bitcoin whitepaper in 2008, suddenly it was possible to implement TEA without that which impeded its viability, i.e., the need for trust (Cai 2019; Rao 2020).

However, this story suffers from a number of problems[9]. Notably, it overlooks the role of Todd Boyle in authoring the concept of triple-entry accounting. In consequence, the impact of the ideas of William E. McCarthy and Robert Haugen in Boyle is also overlooked (without prejudice to the originality of Boyle's work). Hence, the influence of the REA model in the genesis of TEA becomes completely excluded from the genealogical picture.

Furthermore, while Grigg's work was documented in 2005, much of it was undertaken between 1995 and 1997. Moreover, Ijiri's momentum accounting bore almost no relationship with Grigg's TEA. While a number of authors do point this out (Cai 2019; Dai and Vasarhelyi 2017; Gröblacher and Mizdraković 2019; Pacio 2018a; Wang and Kogan 2018), others appear to be unaware of this fact (Faccia and Mosco 2019; Faccia and Mostenau 2019; Vijai et al. 2019; Jeffries 2020). Note that Ijiri's exposition of accounting concepts did have a small influence on McCarthy. Although this can be seen as a historical connection between Ijiri and Grigg which is not recognized in the TEA literature reviewed, it is a minor one.

Finally, blockchain may not have been introduced as a completely exogenous invention that eventually enabled TEA. Instead, the opposite may be true. The bitcoin blockchain accounting model has likely been influenced by TEA; Nakamoto apparently implemented Boyle's shared transaction repository idea, together with many other ideas discussed throughout the 1990s.

This section expands on the previous corrections[10], in order to "set the record straight' and adequately conduct a genealogy of shared ledger systems.

4.1. *Early Antecedents to Triple-Entry Accounting: Momentum Accounting and the Resource-Event-Agent Model*

The year 1982 brought forth the first major innovative challenges to the accounting status quo. A Japanese accounting professor and an American accounting professor produced groundbreaking papers, i.e., Yuji Ijiri and William E. McCarthy, respectively.

Ijiri (1982, 1986, 1989; see also Hsieh 2018) explained that, in single-entry bookkeeping, only wealth (assets and liabilities) was recorded. The double-entry system incorporated income (flow accounts, revenues and expenses) so that, generally, one year's income statements explained the difference between two consecutive years' wealth statements[11], i.e., the rate of change in wealth or "momentum"[12] (Ijiri 1986, p. 747). Thus, a third entry to explain the rate of change in income would constitute a logical extension, that would make accounting systems "more dynamic and not focused on the present state (Balance Sheet), but on the future forecast" (Gröblacher and Mizdraković 2019, p. 60).

In other words, Ijiri had envisioned that a third entry would be used to explain the change between the income statements of two consecutive years, i.e., the rate of change of income or "force." Force, which could also be described as the rate of change in the rate of change in wealth[13], is recorded in a third column named "trebit" (with debit ≡ credit ≡ trebit), together with wealth and momentum. In contrast, momentum and income are recorded in the "credit" column and assets are recorded in the "debit" column (Ijiri 1986, p. 751). Ijiri named this system "triple-entry bookkeeping," though it is also known as "momentum accounting"[14].

Almost simultaneously, McCarthy extended his earlier work (McCarthy 1979, 1980; McCarthy and Gal 1981) on entity-relationship modeling (Dunn et al. 2016) and proposed an accounting framework for shared data environments (McCarthy 1982, p. 554). McCarthy argued that a certain conceptual modeling would be "better able to support multiple "views" [multiple users] of a centrally defined database" (McCarthy 1982, p. 555). This framework was at the antipodes of Ijiri's project to extend double-entry accounting principles, but it nonetheless drew some ideas from Ijiri's previous work on accounting measurements (see Ijiri 1975)[15]. However, Ijiri's momentum accounting bore no relation with it.

The system would not have debits, credits and accounts, which McCarthy deemed inessential for an accounting system, but mere "mechanisms for manually storing and transmitting data" (McCarthy 1980, p. 560). Instead, McCarthy argued for recording detailed transaction histories which could be viewed by different (classes of) users (ibid., p. 569).

McCarthy also criticized traditional double-entry systems for, among other issues, the lack of granularity (excessive aggregation) in the data stored. REA accounting would fix this, be more efficient and accurate, and would identify the agents involved, as well as other details, while preserving the duality (causal relationship) of economic events (Dunn et al. 2016, pp. 554–55, 561). A more recent update to this criticism also included a critique for the lack of automation (McCarthy 2016).

Other precedents to shared ledger systems had a minor historical influence, but should still be mentioned. Much of the work that has originated from the blockchain community in recent years has been related to the cypherpunk movement of the late 20th century. Concepts discussed in mailing lists back then may have had an impact in the following decades, but a precise genealogy is hard to trace. In this context, Eric Hughes's open-book accounting concept deserves a mention.

In 1993, Hughes (1993a) proposed a public transaction record with encrypted private balances. This would be a "single entry account" in a "shared funds account" that would, moreover, be expressed as double-entry bookkeeping for the parties. The accounts would be kept in accordance with each other through a public verification method (Hughes 1993b). Hughes, however, could not make this idea work technically (Grigg 2018).

4.2. The Single Truth 'Revolution'

The 1990s and subsequent decades brought the following five important developments for shared ledger systems: Todd Boyle's coinage of the term TEA in its "modern" sense, Ian Grigg's cryptographic implementation thereof, Satoshi Nakamoto's bitcoin whitepaper, McCarthy and Holman's participation in the REA-related ISO/IEC standards and the emergence of actual TEA use cases.

In 1997, American accountant Todd Boyle (2001d, 2001e) moved back from Japan and set up General Ledger Dialtone in Seattle, an accounting solutions company that specialized in webledgers. While Boyle independently introduced the idea of shared ledgers, he was later influenced by one of McCarthy's collaborators, Robert Haugen. Haugen was a software developer for a Core Components ebXML standards team (Boyle 2015 in Grigg

2014), who had worked in applying McCarthy's REA to supply chain Internet-based collaboration (Haugen and McCarthy 2000). Haugen introduced Boyle to McCarthy's work first, and McCarthy himself later, which had an impact on Boyle's ideas, consolidating his proposal for a shared ledger system.

As stated by Boyle (2003c) himself, "we're followers of McCarthy's economic ontology, and ISO 15944-4". Boyle (2000c) believed that McCarthy's REA framework was "high level (. . .) ahead of its time (. . .) [and] a goldmine" with many merits[16], but envisioned a much more valuable application for it, i.e., TEA. This would be commercially launched as an Internet-based, multi-company and low-cost accounting software. It would enable large supply chains (value networks) supported through a webledger "spitting out" the transactions therein (ibid.), i.e., a "general ledger (. . .) where independent companies could post their resource transfers" (Boyle 2015 in Grigg 2014; see also Haugen and McCarthy 2000). The webledger could contain all internal general ledger entries but its principal use was to "contain those journal rows involving external parties" (Boyle 2001f). To enable automatic reconciliation and external (as well as internal) integration, inter-ledger semantics based on the GAAP (see Appendix A for acronyms) would have been developed to allow different business systems to interface and form a coherent whole (Boyle 2002).

This was designed to have a classic double-entry accounting structure but a non-double-entry interface, for user friendliness (Boyle 2000a), which reflects another of Boyle's criticisms of REA, i.e., he thought that, even though REA was superior to double entry, the quest to replace the latter with the former was "a distraction," as double entry "merely" records data alongside a business system (Boyle 2000c; see also Boyle 2000a).

For this purpose, as well as for other commercial transactions, Boyle believed that a mechanism to communicate with both parties in a transaction where and when an economic exchange has happened ("recognition") should be built in a joint web accounting application (a B2B middleware server; Sachs 2001 in Boyle 2001c, 2001f), rather than delegated to each participant (Boyle 2001c). The mechanism should act as an encrypted "public document repository service," as a "notification service," as a service to record replies (e.g., acceptances), and as an archive and reporting service to provide "persistent and responsive storage of inter-party transactions, sufficient to achieve a robust and intrinsic reconciliation" (Boyle 2001f).

Boyle's webledger architectures would implement this solution in the form of a "shared" or "public transaction repository" (STR or PTR) based on "single-entry hosted transaction tables" (Boyle 2000e, 2000d, 2001a). There would, thus, be a single, shared, network-centric record, but because of the triple-signed structure, the system would be called triple-entry accounting (Boyle 2001b). Boyle (2000c) proposed REA to support the model for the back-end software, and even developed an REA-based economic ontology to conceptually describe this system (Boyle 2003d). Boyle (2003d) would famously say "thanks to Bill McCarthy and his REA school, who were the sources of most of these ideas".

At approximately the same time that Boyle developed GL Dialtone and TEA, oil markets consultant and researcher Chris Cook independently developed OilClear, a petroleum specific STR concept. Cook (2002) argued that "a 'shared transaction repository' and a 'shared title repository' (. . .) connected by clearing and settlement software" were necessary for the new market structure in the age of the Internet and instantaneous communication. The concept, called "Market 3.0," reportedly hit the "Internet neutrality-liquidity paradox," did not find a route to the market and was later fragmented and appropriated by ICE's eConfirm and by CME's Tradehub. While ICE's eConfirm and CME's Tradehub did not stop resorting to exchanges (Cook 2016), nonetheless, OilClear set a milestone.

Additionally, independently from Boyle and Cook (Grigg 2019c), Ian Grigg together with Gary Howland co-developed a similar concept between 1995 and 1997, i.e., the Ricardo payment system and Ricardian contracts, documented in Howland (1996)[17]. This idea, which Grigg (2000, 2004, 2005b) kept developing afterwards, was an attempt to replicate how economic events are recorded internally within firms through an ERP system, in a shared data environment between firms. It involved a shared set of receipts for the transactions common to two parties, and a trusted third party limited to signing, timestamping and ordering. While, originally, two different receipts were conceived, i.e., one for the payer and one for the payee (Howland 1996), shortly after, this idea was abandoned, folding the two receipts into a single one. This constituted the genesis of triple entry[18].

This shared receipt would be the dominating record for a transaction. Moreover, in Grigg's design, the receipt is not just evidence for the transaction, it is the transaction itself, because it holds all the relevant information for building an entire data processing concept around it[19]. Furthermore, in order to prevent any disputes around semantics, these are locked down through a Ricardian Contract (Grigg 2005b), which is a human and machine-readable text file containing both the terms of an agreement and the program executing the financial instrument, such that they are the same thing, i.e., "the issue is a contract" (Grigg 2004, 2000). The parties hold a (cryptographic) key to authorize each transaction and a copy of the receipts issued by the accounting agent (see also Boyle 2003b). To modify the record, the accounting agent needs the signature of both parties. In other words, every modification of the record requires a three-party consensus.

4.3. The Single Truth Convergence

In 2000, Grigg (2000) began to document his work. In 2004, upon realizing that his design could have radical implications for accounting, Grigg pursued further development of his ideas (Grigg 2004), which he called triple-entry accounting, but later pointed out that it was really triple-entry bookkeeping (Grigg 2019a). A draft of the resulting paper was circulated in June 2005, with Boyle commenting on it. Boyle noted that he had been working on the same idea for years as well (Grigg 2016a). As a consequence, Grigg integrated and implemented many of Boyle's ideas within the paper. However, while a draft of the paper "credited Todd Boyle as an author, (. . .) this was later withdrawn at his request due to wider differences between the views" (Grigg 2005b). These differences were related to the breadth of the scope or generalizability of the model.

Grigg first became aware of McCarthy's REA concept in 2017 through Boyle introduced (Grigg 2017a), but McCarthy's influence was, nonetheless, present. He was also unaware of Ijiri's work (Grigg 2020b), though his imprint on TEA had certainly been almost trivial.

Note that, according to Grigg (2017a, 2017b, 2017c, 2020a), his TEB inadvertently implemented key ideas more generally contained in REA: "the Receipt as I describe it in the paper and as it is used, is an REA construct converted to data; the (hash of the) Ricardian contract is the resource, the signing/timestamping by Ivan is the event, and the payee/payer are the agents"[20].

However, before the advent of blockchain, a workable triple-entry system would have necessitated a trusted third-party intermediary, who would also have been susceptible to attack, error or loss. The intermediary would have been vulnerable, similar to the transacting parties themselves. The invention of bitcoin and its blockchain permitted an adaption of Grigg's theory without a single center (Grigg 2019b).

The new solution consisted of replacing the central intermediary with a decentralized ledger, to which the customer's and supplier's accounts are connected, in which both sides of a transaction are recorded, and thus having the entries reaching a consensus. This application may be business-to-business (B2B) or government-to-government (G2G), e.g., between companies' tax and royalty payments to governments.

However, blockchain might have been an endogenous technological development that enabled TEA. Firstly, there are common sources to the ideas of both Boyle and Nakamoto[21]. Furthermore, there are remarkable architectural similarities between Boyle's ideas and bitcoin; bitcoin is a pseudonymous, immutable public transaction repository with an integrated payment layer underpinned by a triple-entry structure (in which the trusted third party is the distributed ledger or community). Moreover, there are anecdotal reasons to think that Boyle's idea of a publicly shared transaction repository was one of many sources in the corpus of preceding work on top of which the Bitcoin edifice was built.

In this vein, one ought to point out that Grigg (2014) has stated that Boyle's "notion of a public, and/or shared ledger is one of those components employed in bitcoin (. . .) Satoshi Nakamoto stands on the shoulders of giants, his design is the very clever assembling of components that were tried beforehand." Note that Grigg himself is closely associated with Satoshi Nakamoto[22]. Furthermore, the value of Boyle's ideas has been considered to be a precursor to blockchain in other discussions within the cryptographic community (Brown and Grigg in Brown 2015; Grigg in Swanson 2015; Sleeter 2014). Nonetheless, since Nakamoto's identity has not been fully confirmed (and might never be), this evidence is limited.

As stated above, Grigg was unaware of McCarthy's REA model and his influence over Boyle's work. Considering also that most TEA use cases and papers follow Grigg's idea (not Boyle's), it is, therefore, unsurprising that recent developments in the REA world have remained unnoticed despite their high pertinence to TEA. Nevertheless, these developments keep happening, with the work of ISO/IEC JTC 1/SC 32/WG 1—a working group of a subcommittee of the joint committee between ISO and IEC—being most relevant.

The ISO/IEC 15944-4 standard was published in 2007[23], then updated in 2015 and is currently under review. It uses the REA ontology to model a formal framework for business transactions named "Open-edi Business Transaction Ontology (OeBTO)" (ISO/IEC 2015, p. v; see also Dunn et al. 2016, p. 555). This framework maintains that the redundancy in mirroring records of a transaction must be abandoned to eliminate the possibility of inconsistencies (ibid., p. vi) and because it is viewpoint dependent. In turn, it proposes an independent, inter-enterprise view of transactions.

While ISO/IEC 15944-4 mostly provides definitions, the joint work of McCarthy and Holman (2019, see also Holman 2019) built upon it in designing ISO/IEC 15944-21, a standard providing guidance on the implementation of an OeDBTR, i.e., a (typically, but not necessarily, a blockchain) shared transaction repository remarkably similar to a TEA system, within the REA ontology. A draft of this standard has already been registered and approved, but the publication process has yet to be completed (ISO 2019).

This has interesting implications, as it opens the door for TEA systems to follow ISO/IEC specifications. In fact, one of the TEA use cases listed in Figure 1, i.e., bBiller, is an OeDBTR implementing the REA ontology. Another TEA use case, Pacio, incorporates the REA ontology in the Standardised Semantic Information Model Database of Facts in the TEA and IDEA diagrams of its whitepaper (Pacio 2020, pp. 6, 9). This facilitates the possibility of a TEA–REA reconciliation, in spite of the neglected influence of REA in TEA.

Moreover, further convergence is conceivable. We established that Yuji Ijiri did not influence TEA, except for the adoption by McCarthy of the terminology laid out in Ijiri's works prior to momentum accounting. Nevertheless, Ian Grigg (2020b) recently stated that there is a connection between TEA and Ijiri's momentum accounting and, furthermore, a potential for symbiosis; Ijiri's momentum accounting requires complicated calculations, but these calculations cannot be reliable if the underlying records are subject to error. This made Ijiri's model too risky for the market (ibid.). The execution of momentum accounting on top of cryptographic triple-signed receipts, however, might allow the former to perform reliably.

5. Discussion

Shared ledger systems are one of the most important innovations of the past decades. They are not a panacea, not replacing many of the traditional functions of accounting and not sufficing to prevent fraud, money laundering, etc. by themselves. Nevertheless, shared ledger systems have led the way for accounting applications in the Internet era. In particular, TEA is one of the pioneering concepts for accounting in shared data environments, delivering many benefits by enabling or facilitating external integration, instantaneous reconciliation, lower redundancy, low-cost real-time auditing, financial reporting, invoice automation, dispute resolution, etc. (Alawadhi et al. 2015; Boyle 2002, 2003f; Dai 2017; Dai and Vasarhelyi 2017; Ibañez 2022; Ibañez et al. 2021; ICAEW 2018; Mohanty 2018, p. 47; Request 2018a, 2018b)

The reliability of bookkeeping records, facilitated by TEA serves as a foundational element for various accounting and industrial applications (Ibañez 2022). Unlike traditional technology, TEA enables external integration, instantaneous reconciliation and low-cost real-time auditing, extending beyond traditional accounting functions (Ibañez et al. 2021). Auditchain (2018), which is a Layer 2 protocol ecosystem developing decentralized continuous audit and real-time financial reporting solutions, exemplifies how TEA's reliability functions as a critical component in the development of solutions dedicated to accounting, auditing and reporting. This shift in the accounting paradigm fosters a new level of trust and efficiency in shared data environments, transforming the way businesses approach financial transparency.

The lack of an integral genealogy of TEA has obscured the role of the accounting discipline in giving birth to TEA. Specifically, Boyle's work was overlooked, and so was the influence of the REA model over TEA. Consequently, the point that TEA is to some extent a historical byproduct of McCarthy's research has rarely been raised in public discourse. As a consequence, REA and TEA have remained two separate streams of research. Nevertheless, it would be very important to bring these streams together.

Furthermore, since Satoshi Nakamoto's bitcoin may likely have been inspired by Boyle's TEA (as well as other influences), McCarthy's REA model may have had an indirect historical impact on the genesis of the blockchain technology itself. It is often said that "blockchain is fundamentally an accounting technology" (ICAEW 2018, p. 1). In the light of these findings, this statement may be truer than ever thought before.

Indeed, the structural resemblances between REA and TEA are not just a coincidence, but a natural outcome given the historical influence of the former over the latter. This may explain why bBiller, for instance, is considered to be a TEA use case (Pacio 2018b), but their designers consider it to be an REA use case. It may also explain why Pacio incorporates part of the REA ontology in its TEA design. Furthermore, if TEA was indeed an influence for blockchain technology, one would similarly expect subsequent blockchain projects to intuitively use TEA principles in their solutions without deliberately implementing the idea nor necessarily using the term.

The theoretical underpinnings and historical lineage of TEA not only provide insight into its conceptual development but also set the stage for its practical applications in the industrial domain. The transition from traditional technology to TEA-based systems represents a significant shift in accounting practices, paving the way for innovative solutions that address contemporary business challenges.

The industrial application of TEA is evidenced by its utilization in contemporary business practices, offering a marked departure from the limitations of traditional technology. Auditchain's approach to decentralized continuous auditing and real-time financial reporting, influenced by Grigg's TEA, showcases the potential of TEA to revolutionize auditing practices. Pacio, working on a TEA system based on Holochain with a standardized semantic data standard, outlines the prerequisites for the successful implementation of TEA in industrial contexts (Ibañez et al. 2021). These cases demonstrate the tangible influence of TEA and reinforce the significance of this dissertation in connecting theoretical understanding with practical applications. By exploring the integral genealogy of TEA and its historical influences, this research contributes to an understanding of TEA's role in the ongoing evolution of accounting and industrial applications, highlighting the transformative impact compared to traditional methods.

6. Conclusions

In this paper, we attempt to trace three intersecting development pathways that represent incarnations of shared ledger systems. In particular, we explore possible connections among the long-established REA and TEA frameworks, and the nascent blockchain technology. By filling in the gaps in the genealogy of shared ledger systems, we correct historical misconceptions and give due credit to related prior works that have been insufficiently recognized. A clearer understanding of the historical evolution of shared ledger systems potentiates the academic debate, as well as further discourse among researchers in resource-event-agents, triple-entry accounting and blockchain.

7. Limitations and Future Research

This research, while striving for a comprehensive understanding of TEA and its relationship with REA, acknowledges some limitations. The perspectives of the key participants interviewed might reflect personal or professional biases, and the selection might not cover all relevant viewpoints in the history of TEA. The rapidly evolving field of TEA and associated technologies may lead to new developments that are not captured in this study, limiting the temporal relevance of the findings. Additionally, the conclusions may have limited applicability to different contexts or applications of TEA outside the scope of the literature reviewed and the participants interviewed. A significant limitation was the inability to achieve full saturation in the extensive REA literature, potentially limiting the depth of understanding in the overlap between REA and TEA. The terminology used in this research, such as the term "entry", may be up for contention, which could affect the interpretation of findings. Finally, the current evidence of practical convergence between REA and TEA is limited, restricting the ability to draw definitive conclusions about their interaction.

Future research avenues could explore TEA use cases within an REA framework, investigate industrial applications for this convergence and examine the usage of blockchain in this context. Such work would not only contribute to a deeper understanding of the practical implications and potential synergies between REA, TEA and blockchain technologies but would also address some of the limitations identified in this study. The exploration of these areas would provide valuable insights into the evolving landscape of shared ledger systems and their impact on contemporary accounting practices.

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Appendix A

Table A1. Acronyms used in this paper.

ANSI/X3	American National Standards Committee on Computers and Information Processing
AVCO	Average Cost
B2B	Business-to-business
DLT	Distributed Ledger Technology
FIFO	First-in, First Out
G2G	Government to Government
GAAP	Generally Accepted Accounting Principles
GL	General Ledgers

Table A1. *Cont.*

IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LIFO	Last-in, First-Out
OeBTO	Open-edi business transaction ontology
OeDBTR	Open-edi Distributed Business Transaction Repository
PTR	Public Transaction Repository
REA	Resource-Event-Agent
SPARC	Standards Planning and Requirements Committee
STR	Shared Transaction Repository
TEA	Triple-entry accounting
TEB	Triple-entry bookkeeping

Notes

1. In the remainder we refer to blockchain or blockchain technology in order to encompass all the possible architectural configurations and, for the sake of simplicity, also the larger family of distributed ledger technologies, i.e., community consensus-based distributed ledgers where the storage of data is not based on chains of blocks. For further understanding of the family of the distributed ledger technologies see Tasca and Tessone (2019).
2. A stub is the counterfoil of a transaction receipt. As envisioned by Boyle (2001b), parties may optionally insert non-essential data in them.
3. For a discussion of the different views on the specificity of double-entry bookkeeping, see Goldberg (1965, pp. 215–19).
4. General Ledger for Reporting (Boyle 2001b).
5. Multi-user accounting suite.
6. In earlier versions, it was defined as a "generalized accounting framework" or "accounting model" (McCarthy 1982, p. 554; McCarthy 2001).
7. See, for instance, Haugen and McCarthy (2000), extending the REA model to conceive a single source of truth for an event-driven generalized representation of material flows throughout supply chains and demand chains.
8. Boyle (2003a, 2003f) noted that it was possible to add more dimensions to the three-dimensional accounting grid, e.g., to allow a breakdown by type, month and/or purpose. In that context, the 3D accounting cube becomes a hypercube.
9. Among others, such as Pacioli not inventing double-entry accounting but merely documenting it.
10. Also note that, while Pacioli (1494) did popularize double-entry accounting, Benedetto Cotrugli (1573) and Marino de Raphaeli (1475 in Sangster 2015) had preceded him in beginning to introduce and develop the concept (Postma and van der Helm 2000; Sangster 2015; Sangster and Rossi 2018). Furthermore, comparable double-entry systems had been developed separately by the Italians, Koreans, and the second Muslim Caliphate at different times for the same purpose (Byeongju 2018; El-Halaby and Hussainey 2016; Zaid 2004).
11. Setting aside changes in equity for the sake of simplicity (Ijiri 1986, p. 747).
12. Which becomes "income" when multiplied by duration (Ijiri 1986, p. 747).
13. And becomes "impulse" when multiplied by duration (Ijiri 1986, pp. 747–48a).
14. Ijiri also advocated cryptosystem solutions involving public encryption keys and private decryption keys to protect business confidentiality (Ijiri and Kelly 1980, pp. 118–20).
15. While McCarthy (1982, p. 56) states that "the REA framework (. . .) is explained using the ideas of a number of accounting theorists, principally Yuji Ijiri," quotes concepts, uses ideas and expresses accounting principles following Ijiri (1975) on several occasions, Holman (personal communication, 21 February 2020) makes clear that "only a few vocabulary terms were adopted in the interest of consistent terminology, and nothing more." Ijiri (1993) defended the "beauty of double-entry bookkeeping," which McCarthy radically opposed. Thus, connections between the two authors can only be properly drawn if adequately contextualized, so as not to present them as allied researchers.
16. Boyle also criticized REA for being mislabeled as an accounting system (when, in his view, it was really a very generalized business information system). He moreover believed that the circumstances that REA had originally come to solve in the 1980s did not exist anymore (Boyle 2000c). For a response, see Haugen (2001) and McCarthy (2001).
17. Ian Grigg was not explicitly credited in this paper. However, the paper states that the company founded by Grigg (Systemics Ltd.) developed the system, and Grigg himself reports being a co-developer in Grigg (2000).

18 Grigg, Ian (personal communication, 15 April 2020).

19 For example, it is possible to calculate Bob's balance by reading and calculating the net sum of all the receipts mentioning Bob.

20 Grigg, Ian (personal communication, April 15, 2020). For further discussion on how TEA may offer an implementation of more generalized ideas contained in REA, see Grigg (2020b).

21 Boyle was a part of the same cypherpunk mailing lists in which cited influences in the Bitcoin whitepaper like Adam Back and Wei Dai participated (see Nakamoto 2008; Venona Cypherpunks Archives 2004)

22 Some believe Grigg is Satoshi Nakamoto himself, based on, inter alia, stylometric studies (Bits n Coins 2019; Helsel 2018), a claim we are unable to verify. Grigg (2016c) has denied being a member of the Satoshi Nakamoto team. However, Grigg (2016b) has also claimed direct knowledge of its internal workings.

23 Boyle (2003c) claimed to be a follower of ISO 15944-4 in 2003, which means that he was aware of the draft before publication.

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