RESEARCH STATEMENT

Oshani Seneviratne (senevo@rpi.edu)
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My research focuses on the novel application of decentralized information systems such as the world wide web and blockchain technologies to advance human endeavors. From the invention of the world wide web three decades ago to the formulation of blockchain technologies only a little over a decade ago, decentralized information systems have transformed various aspects of human experience from healthcare, finance, education, entertainment, research, and social connections through creative and timely breakthroughs. Various fields at the intersection and periphery of decentralized information systems, such as artificial intelligence, knowledge representation, knowledge graphs, security, privacy, human computer interaction, are essential components of my research.

Past Research

As outlined below, I have experienced the academic, industrial, and standards-body points of view on the conceptualization, implementation, and application of decentralized information systems research within computer science.

Doctoral Thesis Research: During my graduate studies at MIT in computer science, I conducted research on policy-aware, accountable systems for the web [1] at the Decentralized Information Group under the supervision of Sir Tim Berners-Lee, the inventor of the world wide web. I developed a novel web protocol called HyperText Transfer Protocol with Accountability (HTTPA) [2], which demonstrated its effectiveness in several domains, including electronic health records transfer and intellectual property protection in web-based systems [3]. HTTPA utilizes a distributed hash table-based implementation for web-based peer nodes to discover protected content expressed using a policy language grounded in semantic web technologies [4]. HTTPA allows protocol participants to declare usage restrictions and allowances of the content shared [5], and logs data access, share, reuse transactions to provide audit trails to interested rightful owners of the data items in a provenance-centric way [6]. A key innovation of this research was enabling information infrastructures to offer privacy through transparency of the data use transactions [7]. Moreover, I investigated effective tools and applications for keeping data reusers honest through policy-aware content reuse [8]. I also co-formulated the design and development of a decentralized online social network [9], as well as an explanation interface [10] for the Tabulator[1]. Some of the work leading up to my dissertation work received the Yahoo! Key Scientific Challenge Award[2].

Industrial Research: Since graduating from MIT, I spent three years at Oracle Inc., specializing in enterprise provenance systems and governance, risk, and compliance suite of tools implemented in standards-compliant Web Ontology Language (OWL)[3] rules. During this period, I had strong connections to standards bodies such as the W3C and acted as a liaison for connecting some of the standards-body work and academic research into Oracle's product offerings. To that end, I contributed to Oracle's reference implementations of the Prov Data Model[4] and the Linked Data Platform[5] recommendations. I was also a co-inventor on a patent on visualizing provenance in enterprise information flow [11]. Furthermore, I led the research and development work on employee wellness tools incorporated into one of the core business products on human capital management.

(Post-doctoral) Academic Research: Since joining Rensselaer Polytechnic Institute, as the Director of Health Data Research, I coordinated the research operations of the IBM Research AI-Horizon Network funded Health Empowerment through Analytics Learning and Semantics (HEALS) project[6]. I have been working very closely with the faculty principal investigators of the project on several research thrusts over the past five years. Several noteworthy research directions with respect to decentralized systems research that I coordinated and collaborated within HEALS include: the explanation ontology for AI models in healthcare settings[7] [12, 13], the FoodKG (a knowledge graph consisting of over 1 million recipes) [14, 15], ontological models for breast cancer diagnosis and treatment [16, 17], ontology for guideline provenance [18],

[1] Tabulator is a read-write linked data browser, conceptualized by Sir. Tim Berners-Lee. For more information, please see `https://github.com/linkeddata/tabulator`.

[2] `https://www.csail.mit.edu/news/seneviratne-selected-yahoo-key-scientific-challenges-program`

[3] `https://www.w3.org/OWL`

[4] `https://www.w3.org/TR/prov-dm`

[5] `https://www.w3.org/TR/ldp`

[6] `https://idea.rpi.edu/research/projects/heals`

[7] The Explanation Ontology won the best resource paper award at the International Semantic Web Conference in 2020 and is being extended in a clinical risk prediction use case.

characterization of study cohorts in understanding clinical populations [19, 20, 21], techniques for enabling trust in clinical decision system support recommendations through semantics [22], and personalizing health recommendations with semantics and machine learning [23, 24, 25, 26, 27]. Since knowledge representation and machine learning are critical components in effective decentralized information systems, these projects helped me cement several for future research.

Grants

I was fortunate to receive a grant as a lead PI to conduct original research, and I am currently involved in several grant proposals as outlined below.

Funding Received: I was awarded a $100k grant in 2018 to conduct research on the Smart Contracts Augmented with Learning and Semantics (SCALES) project[8] as part of the IBM-RPI Artificial Intelligence Research Collaboration. Smart contracts enable the execution of simple programs that carry out transactions on the blockchain. Since smart contracts are immutable, trust and transparency are preserved. However, many decentralized applications require intelligence beyond the execution of logical constructs conceptualized initially. A motivating example is a "break glass" scenario involving access to a patient's medical records when the patient is unconscious to share data in an initially unforeseen circumstance. As part of SCALES, I investigated solutions for such situations with smart contracts, as they are inflexible to any changes after deployment. The solutions I investigated utilized effective sandbox environments for smart contract execution [28], enhancing the expressivity of the decentralized application semantics using ontological concepts [29], and an exemplar healthcare application that uses Fast Healthcare Interoperability of Resources in smart contracts [30]. Furthermore, as identity mechanisms in decentralized systems are notoriously hard at being user-friendly, and there is no recourse if the user's key is lost, I have co-investigated computational social choice mechanisms for choosing the best option for account recovery [31]. The permissionless innovation afforded by blockchain technologies provides many opportunities for future research, such as the research contributions of the SCALES project.

Planned Funding Proposals: I am currently awaiting decisions on or planning several grant proposals to secure funding on several research ideas outlined in the "Planned Research" section below. The proposals I am leading include an NSF Smart Connected Health proposal, in which I am proposing a decentralized research data sharing platform incentivized by blockchain technologies to reduce the time it takes to bring a scientific innovation from "bench" (basic research) to "bedside" (practical application).

I have been invited to join as a co-PI or senior personnel in several other proposals, including a mega proposal that spans over 20 institutions worldwide to advance blockchain research funded by the Algorand Foundation, an NSF AI institute proposal on democratic group decision making, NIH R01 proposal on personal health libraries, NSF LEAP proposal on open data platform for the data-driven transformation of the building industries, an NSF STTR proposal on "Smartchain" for developing an AI-backed blockchain computing platform, and an NSF Industry-University Research Partnerships Collaboration center at RPI called Center for Research in Advances in Financial Technologies, where I have co-proposed investigating blockchain transactions for identifying "risky business" in decentralized finance and a framework for reducing information asymmetry powered by blockchain and IoT for the healthcare industry.

Planned Research

In my future research agenda, I plan to build upon my past research threads that have shown extreme promise to advance state of the art in computer science. I am interested in the following five research themes that complement each other and have the potential to revolutionize decentralized system research.

Interpretabale AI Infrastructures: AI research has been pursuing optimal performance often at the expense of explainability and interpretability. However, the crucial questions driven by a social reluctance to accept AI-based decisions may lead to entirely new dynamics and technologies, fostering interpretability and authenticity [32]. Blockchain technologies could be used to tackle trust issues in AI models and address the lack of interpretability by providing data and cryptographically verifiable AI model provenance [33]. In particular, the following key features that are available in decentralized blockchain technologies are very desirable for interpretabale AI infrastructures:

(i) Transparency and visibility of the data and AI algorithms
(ii) Immutability of the input data and parameters
(iii) Traceability and nonrepudiation of the output

[8] `https://idea.rpi.edu/research/projects/scales`

(iv) Automatic execution of logic through smart contracts

In addition, blockchain technologies can enable a marketplace for data for the AI models, thus making access to the data more democratic. Owners of datasets would be rewarded for their contributions, the authenticity of the data, and other such criteria (e.g., the quality of the results of the AI models). These aspects can be easily automated using smart contracts for the model execution and the reward mechanism. By tracking behaviors of AI-based systems across different data input and application scenarios, we understand and have confidence in the decisions made by those systems. In case of unfortunate and unforeseen incidents that arise due to the application of the AI models, these blockchain-based "audit trails" will be essential to determine whether humans (and who precisely) or machines are at fault. Specifically, I plan to address the challenge of developing agent-driven smart contracts on the blockchain and effective information infrastructures on the web with semantics and advances in machine learning. Specifically, I believe that advances in future decentralized systems would involve constructing smart contracts that act as autonomous agents with feedback, rethinking the program execution to make allowances for data ascertained at a later point in time, and the integration of various data streams for effective decision making in the absence of a centralized coordinator.

Accountable Incentivized Data Sharing: I have begun investigating the application of decentralized techniques such as blockchain technology in addressing the challenge of designing an effective data-sharing infrastructure, with a view towards making it accountable (i.e., there is transparency in how the data is used), and the data sharing is incentivized (i.e., to ensure the adoption of the system will scale organically). To achieve this ambitious goal, I have already begun developing an exemplar application to address the costly and time-consuming effort needed in bringing scientific innovations from the bench (basic research) to bedside (clinical level), which has culminated in a decentralized application for researchers to share their research artifacts [34]. Since this system will operate in a decentralized environment, a particular focus will be given to investigating novel consensus mechanisms that will enable reporting the impact of scientific data and the reproducibility of the research methods, thus providing incentives to scientists in supplying well-annotated, highly reusable data and reproducible research methods. To facilitate such decentralized scientific research infrastructures, I have begun the development of an expressive, provenance-centric language, called Science Capability-based, Intention-centric, Experiment-oriented, Networked Collaborative Expression (SCIENCE) language that will capture the "science-capability" of research datasets. The SCIENCE language uses tried and tested ontologies grounded in the Semantic Web, such as the Provenance Ontology, and provides an actionable mechanism to capture provenance and responsible data usage in the scientific process. Moreover, I have analyzed how combating misinformation, such as false information on cryptocurrency, can be tackled using affordances allowed in decentralized information systems [35]. A key innovation in this proposed work is formulating a methodology for smart contracts that encodes data use agreements and shared governance of data to create computational data use agreements supporting the automatic compliance evaluation.

Personalization: I am investigating the integration of personal health device data coordinated with blockchain-based technologies, specifically smart contracts, for supplementing clinical decision support systems for giving clinicians effective data points for the personalized treatment and monitoring of patients with chronic conditions or requiring specialized post-operative care [36]. Smart contracts, at the moment, can only be implemented with explicit logic. However, this can be very limiting in implementing expressive logic required in complex application domains or where there is a need for plugging in machine learning models. For example, these techniques could assist in sending clinicians alerts and notifications if an adverse event is detected from the data stream from the patient's personal health devices. In order to overcome the smart contract limitations mentioned above, I have co-led the development of the Read-Execute-Transact-Eval-Loop (RETEL) method for smart contracts to connect to data streams from IoT devices [37]. I have also developed a special-purpose smart contract family called Swarm Contracts that have shown to be effective when there are byzantine (random and adversarial) agents and agents with varying capabilities in decentralized settings [38]. Swarm contracts can effectively coordinate heterogeneous agents in multi-agent environments in a mutually beneficial way, optimizing personal rewards.

Interoperability: One of the most crucial research contributions in my future research agenda will be the idea of decentralization semantics to allow different stakeholders to work asynchronously and separately on parts of the semantics and share the relevant pieces of the data in knowledge graphs. Safe cross-platform interactions in complex decentralized systems are rooted in the assumption that the composite parts in the system are secure and resilient to attacks. I am interested in investigating how emerging decentralized application infrastructures can be interoperable to be secure while reducing data and value silos. There is a need for robust methodologies grounded in solid computer science theory to understand systemic risks in cross-platform decentralized applications, such as the emerging Decentralized Finance (DeFi) applications. The composition of these systems is fundamentally different and will have varying degrees of security, trust,

and identity mechanisms. For example, asset transfers between a financial institution to a DeFi application may have a cross-blockchain component composed of various solutions, including decentralized exchanges, money markets, and insurance. There are risks at the points of intersection that the users may not be fully aware of since the data structures, communication mechanisms, authentication, authorization procedures are different between these systems. Furthermore, having multiple blockchains performing transactions is more complicated than the sum of its parts, as there is extra complexity, and there are risks if parts of the service become obsolete and shut down, which adds many challenges to the governance of the integrated infrastructure as a whole.

Decentralized Edge Computing: Decentralized information systems are not complete without innovations in mobile or edge application development. The devices at the edge provide ubiquitous access to information and provide a more secure, privacy-preserving way to gain insights from a gold mine of data. There are fundamental questions on effectively collecting, organizing, performing knowledge representation, and leveraging the data from the edge. Many of these questions have not yet seen scalable answers, and given my interests and expertise, there are many potential avenues of exploration in this space. With specific to computing infrastructures for mobile application development, I have been a core research contributor to the MIT App Inventor's Punya framework[9]. I have contributed to linked data components that allow a mobile application developer to quickly build applications that consume, produce, and reason over linked data [39], and a framework for IoT application development [40]. The Punya project was initially conceptualized to prototype disaster response applications rapidly [41]. We have since expanded the focus to building research apps leveraging the vast amounts of data available on the linked open data cloud [42, 43, 44]. Given my involvement in the Punya project, and the fact that the parent MIT App Inventor project has millions of users, I believe the innovations in the research thread could be highly influential. In addition, innovations that I have co-led, which are at the intersection of blockchain and IoT, such as BlockIoT [36], RETEL [37], and Swarm Contracts [38] provide the basis for further innovations in this space, in particular on trustworthy, self-governing, decentralized computing platforms. Many extensions of this work are possible in several different research avenues, including federated learning and personal health data insights generation.

Service to the Broader Research Community

I am passionate about the development of and the scientific discourse in emerging research areas. I co-founded and co-organized the AIChain workshop series[10] at the IEEE Blockchain conference in 2019, and it has been running successfully ever since. I also co-chaired the Personal Health Knowledge Graph workshop series[11] at the Knowledge Graph Conference in 2020 and 2021, and the AAAI Symposium on AI for Social Good[12] in 2019 and 2020. I am the program co-chair of the ACM Web Science conference in 2022, and I have served in the organizing and program committees of many conferences, including the International Semantic Web Conference, Web Conference, Web Science Conference, IEEE Blockchain Conference, and IEEE International Conference on Decentralized Applications and Infrastructures. I am currently a co-editor of the Semantic Technologies for Data and Algorithmic Governance issue at the Semantic Web Journal and the Personal Health Knowledge Graphs special issue at the Data Intelligence Journal. I am also on the editorial boards of journals such as Web Semantics, Medical Internet Research, and Biomedical and Health Informatics. I plan to continue such professional service activities that I believe are mutually beneficial to the university and the research community.

Conclusion

I am optimistic that the decentralization of information is the most sustainable information model for future computing and information systems. We are seeing evidence of the success of such systems, starting from the web and the most recent widespread adoption of blockchain-based applications. There are many challenges in these nascent areas that warrant careful scientific investigation to understand and realize these technological innovations' full potential. I am excited to be taking up these challenges and advancing the state-of-the-art in computer science and related disciplines.

[9] http://punya.mit.edu
[10] https://ai4blockchain.github.io
[11] https://phkg.github.io
[12] https://ai-for-socialgood.github.io

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