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The Integration of Blockchain Technology into Database Management Systems for Enhanced Security and Transparency

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***Abstract*—** *The increasing prevalence of data breaches and cyberattacks underscores the urgent need for enhanced security and transparency in database management systems (DBMS). This paper explores the integration of blockchain technology into DBMS to address these challenges, leveraging the inherent features of blockchain—decentralization, immutability, and transparency—to create tamper-proof and trustworthy data environments. Using SQLite as a foundational example, we demonstrate the step-by-step process of blockchain integration and present a practical application through a fitness-based social platform that allows individuals to securely claim and verify personal fitness data. The research extends its implications to diverse fields such as public administration, electronic health records, educational institutions, and social science research, highlighting the versatility and potential of blockchain-enhanced DBMS. We develop a comprehensive taxonomy to classify integration methods, evaluate existing blockchain-integrated DBMS solutions, and identify key benefits and challenges associated with this convergence. Through theoretical models and practical implementations on platforms akin to Bitcoin and Hyperledger Fabric, our findings reveal significant improvements in data integrity, trust, and transparency, while also addressing storage and scalability concerns. Additionally, case studies illustrate real-world applications in e-voting, Industrial Internet of Things (IIoT), and healthcare, demonstrating the practical relevance and transformative potential of blockchain technology in modern data management. The paper concludes by outlining future research directions and emerging trends, emphasizing the critical role of blockchain in advancing secure and transparent database systems.*

***Keywords*—** *Blockchain Integration, Database Management Systems, Data Security, Transparency, Decentralization, Immutability, Data Integrity, Smart Contracts, Public Administration, Electronic Health Records, Big Data, Industrial IoT, Secure Data Management*.

I. INTRODUCTION

Using SQLite, we will illustrate each of the steps in preparing the integration of blockchain. Further, we will provide an example of a fitness-based Twitter that enables unique individuals to claim stored information (Kalajdjieski et al., 2023). This includes body weight upon reaching specific distances or times for a specific running race. Individual blocking implications are discussed. The goal of this research is fields of public administration, public affairs, public management, and big data sets (Jin, 2022; Gilbert, Oluwatosin & Gilbert, 2024). Further, blockchain integration can be extended into electronic health records and student files for educational institutions, where student records and student payment transactions can be made transparent to assure security and honesty (Gilbert & Gilbert, 2024a; Christopher, 2013). Also Ali et al. (2018), propounded that personal profiles in social science research can offer a level of personal security not currently available.

The global number of computer security incidents increased by 33 percent in 2012 and 25 percent in 2014, according to the U.S. Computer Emergency Readiness Team (Morgus et al.,2022). Data breaches affecting millions of personal records and the hacking or manipulation of voter information in politically motivated incidents threaten confidence in modern computerization (Gulyamov & Raimberdiyev, 2023; Cheng et al., 2018; Gilbert, Auodo & Gilbert, 2024). Decentralization, immutability, and transparency are the core features of blockchain, enabling tamper-proof data storage, the tracking and exchange of information, smart contracts, and decentralized autonomous organizations (Dong et al., 2023; Gilbert & Gilbert, 2024t). This research details a methodology for integrating blockchain technology into modern database management systems to enhance security and create transparency of personal information on an individual, case-based level.

1.1. Background and Context

The core purpose of distributed databases is to enable the efficient maintenance and retrieval of data in a distributed (decentralized or federated) fashion. In essence, distributed databases can be considered as the unification of the two mostly disjoint fields of distributed systems (with the "reading" aspect) and databases (mostly handling the "writing" aspect). A side advantage is the robustness of the system due to the inherent data redundancy without the need for a fully replicated or mostly replicated centralized architecture. However, robustness is currently replaced by fragility in centralizing and decentralizing the IT infrastructure in a time span lower than that of a general human individual career. This, in turn, implies the concentration of a lot of control in a few IT infrastructure entities and the need for the evaluation of the IT infrastructure beyond efficiency concerns (Merlec & In, 2024).

This paper investigates and introduces blockchain technology to the cause of secure transactional log management

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and digital signature tracking, bringing decentralization to logs and security to blockchain block headers. We add support for tamper-evident query result generation to the blockchain database and show its application in secure, block-by-block storage and tamper-secure visualization of blockchains through conventional blockchain explorers, including the history of changes of the query results. The stored metadata of the conventional block headers can be tailored using database query results, and a potentially important addition is the transparency of these query results (Zhang et al., 2023; (Abilimi et al., 2015). We show that the scheme is feasible and study the trade-offs. We have implemented the system in bitcoin-like and fabric-like blockchains. Presented results show a practical difference in storage capacity and usage for the traditional and the tamper-evident blockchains, which is an important metric in the industry.

1.2 Research Approaches, Tools, and Methods Used

In this paper, we explore how combining blockchain technology with database management systems (DBMS) can improve security and transparency. To tackle this topic, they used a variety of research methods and to. See the sum-up of how they approached their study:

I. Exploring Existing Research

The paper began by diving deep into existing literature to understand the current state of both blockchain technology and database management systems. This involved:

Learning How Blockchain Has Evolved: It looked at how blockchain started as the technology behind cryptocurrencies like Bitcoin and expanded into various other fields.

Understanding the Basics of DBMS: It revisited what database management systems are all about—their key components, how they function, and the challenges they face.

Recognizing Security Issues: With the rise in data breaches and cyberattacks, they highlighted the pressing need for better security measures in data management (Leewis, Smit & van Meerten, 2021; Yeboah & Abilimi, 2013). This research helped them set the stage, showing why it's important to integrate blockchain with DBMS to enhance security and transparency.

II. *Developing New Ideas and Models.* The paper didn't just rely on existing knowledge; it came up with new theoretical models to show how blockchain and databases could work together:

Creating Different Integration Models: It proposed various ways to integrate blockchain into databases, including fully centralized and partially centralized systems.

Redefining Consensus Mechanisms: It adapted the way blockchain reaches agreement (consensus algorithms) to fit into traditional database environments, ensuring data remains consistent and trustworthy.These models provided a blueprint for how integration could work, serving as a foundation for practical implementation (Lohachab et al.,2021; Yeboah, Odabi & Abilimi Odabi, 2016)

III. *Getting Hands-On with Tools.* To bring their ideas to life, the paper used specific tools and technologies:

Using SQLite: The paper demonstrated the steps of integrating blockchain with a lightweight database system like SQLite.

Testing on Blockchain Platforms: We tried out their concepts on platforms similar to Bitcoin and Hyperledger Fabric to see how they perform in real-world scenarios.

Creating a Practical Example: We illustrated their ideas with a hypothetical fitness app where users can securely store and share personal fitness data. By practically implementing their models, they could test and validate their theories, showing the potential benefits and identifying any challenges (Verma, Tripathi & Pant, 2024).

IV. *Looking at Real-World Applications.* The paper didn't stop at theory and testing; it also examined how these integrations could be applied in real life:

Secure Voting Systems: Exploring how blockchain can make electronic voting more transparent and tamper-proof.

Industrial Internet of Things (IIoT): Discussing the role of blockchain in securing data in industrial settings.

Cloud Databases: Evaluating how blockchain can enhance data authenticity and durability in cloud storage. These case studies helped them understand the practical implications and potential impact of their work (Tyagi, 2024).

V. *Focusing on Security.* Security was a major concern throughout their research:

Identifying Threats: The paper pinpointed possible security risks like unauthorized access, data tampering, and inconsistencies.

Proposing Solutions: Suggested ways to mitigate these threats, including better access controls, encryption, and large-scale user authentication. Addressing security threats was crucial to ensure that the integration would genuinely enhance data protection (Teimoor, 2021)

VI. *Creating a Framework for Understanding*. We developed a comprehensive taxonomy—a classification system—to organize and understand the different methods of integrating blockchain with databases. This included:

Defining Key Dimensions: We categorized integration methods based on types, properties, concepts, and categories.

Highlighting Research Gaps: Identifying areas where more study is needed. This framework helps others navigate the complex landscape of blockchain and DBMS integration and guides future research (Giannaris & Mastorakis, 2023)

VII. *Comparing What's Already Out There.* The paper looked at existing blockchain-integrated database systems to see how their proposals stack up:

Evaluating Current Solutions: It assessed how well current systems address security and transparency.

Pointing Out Limitations: Noted where existing solutions fall short, reinforcing the need for their new approaches. This comparison helped them refine their models and highlight the importance of their research (Tran, Babar & Boan, 2021)

VIII. *Thinking About the Future*. We also considered where this technology is headed:

Emerging Trends: Discussing how blockchain-integrated databases could support future technologies like smart cities and big data management.

Potential Innovations: Suggesting new business models and economic benefits that could emerge from this integration. Looking ahead helps ensure that their research remains relevant and provides value in the long term (Zhong et al., 2023)

IX. *Summing Up and Offering Recommendations.* In conclusion, of the paper:

Emphasized the Importance of Integration: Highlighted how combining blockchain with databases can significantly improve security and transparency.

Called for Systematic Adoption: Encouraged a methodical approach to integrating blockchain into existing systems, rather than ad-hoc solutions. It aimed to inspire others to consider this integration and provided guidance on how to proceed (Cao et al., 2022)

In overall approach, the combined theory with practical application:

Theoretical Exploration: Developing new models and frameworks to conceptualize the integration.

Practical Implementation: Using actual tools and platforms to test and demonstrate their ideas.

Security Emphasis: Keeping security at the forefront throughout their research.

Tools and Technologies Used

SQLite: A lightweight database used to demonstrate integration steps.

Blockchain Platforms: Bitcoin-like and Hyperledger Fabric platforms to test real-world applicability.

Security Measures: Encryption, digital signatures, and tamper-evident techniques to enhance data integrity.

How They Applied These Tools

Demonstration and Testing: Used SQLite and blockchain platforms to show how integration works in practice.

Model Validation: Practical implementations helped validate their theoretical models.

Security Enhancements: Applied security measures to address identified threats. By blending theoretical models with hands-on experiments, the authors showcased how integrating blockchain technology into database management systems can significantly enhance security and transparency. Their research methods were thoughtfully chosen to address the complexities of this integration, focusing on practical applicability and robust security. This work not only contributes valuable insights but also paves the way for future innovations, encouraging others to adopt a careful and security-focused approach to integrating blockchain in data management (Gami et al., 2023)

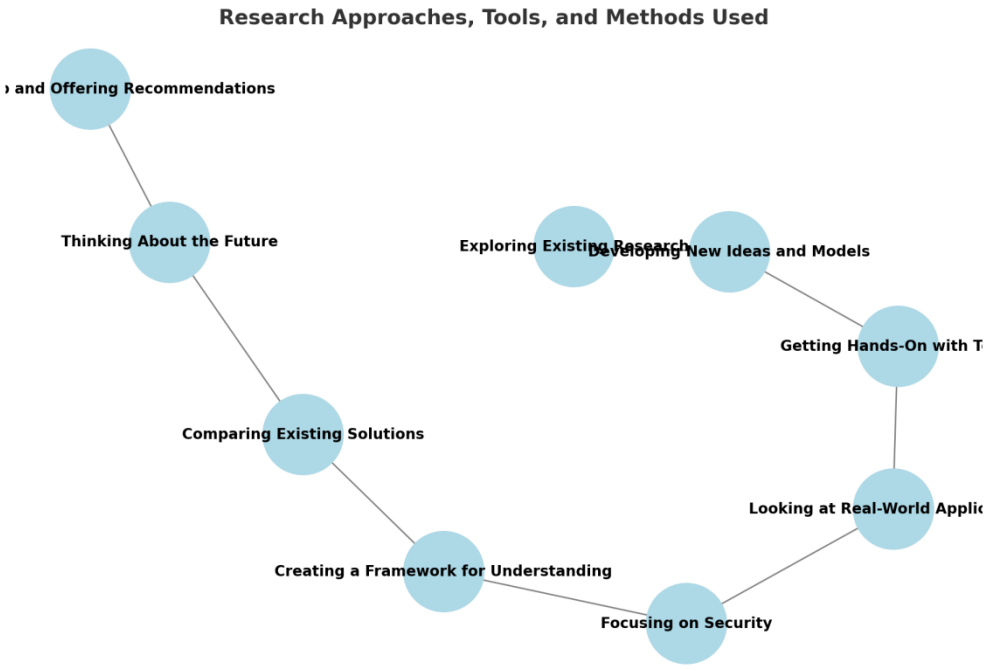

Figure 1: Researching blockchain integration with database systems.

This flow diagram (Figure 1) visually represents the key steps and focus areas in the research process described in the paper. Each point highlights an important phase, from exploring existing knowledge to developing practical models, testing tools, and considering real-world applications. The arrows guide you through the logical flow of the study, showing how each step builds upon the previous one.

II. Blockchain Technology Overview

Blockchain technology was developed for the purpose of enabling peer-to-peer transactions without the need for an intermediary and was originally associated with digital currencies such as Bitcoin (Esmat et al., 2021). Over time, the potential of blockchain technology was realized, new functionalities were developed, and numerous novel applications in diverse fields appeared. Currently, barriers to more widespread adoption are being lowered, and awareness has been rapidly growing. This is driven by the extraordinary surplus data that people are generating and by the inevitable misuse of this valuable data by many organizations. As a result, people are increasingly understanding the importance of data transparency, data security, and data integrity. The inability to trust data strongly encourages people to delete their personal

data and to stop using a variety of devices and systems, such as smart home devices, health trackers, and so forth. Organizations, including governments, industries, environmental groups, and others, can also benefit from an increase in the generation of data and the ability to access trust monetarily, and to reduce vulnerabilities, to improve communication and interactivity, and to enable new business models, and this is so for many promising future technological areas (Habibzadeh et al. 2019).

This paper provides an overview of blockchain technology and discusses how several issues related to data security can be addressed by integrating blockchain technology into database management systems. The methods for achieving this integration are discussed in detail, and pioneering research efforts in the field are reviewed. The paper concludes with a summary and some future directions.

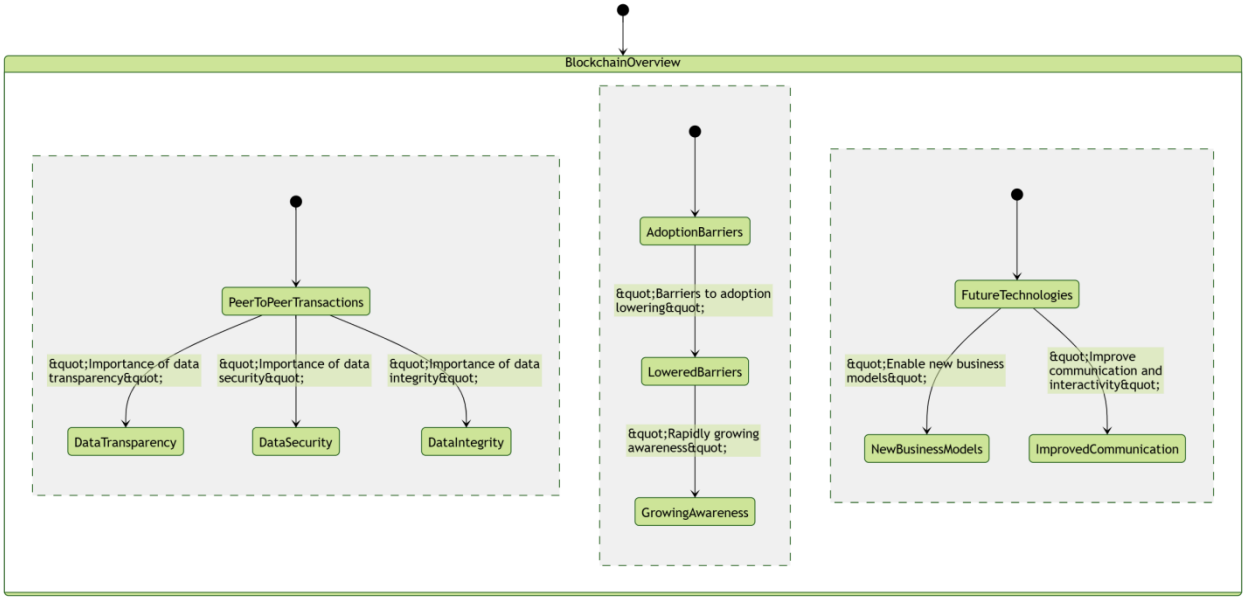

Figure 2: Overview of blockchain technology and its benefits.

The diagram (Figure 2) shows how blockchain addresses fundamental issues like security and transparency, tackles adoption challenges, and has the potential to revolutionize technology and business in the future. It's a journey from solving current problems to unlocking future possibilities.

2.1 Definition and Key Concepts

Blockchain technology was arguably first introduced by Nakamoto (2008) in his widely cited paper, where he defined blockchain as a chain of blocks. These "blocks" refer to new sets of transactions that must be confirmed and added to a ledger known as the blockchain. The process of block creation and confirmation, known as "block mining," involves miners solving complex problems based on proof-of-work principles. Each block contains the hash of the previous block, ensuring the integrity and chronological order of the chain.

Nakamoto's goal was to create a method of electronic transaction that relies on technology rather than trust, allowing two willing parties to transact directly without intermediaries. This approach is presently significant in database management systems (DBMSs) used to manage and control the electronic transactions of companies, organizations, and the general public.

One day after the publication of his paper, Nakamoto continued to argue that the Bitcoin system could be considered partially secure and might change if a party with more processing power found an alternative block model (Nakamoto, 2008). Since the blockchain was introduced, the concept has evolved with technology into a range of different reference databases, and a wide variety of blockchains have been created to potentially enhance service properties. Four clear levels are demonstrated using a text-based metaphor. Avoidance and counteraction mitigate potential problems in which conflicts frequently develop, as they could be either recursive or unresolved. Specific rules help prevent conflict situations, and the following are dispute decision-making methods when disputes are being arbitrated.

Due to blockchain's unique features, several companies have been using the technology for numerous internal and external operations, establishing hundreds of worldwide support services for stakeholders. However, not many DBMSs are equipped to meet the needs of these activities.

In addition, at the very beginning of this field, Liu, Sheng & Wang (2021), defined blockchain as an electronic ledger that keeps track of all transactions in a transparent, efficient, and secure manner. Since 2013, the term "blocks" has evolved from being a sequence or list of transaction ledgers to being more of a "container type." The use of original files and cryptographic representations of additional data has led to the validation of transactions through what we now call "smart contracts."

Furthermore, the original public and permissionless consensus algorithm proposed by Nakamoto (2008) has evolved into permissioned consensus algorithms, including

Byzantine Fault Tolerant (BFT) algorithms like the one developed by Castro and Liskov (1999), and even a number of "consensus-as-a-service" provider algorithms with or without tokens.

Moreover, blockchain technology can now achieve a more general purpose beyond the realm of virtual cryptocurrencies. It can be used to manage, authenticate, list, and secure all sorts of items, documents, files, or electronic records—often referred to as "paper notes" in earlier terminology.

TABLE 1: The key definitions and concepts related to blockchain technology's development

Aspect	Definition and Key Concepts
Origin	Introduced by Nakamoto (2008) as a chain of blocks. Defined as a method of electronic transaction not based on trust, enabling direct transactions between parties without intermediaries.
Evolution of Blocks	Initially a sequence of transaction ledgers, now a "container type" including the original file and cryptographic data, enabling concepts like "smart contracts."
Consensus Algorithms	Evolved from public and permissionless (e.g., Nakamoto consensus) to permissioned algorithms like Byzantine Fault Tolerant (BFT) and "consensus-as-a-service" providers, with or without tokens.
Applications	Extends beyond cryptocurrencies to managing, authenticating, and securing diverse items, documents, files, and records.
Mining and Proof-of-Work	Block creation involves miners solving problems to validate transactions based on proof-of-work principles. Each block contains the hash of the previous block, ensuring integrity and sequence.
Conflict Resolution	Avoidance and counteraction are used to mitigate conflicts, either recursive or unresolved. Specific rules help in conflict prevention, and arbitration handles disputes.
Blockchain in DBMS	Used in database management systems to track, authenticate, and secure electronic transactions, supporting both internal and external operations for organizations and stakeholders.
Transparency and Security	Blockchain acts as an electronic ledger that is transparent, efficient, and secure, as initially defined by Bybee et al. (2013).
Elimination of Middlemen	Eradicates the need for intermediaries in transactions, focusing on trust in technology rather than human trust.
General Purpose Use	Beyond financial transactions, blockchain technology supports numerous fields, including document registration, secure data management, and providing worldwide support services for stakeholders.

This table provides an easy-to-follow overview of the key concepts and developments in blockchain technology, highlighting its evolution and potential applications.

III. Database Management Systems

A Database Management System (DBMS) is software that interacts with users, applications, and the database itself to capture and analyze data from various perspectives. It manages data requests, specifies user data requirements, and controls data management, command processing, security, protection, and performance tuning of applications (Silberschatz, Korth & Sudarshan, 2011).

The DBMS acts as an interface between application programs and the database, allowing applications to request input/output services (read/write operations) for data. Often referred to as a database server, the DBMS typically utilizes client-server architecture to store, retrieve, and access large volumes of data. It handles tasks such as reducing data redundancy, providing multiple access paths to records, and minimizing the time and storage required to process requests. Common automated functions include backup, recovery, and ensuring the integrity of database transactions (Elmasri, 2008).

A DBMS comprises software capable of manipulating, retrieving, capturing, and displaying the desired information (Abilimi & Adu-Manu, 2013). Data is generated, collected, entered, processed, managed, stored, and retrieved by businesses, organizations, and computer systems. It involves user interactions with systems and applications. The DBMS manages three critical components: the data itself; the database engine that enables data access, storage, and modification; and the database schema, which defines the logical structure of the database (Connolly, 2015; Abilimi et al., 2013).

This diagram 3 shows how a Database Management System (DBMS) works as the brain behind modern data management. Here's the story:

- *Users and Applications*: Think of users as the people and applications as their tools. Users make requests through applications, and the DBMS does the heavy lifting behind the scenes.
- *The DBMS's Role*: The DBMS organizes, processes, and protects the data. It's like the librarian of a massive digital library:
  - It stores data securely in well-defined structures (called schemas).
  - It processes requests, like fetching or updating records, quickly and efficiently.
  - It acts as a gatekeeper, ensuring only authorized people can access the data.
  - It keeps things running smoothly with performance tuning and backups, ensuring nothing gets lost or corrupted.

3.1. Key Components and Functions

In a blockchain network, transactions received into the transaction pool are verified by multiple connected transaction verifiers. Miners collect these verified transactions and use the ordered data to create a proof of work (PoW) for the block (Nakamoto, 2008). Once created and verified, these blocks become part of the blockchain.

The initiation of a transaction sets off a sequence of events leading to its confirmation within the blockchain. The concept of confirmation depth represents the number of blocks added on top of the block where the transaction was first included (Antonopoulos & Harding, 2023). If a transaction is removed due to a block becoming orphaned, it reverts to the pending state.

Previous studies have proposed distributed blockchain-based database management systems for managing metadata and data relationships (Zheng et al., 2017). Additionally, publicly verifiable database systems store pointers to data,

allowing administrators to conduct searches to ensure data existence and integrity (Chen et al., 2018). In such systems, every verification node stores a copy of all data, meaning each node not only uses the data but can also generate it, even if some nodes contain errors.

A block in the blockchain contains:

- Information about the current transaction
- Addresses
- Public and private keys of the sender
- Hash of the previous block (32 characters in the current implementation)
- A hash formed from all the above elements

Transactions within the block are verified using the current blockchain implementation (Swan, 2015).

Figure 3: DBMS manages data, processes requests, and ensures security.

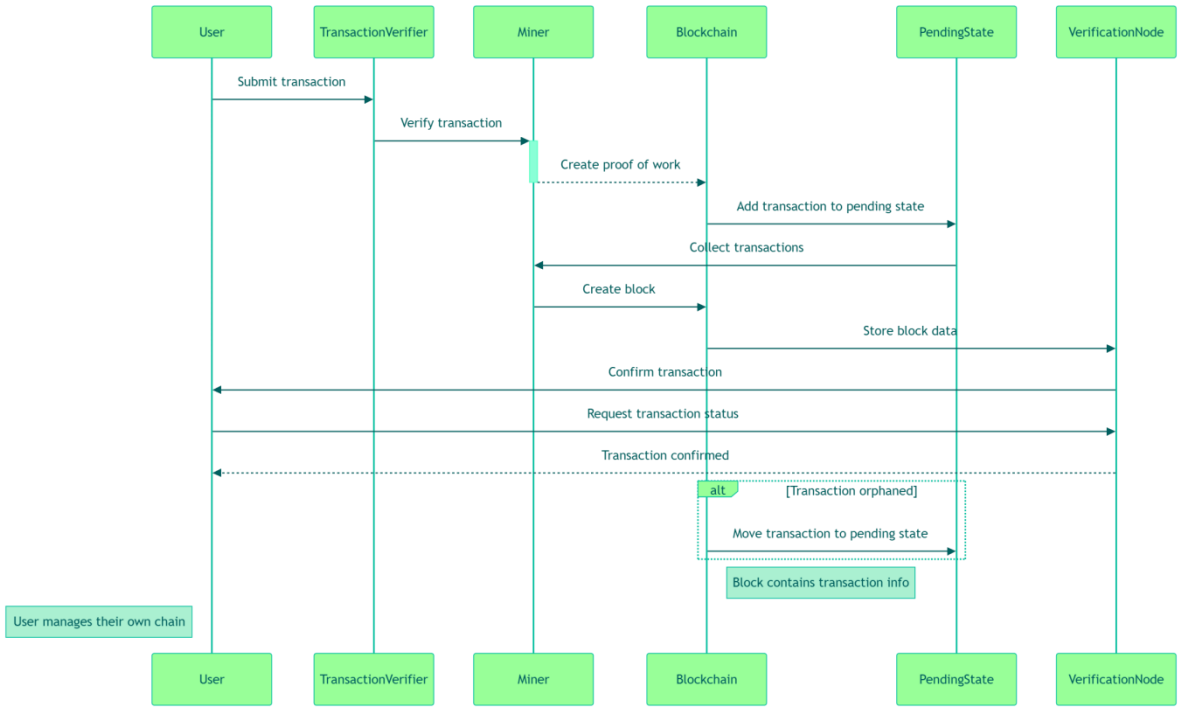

Figure 4: Transaction flow in a blockchain system.

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An account is identified by a name and an associated public/private key pair. Transactions are sent from one account to another, and the sender's code provides a straightforward method to submit a transaction to the network. The signature is generated using the sender's private key (Rosa-Bilbao & Boubeta-Puig, 2023). All transactions are visible in the pending state until they are confirmed.

The block candidate is derived from the unconfirmed transaction pool according to the PoW algorithm. Every user manages a chain; this user's chain is public and can be updated independently of others (Buterin, 2014; Kwame, Martey & Chris, 2017; Opoku-Mensah, Abilimi & Boateng, 2013).

Imagine you're sending money to someone using a blockchain-based system. Here's what happens behind the scenes:

i. Starting the Process: You, the user, hit "send." Your transaction is like a digital package that needs to be verified and added to a secure ledger.
ii. Checking the Package: A Transaction Verifier reviews your transaction to make sure it's valid (e.g., you have enough funds).
iii. Securing the Package: A Miner picks up your transaction along with others and works hard to solve a complex puzzle. This ensures your transaction is tamper-proof.
iv. Adding to the Ledger: Once the miner solves the puzzle, your transaction is bundled into a block and added to the blockchain, the digital ledger everyone trusts.
v. Confirmation: The system updates you: "Your transaction is complete and securely stored!"

IV. Integration of Blockchain Technology

Blockchain technology has the potential to revolutionize data management by enhancing security and trust across various industries. Integrating blockchain into existing database management systems can improve the trustworthiness of system records, strengthen audit trails in regulated sectors, streamline information validation processes, and optimize data sharing mechanisms (Zheng et al., 2017; Abilimi & Yeboah, 2013). However, current implementations often fall short of delivering significant improvements in security and validation compared to the technology's much-publicized potential. To fully harness the advantages of blockchain, database management systems and their software engineering practices must evolve to accommodate its unique characteristics.

A new database paradigm is emerging that combines the robust functionalities of traditional database systems with the strengths of blockchain platforms. This hybrid approach aims to create advanced systems capable of handling data with enhanced security, validation, and trust properties (Biswas & Muthukkumarasamy, 2016). By leveraging blockchain's immutable ledger and decentralized architecture, these systems can offer secure and transparent data management solutions.

Blockchain offers exciting possibilities that can impact enterprise systems across all industries. It opens up opportunities for business model innovation by providing benefits such as increased speed, improved validation processes, enhanced data security, censorship-resistant transactions, and heightened trust (Casino, Dasaklis & Patsakis, 2019). The technology enables secure and immutable data storage, offers transparency and access to authorized parties, simplifies transaction and settlement flows, and supports the use of smart contracts (Treiblmaier, 2019). The integration of database management systems with blockchain technology is already delivering gains in security and transparency, with the potential for much more in the future.

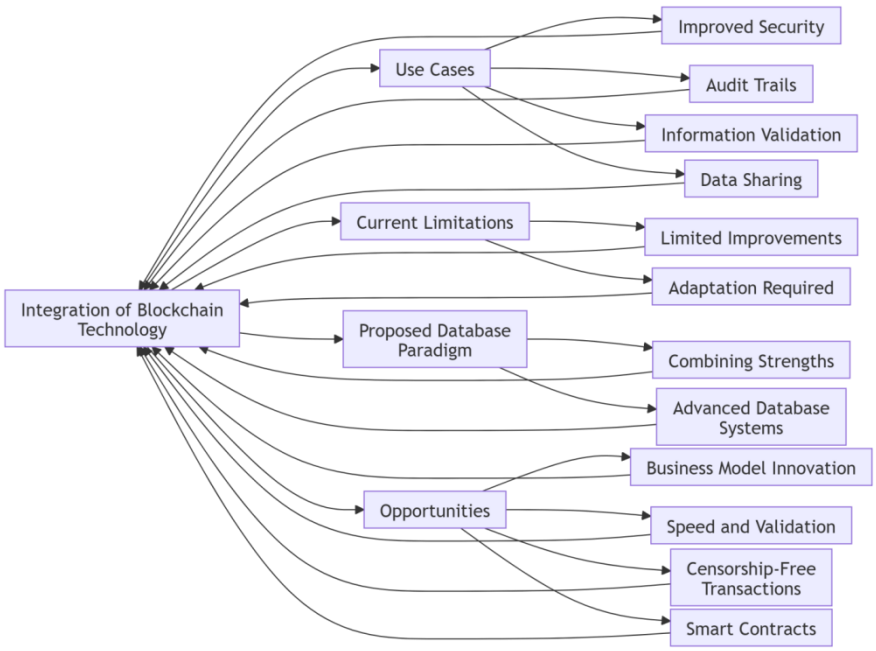

Figure 5: Blockchain enhances database security and trustworthiness.

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Several projects exemplify these developments and suggest a promising trajectory. For instance, blockchain integration in supply chain management has led to significant improvements in traceability and transparency (Kouhizadeh & Sarkis, 2018; Kouhizadeh & Sarkis, 2021). In the healthcare sector, blockchain is being used to secure patient data and streamline information sharing among authorized parties (Angraa, Krumholz & Schulz, 2017). These examples demonstrate how blockchain integration can lead to successful outcomes, although further research and development are necessary to overcome current limitations.

This diagram (Figure 5) paints a clear picture of how blockchain can transform database systems:

i. *Where Blockchain Shines*: Blockchain isn't just about cryptocurrencies; it's a game-changer for improving security, creating audit trails, and making data sharing and validation seamless. It ensures everything is recorded and verified transparently.
ii. *Challenges to Keep in Mind*: But it's not all smooth sailing. Integrating blockchain into existing systems requires significant changes, and the benefits may be incremental rather than revolutionary in some cases.
iii. *A New Way Forward*: The solution? Merge the advantages of both realms—blockchain's protection and decentralization along with the effectiveness of conventional databases. This integration could lead to smarter database systems and open up innovative business models.
iv. *The Big Opportunities*: The future looks exciting. Blockchain could make processes faster, ensure censorship-free transactions, and even automate tasks through smart contracts. It's all about creating systems that are more efficient, secure, and transparent.

4.1 Benefits and Challenges

Auditing is a vital aspect of database management, ensuring that databases are utilized as intended and protecting them from unauthorized modifications. Traditional methods often employ audit columns to monitor data manipulation operations such as insertions and updates. However, users unaware of these auditing mechanisms might attempt to modify tables directly and alter the audit columns to evade detection. Bypassing table triggers is a common tactic that undermines the integrity of the auditing process.

Blockchain technology offers a more reliable solution to these challenges by enhancing data integrity and preventing the manipulation of audit trails. By recording every change and preserving the original state of the database, blockchain provides a tamper-evident ledger that strengthens the security of database systems (Kumar, Gupta & Tripathi, 202; Dlimi, zzati & Ben Alla, 2023).

Integrating blockchain with database management systems brings significant benefits, particularly in building trust among users. Blockchain's consensus mechanism allows multiple users to agree on the sequence of data transactions, thereby enhancing transparency and integrity (Chen et al., 2017). When updates to a database are recorded on a blockchain and synchronized among peers, new users can verify the sequential transaction history, fostering trust in the database information. The database management system mirrors the blockchain records, ensuring consistency and reliability across the network.

This table summarizes the benefits and challenges of integrating blockchain technology with database management systems. Let me know if you'd like further refinements!

This paper presents a theoretical framework comprising four categories of models to conceptualize blockchain-based databases. These models explore how such databases can be designed and how they will behave—whether following the original decentralized intent of blockchain technology or adopting a more centralized approach—by considering various proposals.

TABLE 2: The benefits and challenges of integrating blockchain technology with database management systems

Aspect	Benefits	Challenges
Auditing	Verifies database usage adheres to design. Prevents illicit modifications. Records every change, ensuring database integrity.	Agents may attempt to bypass audit systems by subverting triggers or manipulating audit columns.
Trust	Enhances trust through blockchain's ability to reach consensus on transaction sequences and synchronize updates among peers.	Requires consistent synchronization and peer validation.
Transparency	Blockchain records updates that are verifiable, promoting transparency in database operations.	Complexity in integrating blockchain with traditional database management systems.
Data Integrity	Ensures data integrity by preventing tampering of audit tables and enabling verification of sequential transactions.	Potential overhead in processing and validating blockchain transactions alongside database operations.
User Trust	New users can trust the original database by verifying blockchain records for sequential transaction history.	Adoption barriers as users may require understanding of blockchain concepts for proper system interaction.
Operational Security	Prevents unauthorized manipulation of database records by relying on immutable blockchain-based change logs.	Risk of scalability issues as database size grows with blockchain ledger.

According to this framework, integrating blockchain technology with databases is essential to ensure that the system achieves eventual consistency in the properties required by robust systems (Li et al., 2020; Gilbert & Gilbert, 2024a). This integration promotes enhanced data usability through privileged operations from both systems and heightens the security needed in certain environments (Zheng et al., 2017; Gilbert & Gilbert, 2024e). The paper concludes by proposing that the viability of future advances in blockchain technology depends on an in-depth understanding of how these integrative bases function with the technology. Additionally, it emphasizes the importance of thoroughly considering aspects such as system scale and data representation (Ito & O'Dair, 2019; El-Madafr et al, 2023; Gilbert & Gilbert, 2024h). We believe that this proposal is also valuable for researchers aiming to use blockchain technology as a means of integration in various

fields or even in vertical production systems, such as document registration and creation through mobile applications (Verma et al., 2022; Gilbert & Gilbert, 2024e).

This paper extends the best practices of existing models proposed for asynchronous decentralized architectures and demonstrates how they are applied in the context of a centralized approach based on a tight cluster through the proposal of two new categories of models: fully centralized and partially centralized. The fully centralized model is pioneering and provides the basis for constructing a specialized model of wider use—the partially centralized model—which aims to present the behavior of a specific proposal characterized by the uniformity of the first category of models.

The two new categories of models, fully centralized and partially centralized, capture exclusive behaviors and impacts on system operations by considering both the integrative dimension—intrinsic and characteristic of blockchain operations—and the environmental dimension—the interaction with the database system (Ali et al., 2016; Cao et al.,2022; Gilbert & Gilbert, 2024f). Both models share a perspective on how blockchain technology should bridge with data manipulation primitives in accordance with its foundations and requirements, and how the integrative features related to its decentralized nature would function with reference to a single physical location.

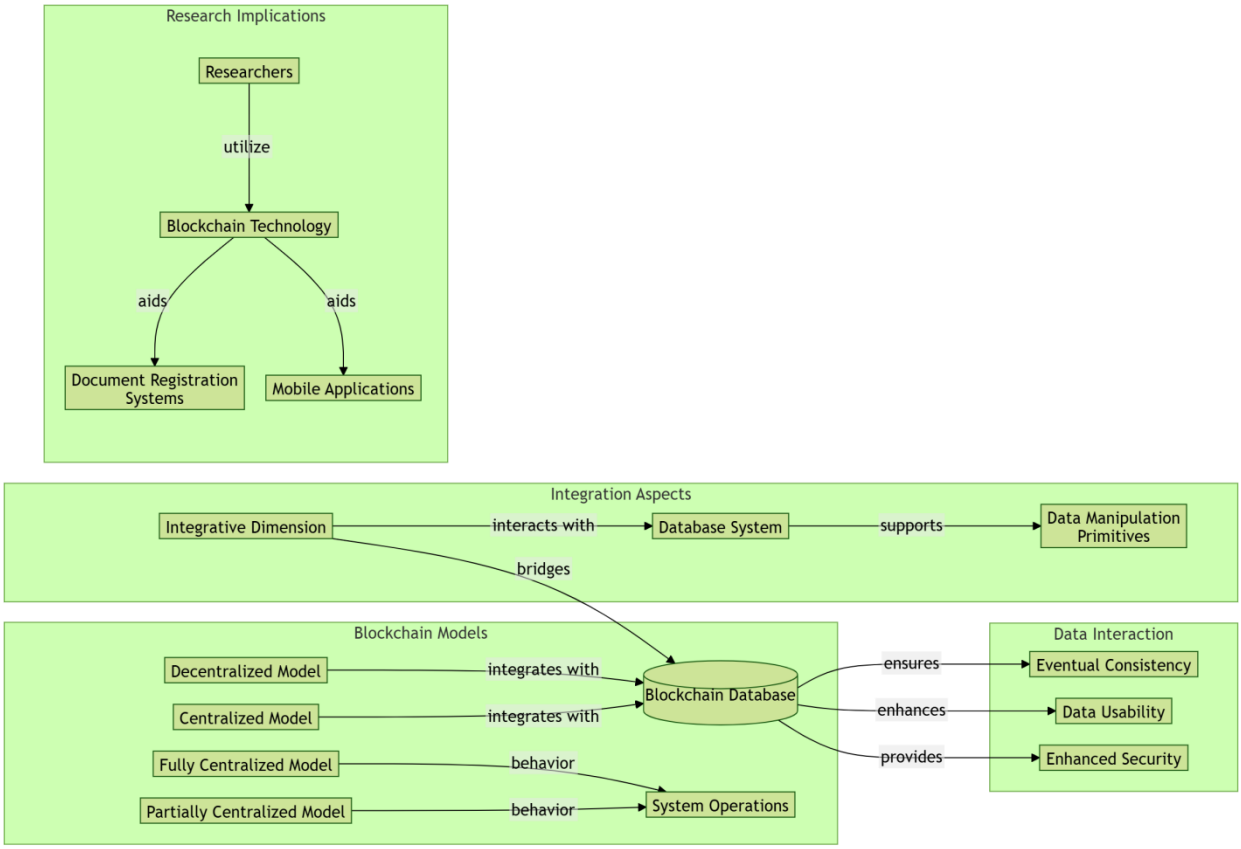

Figure 6: Blockchain models integrate with databases for consistency.

This diagram (Figure 6) shows how researchers are exploring new ways to combine blockchain technology with databases to make them more secure, reliable, and user-friendly.

i. Why Use Blockchain?:Blockchain helps with tasks like managing documents securely and building safer mobile apps. It's a tool researchers are using to tackle real-world problems.

ii. How Does Blockchain Work with Databases?:Blockchain doesn't replace databases—it works with them! By connecting the two, we get:
- More secure operations for updating or adding data.
- A better flow of information between systems.

iii. Different Models for Different Needs: There's no one-size-fits-all approach. Depending on the use case, systems can be fully decentralized (great for transparency) or centralized (better for control).

iv. The Benefits. By combining blockchain and databases, we can:
- Keep Data Consistent: Even if different parts of the system update at different times, everything syncs eventually.
- Make Data More Usable: Blockchain makes it easier to manage and share information.
- Increase Security: Protects data from tampering and unauthorized changes.

5.1 Consensus Mechanisms

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The consensus mechanism is crucial for ensuring that master data operations remain fully transparent and tamper-resistant among all authorized users within the alliance (Buterin, 2014). Traditional distributed consensus protocols maintain state through distributed replication (Lamport, Shostak & Pease, 2019; Maheshwari et al., 2021; Gilbert & Gilbert, 2024i). However, our approach differs philosophically by relying on centralized functionality, prompting the question: How do we agree on the ordering of operations?

In our proposed Blockchain Database Management System (BCDBMS) framework, we redefine the consensus algorithm—an essential component of blockchain technology—based on centralized database management mechanisms. Similar to permissioned blockchain platforms like Hyperledger Fabric, where consensus is managed by designated authorities (Androulaki et al., 2018; Correia et al., 2024; Gilbert & Gilbert, 2024j), our central authority has the final say in data distribution within the alliance blockchain. Major data manipulation operations are executed by a trusted center through batch processing, utilizing hash values, signature verification, and Trusted Execution Environments (TEEs) to enhance security and efficiency (Cheng et al., 2019; Liu et al.,2022; Opoku-Mensah, Abilimi & Amoako, 2013).

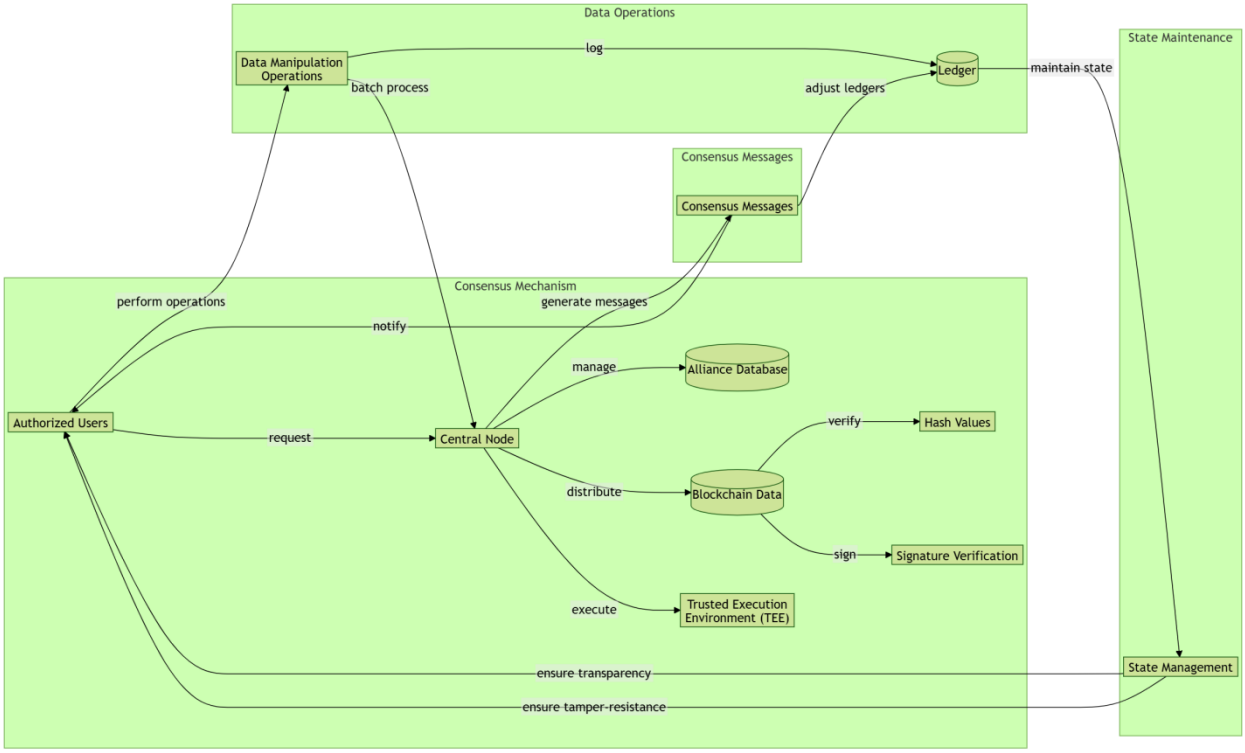

Figure 7: Consensus mechanism ensures secure data operations transparency.

This diagram (Figure 7) showcases a well-coordinated blockchain-based system that prioritizes security, transparency, and state consistency. The central node acts as the backbone, while tools like ledgers and trusted environments ensure that everything runs smoothly and securely. It's like having a digital accountant that tracks, verifies, and secures every single transaction.

V. Implications for Data Security and Privacy

One of the most pressing challenges in database management today is ensuring data security and privacy while maintaining transparency and enabling the interconnection of multiple heterogeneous systems (Bertino & Sandhu, 2005; Moin et al., 2019). With the increasing emphasis on transparency associated with blockchain technology, a system has been developed to integrate intelligent electronic devices across the entire electric power supply chain using blockchain (Mengelkamp et al., 2018). Specifically, parts of the power management system architecture are designed based on the traditional three-layer model. The development and operation of this system focus on high-entropy quantum security interfaces, providing secure connections between offline manufacturing processes and blockchain mining activities (Gilbert & Gilbert, 2024b; Puthal et al., 2018). These secure links aim to enhance security, eliminate internal fraud, and improve the efficiency of the power grid and the entire supply chain system. The outcomes of this work provide a foundation for further research and offer theoretical and practical insights for implementing this technology.

Blockchain technology has attracted significant attention from experts and professionals focused on enhancing security and decentralizing internet technologies, especially in controlling, processing, and transmitting information (Nakamoto, 2008; Christidis & Devetsikiotis, 2016; Gilbert & Gilbert, 2024c). This study examines the critical implications of integrating blockchain technology into database

management systems. It outlines the development and implementation of a flexible system based on multi-layer architecture techniques to integrate the entire electric power supply chain with blockchain technology (Kaif, Alam & Das, 2024; Gilbert & Gilbert, 2024d). Extensive data from the energy management system are validated within an off-chain blockchain structure through specific interface circuits. Additionally, a field-programmable gate array (FPGA) is utilized to provide secure hardware interfaces between the off-chain blockchain and each monitored electronic device (Wang et al., 2019; Gilbert & Gilbert, 2024g).

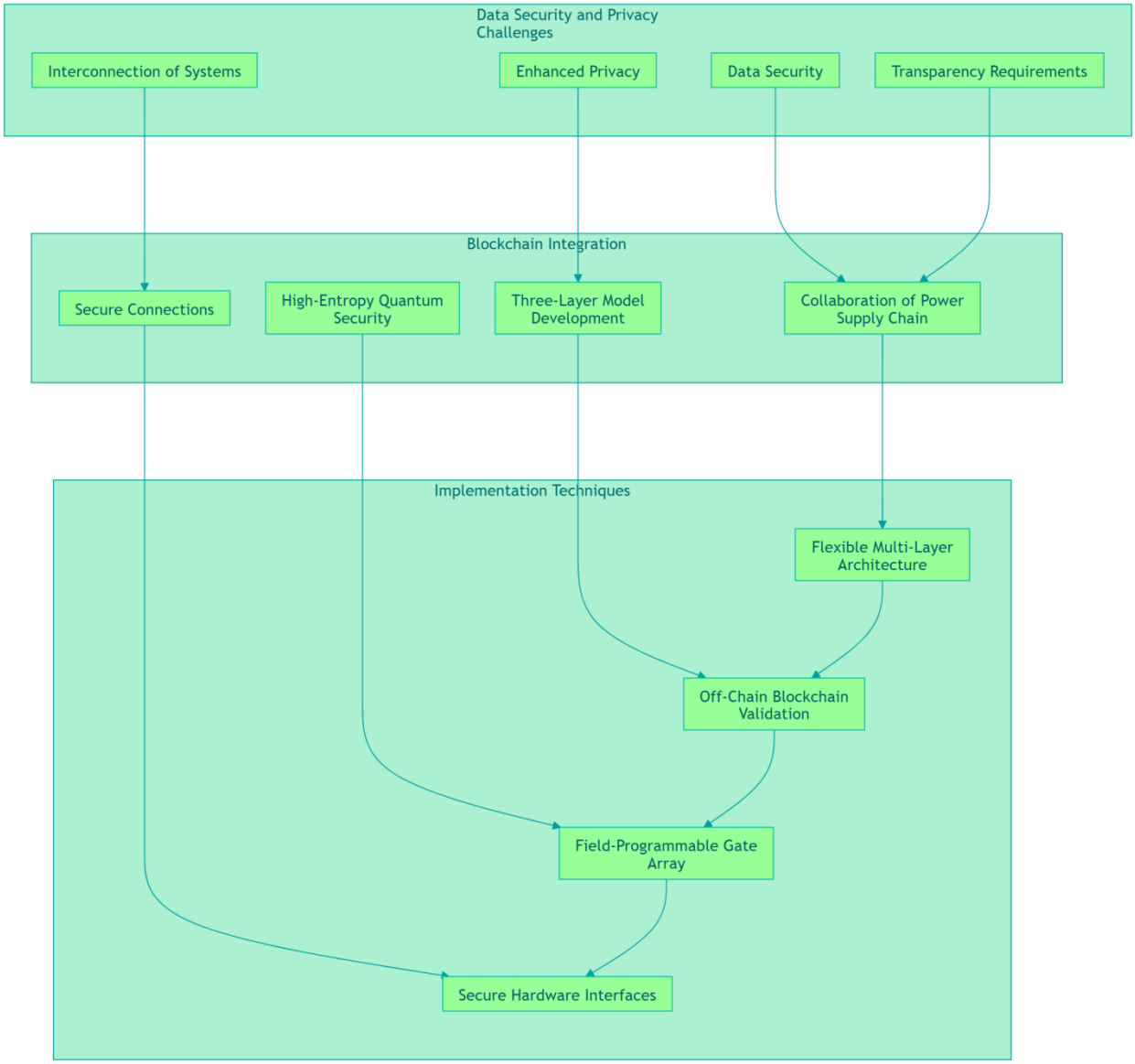

Figure 8: Integrates blockchain for secure power supply management.

This diagram (Figure 8) shows a roadmap for tackling modern data security and privacy issues using blockchain technology. By combining robust integration methods with advanced implementation techniques, we can create systems that are secure, transparent, and ready for the future. It's a mix of powerful software, hardware, and forward-thinking design.

5.1 Threats and Mitigation Strategies

Our proposed methods aim to address several security threats that could compromise the integrity and confidentiality of information. In this section, we summarize some of the main threats and propose solutions to mitigate them. While our solution focuses on streamlining data acquisition, securely storing data and preventing unauthorized access remain critical challenges to be addressed.

i. Unauthorized Access to Query Results

Unauthorized access to query results occurs when malicious users gain access to data they are not authorized to view, potentially leading to the misuse of sensitive information. To mitigate this threat, we propose limiting user privileges based on specific criteria, ensuring that only authorized individuals can access certain data. Additionally, regulatory bodies may

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require controlled access mechanisms to unlock query results for legal institutions, allowing for ledger verification to resolve disputes (McCallister, 2010; Priem. 2020; Gilbert & Gilbert, 2024k).

II. Data Inconsistency Due to Lack of Consensus

This threat exploits the lack of consensus among multiple user agents, leading to inconsistent data being stored in the ledger. Discrepancies arise when some user agents recognize data that others do not. To mitigate this, we rely on involving a large number of users in data authentication processes, enhancing consensus and data consistency across the network (Janani & Ramamoorthy, 2024; Gilbert & Gilbert, 2024l).

Iii. Data Tampering and Unauthorized Modification

Data tampering involves unauthorized agents illegally modifying data, resulting in discrepancies between the data stored in the ledger and the data retrieved through queries. To prevent this, we can employ various methods such as implementing digital signatures, secure hashing algorithms, and robust encryption and decryption techniques to protect data integrity (Stallings, 2021; Gilbert & Gilbert, 2024m).

By implementing these strategies, we aim to enhance the security of the system and protect against threats that could compromise the information. However, challenges remain in securely retaining data and preventing unauthorized access to confidential information, which require ongoing efforts to mitigate.

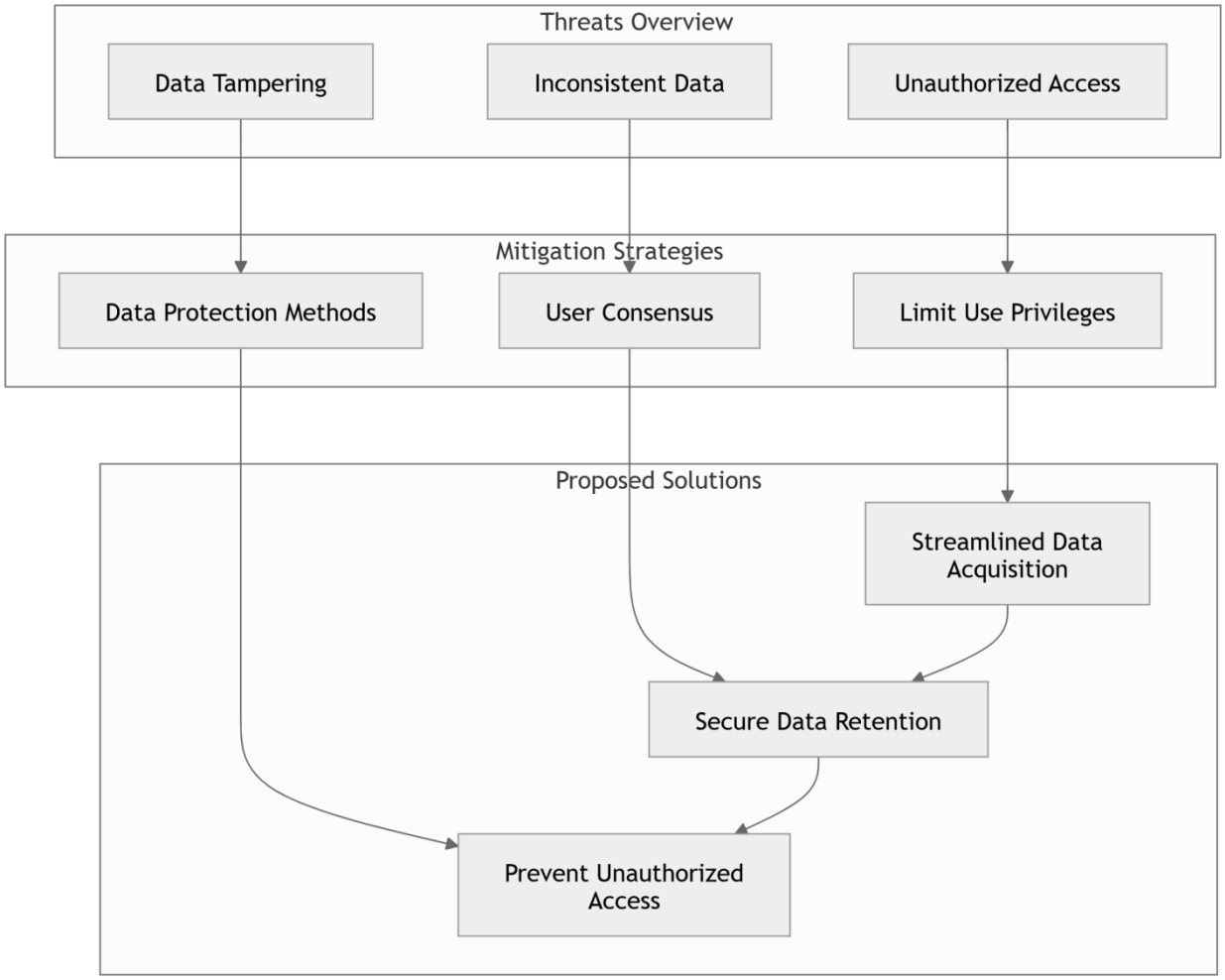

Figure 9: Diagram outlines threats and their mitigation strategies.

This diagram (Figure 9) provides a step-by-step framework to handle modern data threats, focusing on prevention, accuracy, and security. It's about building trust in the system while keeping data safe from errors or unauthorized use.

VI. Case Studies and Applications

Blockchain technology has found practical applications across various domains, showcasing its potential beyond theoretical concepts. One such application is in electronic voting systems, where blockchain-based ledger prototypes offer transparent vote tabulation for participants while preventing unauthorized alterations to tallies (Daraghmi, Hamoudi, & Abu Helou, 2024; Gilbert, 2012). In the realm of Industrial Internet of Things (IIoT), blockchain can utilize ledger reputation metrics to differentiate between legitimate security incidents and data errors, enhancing the overall security framework (Demertzi, Demertzis & Demertzis,2023; Gilbert & Gilbert, 2024n).

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Cloud-based database management systems can leverage blockchain to chain signed databases, serving as a witness that attests to data authenticity and durability (Yang et al., 2022; Gilbert & Gilbert, 2024o). This approach ensures that data remains unaltered and verifiable over time. In healthcare, wearable and implantable mHealth devices, which are not inherently water- or tamper-proof, can benefit from blockchain's tamper-resistant ledgers to manage the lifecycle of risk and attestation proofs, thereby improving personal identification and data system credibility (Chen et al., 2021).

Biometric recognition methods such as iris scans, facial recognition, fingerprints, voice, keystroke, and gait analysis all carry inherent risks (Kokal, Vanamala & Dave, 2023; (Yeboah, Opoku-Mensah & Abilimi, 2013a). Strengthening identity management through blockchain can enhance trust in encryption forms and degrees by maintaining secure logs and channels (Li et al., 2020; Yeboah, Opoku-Mensah, & Abilimi, 2013b). Data privacy regulations often necessitate adherence to data residency, encryption, and immunization requirements, all of which can be addressed through blockchain's immutable and decentralized nature (Mustafa et al., 2024; Gilbert & Gilbert, 2024p).

The implementation of blockchain in airline flight and maintenance logs addresses the hazards of a single point of failure by increasing resilience and enhancing security through an append-only architecture (Joeaneke et al., 2024; Mehmood et al., 2023). Similarly, blockchain-based healthcare ledgers provide provable audit trails for the use of Health Insurance Portability and Accountability Act (HIPAA) records, ensuring compliance and data integrity (Guo et al., 2018). Authentication processes between individuals or legal entities completing transactions are crucial measures that assure data lineage, and blockchain facilitates these processes by providing a transparent and secure platform (Nakamoto, 2008).

In conclusion, case studies and practical applications of blockchain and distributed ledger technologies are maturing, demonstrating that theoretical advancements have significant practical relevance. The demand for transparent public trust and the growth of cryptocurrency have propelled blockchain applications into new domains, leveraging its attributes of decentralization, shared control, and tamper-resistant immutability.

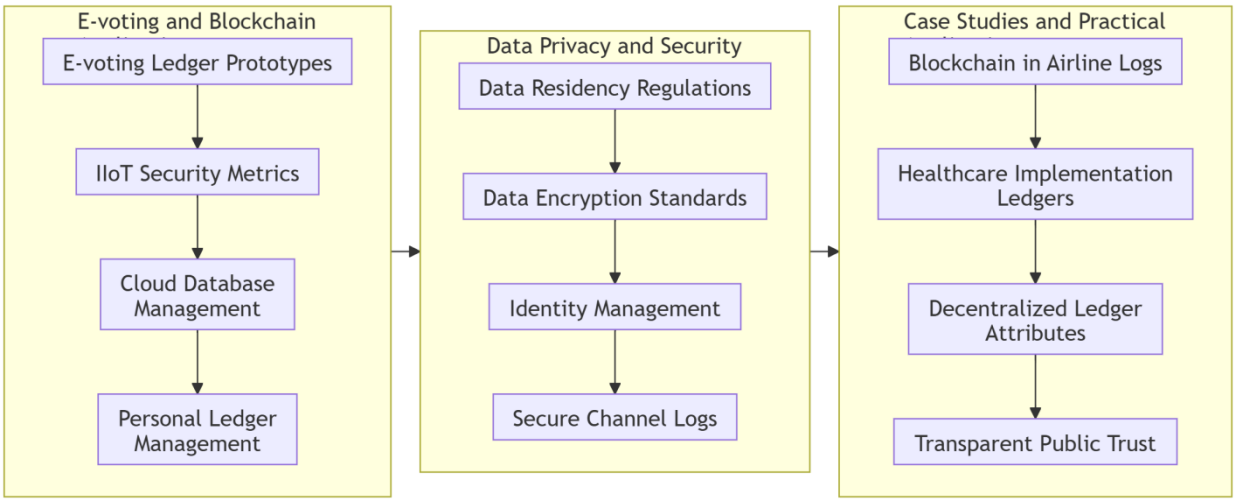

Figure 10: Blockchain applications enhance security and transparency.

This diagram (Figure 10) provides an organized view of how blockchain is applied across three domains: E-voting and Blockchain**,** Data Privacy and Security, and Case Studies and Practical Applications. Blockchain is more than just technology—it's a solution to challenges in security, privacy, and trust. Whether it's securing votes, managing sensitive data, or creating public trust, blockchain offers reliable and transparent ways to improve systems across industries.

6.1 Real-World Examples

One of the simplest blockchain database systems discussed in this section is BigchainDB (McConaghy et al., 2016). BigchainDB is a scalable blockchain database that combines the advantages of traditional distributed databases with blockchain technology. Its main design principles include decentralization, support for distributed transactions, and a development architecture for decentralized applications (dApps) that allows for standard database queries without the need for a bureaucratic layer.

Implemented on top of a customized version of MongoDB, BigchainDB achieves high throughput and low latency for database operations. The system is designed to handle a large number of transactions per second, providing real-time authentication and integrity verification. By optimizing indexing, BigchainDB can execute standard database operations efficiently with relatively few core instructions.

As a use case, BigchainDB has been applied to scenarios like asset transfer and digital rights management, demonstrating its ability to handle significantly more transactions than some other blockchain platforms. Additionally, BigchainDB has been involved in various projects funded by private entities and has received support from the European Union for its contributions to decentralized technology.

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In this section, we also explore prominent projects and companies pioneering the use of blockchain in database technology. Notably, the Hyperledger Project, initiated by the Linux Foundation, anticipated the integration of blockchain into novel database schemas, incorporating elements like currency and time into database records (Androulaki et al., 2018; Gilbert & Gilbert, 2024q). Before blockchain became a widespread term, projects like Hyperledger Fabric delved into the core features of blockchain technology.

These early implementations discussed the functions and performance trade-offs of blockchain schemas, concluding that their systems were slower than traditional databases for most operations but sufficient to support multi-user non-transactional applications (Gilbert & Gilbert, 2024r). Although these systems were initially designed for relational databases, the rise of the NoSQL movement has led many organizations to implement and benchmark blockchain database systems.

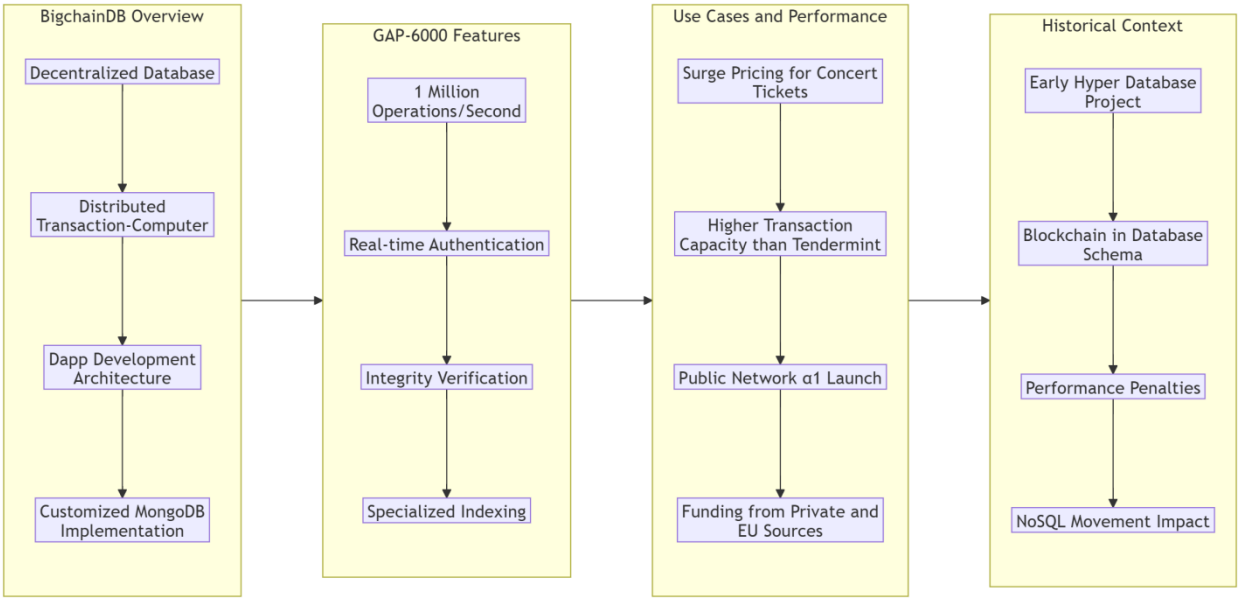

Figure 11: BigchainDB is a decentralized blockchain database system.

This diagram (Figure 11) provides an overview of BigchainDB, highlighting its features, use cases, performance, and historical context. BigchainDB is a powerful tool that brings blockchain-level trust to database systems while retaining high performance and scalability. Its ability to handle complex, high-speed transactions makes it ideal for use cases like ticketing, finance, and IoT.

VII. Future Directions and Emerging Trends

As blockchain technology continues to be adopted across various sectors, its unique characteristics and enabling technologies have prompted researchers to conduct domain-specific reviews of its implementations (Zheng et al., 2018). In our study, we first define the essential features that set blockchain apart from other technologies, followed by a categorical presentation of a taxonomic framework (Zheng et al., 2019). We characterize enabling technologies across four domains: technical, developmental, application, and operational concepts (Casino et al., 2019). In each domain, we provide a comprehensive literature review from both academic and industry perspectives, highlighting relevant blockchain characteristics, challenges, and future research directions (Drescher & Drescher, 2017; Gilbert, 2018).

Although the potential role of blockchain in developing Smart City applications has been acknowledged (Biswas & Muthukkumarasamy, 2016), it is crucial to investigate the enabling features that facilitate this development. In this article, we survey the characteristics of Smart Cities alongside blockchain features to better understand their interrelationship (Allam & Dhunny, 2019). Concurrently, we identify functional challenges and propose potential technical considerations for implementation (Shen et al., 2019). We conduct an in-depth analysis of blockchain technology to elucidate the relationship between its potential benefits and the barriers to participation in Smart Cities (Sun et al., 2016). We explore how blockchain can effectively address these barriers, integrating the essence of Smart City concepts at its core. We propose novel blockchain characteristics that can foster the development and implementation of Smart City projects (Kouhizadeh et al., 2021). By leveraging these characteristics, blockchain technology can overcome Smart City barriers and enhance citizen participation in development activities.

Emerging smart solutions—including Smart Cities, Smart Grids, Smart Buildings, and the Industrial Internet—highlight the importance of adopting intelligent technologies in today's world (Aquila et al., 2023). Among these technologies, blockchain plays a pivotal role due to its decentralization, tamper resistance, and transparency (Li et al., 2020). However, the relationships between these emerging smart technologies and blockchain remain underexplored (Xu et al., 2019). Developing smart solutions within cities generates substantial volumes of heterogeneous and dynamic data—including human

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location data, traffic conditions, energy consumption patterns, and more (Dildar Korkmaz, 2023). Consequently, big data techniques have emerged to efficiently manage and analyze this information (Sagiroglu & Sinanc, 2013).

While integrating blockchain into big data management introduces challenges—such as data transaction agreements, inefficient data uploading, and limited ledger management features—we provide a state-of-the-art review of blockchain in big data from both academic and industry perspectives (Yli-Huumo et al., 2016). The push for shorter communication distances and energy-saving objectives in the Internet of Things (IoT) necessitates the integration of blockchain technology (Christidis & Devetsikiotis, 2016; Gilbert & Gilbert, 2024s). We discuss the relationships between these existing technologies and blockchain (Makhdoom et al., 2019). Additionally, we present a comprehensive review from both academia and industry, highlighting enabling technologies for blockchain integration, associated challenges, and future research directions (Zhang & Wen, 2017).

Figure 12: Explores blockchain's role in smart city development.

This diagram (Figure 12) maps out a detailed exploration of blockchain technology's current applications**,** challenges, and future directions, particularly in smart cities and other emerging domains. Blockchain is paving the way for smarter, more transparent systems across industries. While there are challenges to overcome, the potential for improved citizen participation, efficiency, and security makes it a technology worth investing in.

7.1 Potential Innovations

Achieving Win-Win Outcomes in Information Systems

Integrating blockchain technology into operational systems can create open and transparent services, encouraging greater participation and resource investment. This approach accelerates the development of mutually beneficial scenarios for all stakeholders involved. At the core of these systems is the significant data generated through user interactions. Research indicates that combining blockchain technology with database systems can enhance the collective value of data in various ways (Xu, Weber, & Staples, 2019; Gilbert & Gilbert, 2024a).

Facilitating Sustainable Data Trading

The fusion of blockchain technology with database systems enhances data independence and flexibility, helping to bridge the gap between data supply and demand. This integration offers trading mechanisms for low-value data—which traditionally holds little to no market value—and for high-value personal or subjective data. Blockchain support enables data to become a tradable asset capable of generating significant commercial value (Zyskind & Nathan, 2015).

Economic Value from Blockchain-Database Integration

Integrating blockchain technology into database architectures is expected to add substantial value across numerous use cases. Blockchain's dual features of decentralization and strong immutability allow for a wide range of flexible applications and promote trustworthy computing. This innovation transforms the information exchange framework from a dependent relationship to a mutually beneficial cooperation. Consequently, data in blockchain-enhanced database systems can itself become a valuable asset (Swan, 2015).

This diagram (Figure 13) explores the potential innovations enabled by blockchain technology, focusing on its role in information systems**,** data trading, and economic value generation. It highlights the transformative impact of blockchain across various domains. Blockchain is reshaping the way we think about data and its value. By enabling transparent systems, secure data trading, and creating economic opportunities, blockchain is unlocking potential in ways that are fair, efficient, and mutually beneficial. It’s a win-win for both users and system.

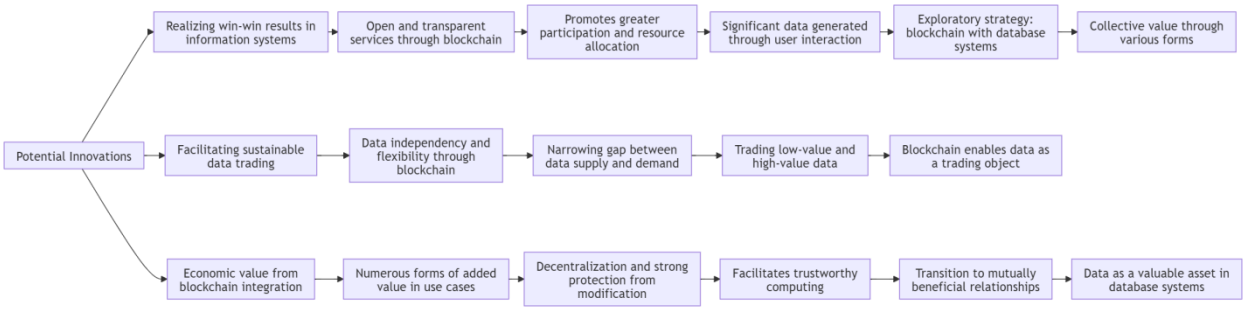

Figure 13: Innovations in blockchain enhance data trading and value.

VIII. Summary of Findings and Conclusions

8.1 Summary of Findings

This study provides a comprehensive analysis of integrating blockchain technology into database management systems (DBMSs). The research is structured as follows:

- *Section 2:* Discusses the motivation behind the research.
- *Section 3:* Offers a conceptual overview of blockchain technology and the roles of DBMSs.
- *Section 4:* Reviews various research studies and business trends, highlighting the limited scope of existing studies.
- *Section 5:* Identifies potential risks and threats associated with integrating blockchain into DBMSs.
- *Section 6:* Develops a comprehensive taxonomy based on four dimensions: Types, Properties, Concepts, and Categories. This taxonomy aids in identifying areas requiring further understanding and integration.
- *Section 7:* Analytically evaluates various technologies, assessing their successes and challenges concerning different deployment objectives.
- *Conclusion:* Summarizes findings and suggests future research directions.

Key contributions of this study include:

Addressing Research Gaps: While existing surveys often focus on digital currencies, this study explores the integration of blockchain technology into both SQL and NoSQL DBMSs, proposing adjustments and enhancements to align database properties with blockchain characteristics (Zhu et al. 2023).

Proposing a Comprehensive Taxonomy: The study introduces a novel taxonomy for integrating blockchain technology into DBMSs, revising and combining prior taxonomies while addressing potential threats to DBMSs (Seufitelli et al., 2023).

Providing a Detailed Analysis: Beyond presenting the taxonomy in tabular form, the study offers a thorough written analysis, serving as a valuable resource for businesses, researchers, and academics (Raddats et al., 2019).

The qualitative assessment highlights areas for future research, emphasizing the need for deeper exploration into the integration of blockchain and DBMSs.

9.2 Conclusion

Blockchain technology has gained significant traction beyond cryptocurrencies, prompting efforts to integrate it with existing database technologies. Currently, many industrial DBMSs operate in a centralized manner, making them vulnerable to hacking, data modification, and issues of data veracity. Blockchain's attributes—transparency, tamper-proofing, and security—offer substantial improvements to these systems (Habib et al., 2022).

This research examines various integration methods, providing a systematic approach to merging existing DBMSs with blockchain technology. Prototypes like BigchainDB demonstrate the feasibility of such integrations, and increasing interest from major DBMS providers suggests that blockchain-enhanced databases (BlockDB) may become prevalent as the technology matures.

Blockchain's robust security and transparency make it suitable for diverse applications, from system transactions to supply chain management and voting systems. However, implementing blockchain at scale presents challenges, particularly regarding data storage and system integration. Advancements in blockchain technology are essential to address these challenges and fully realize its potential in enhancing DBMSs.

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