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(54) **ENCRYPTION KEY MANAGEMENT AND TRANSPARENT DECRYPTION**

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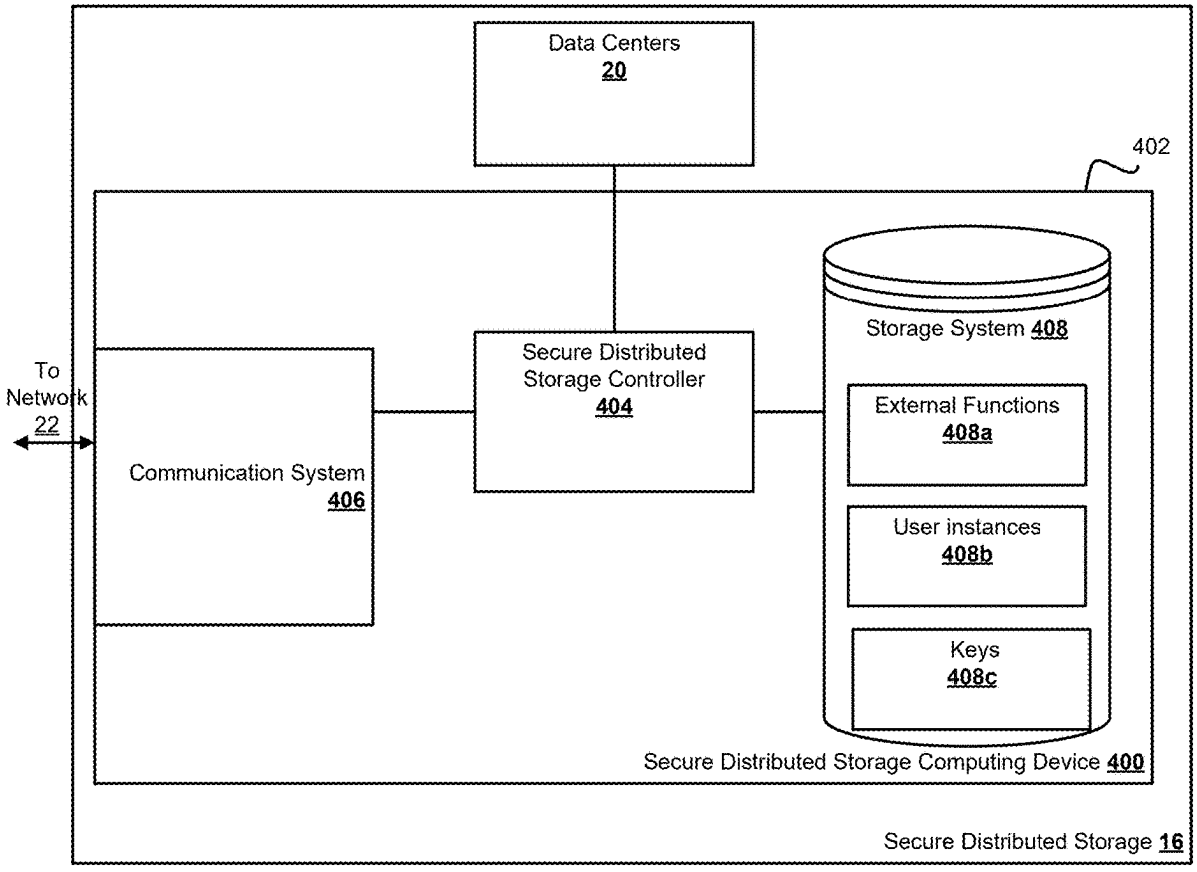
(57) **ABSTRACT**

A system and method are provided for encryption key management, transparent decryption, and secure key sharing within a secure distributed storage environment. A master encryption key is generated for a user and encrypted using a wrapper key. Database keys are generated and encrypted using the master key, and then stored at a user-associated storage instance. In response to a query, the encrypted database key is decrypted using the master key and used to decrypt encrypted data. Masking policies may determine whether decrypted or encrypted data is returned to the user. Format-preserving encryption may be applied using a tweak value. Encrypted keys may be securely shared across independent encryption domains by re-encrypting under a temporary session master key. At no point is raw key material exposed to untrusted systems. The techniques improve key lifecycle security, enable policy-based access, and support multi-tenant data environments such as cloud-hosted data warehouses.



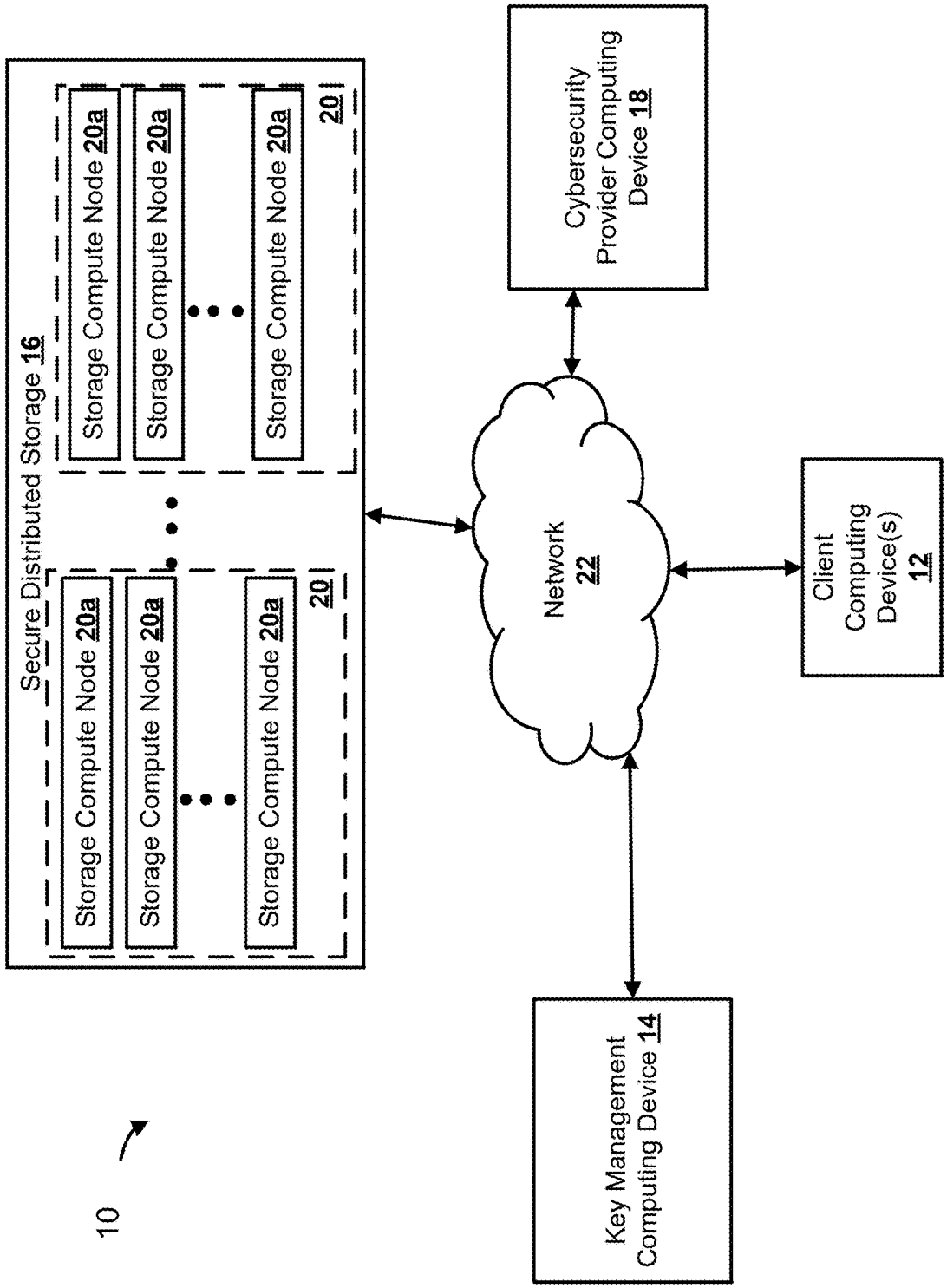

10
Secure Distributed Storage 16
Storage Compute Node 20a
Storage Compute Node 20a
Storage Compute Node 20a
20
Storage Compute Node 20a
Storage Compute Node 20a
Storage Compute Node 20a
20
Network 22
Cybersecurity Provider Computing Device 18
Client Computing Device(s) 12
Key Management Computing Device 14

FIG. 1

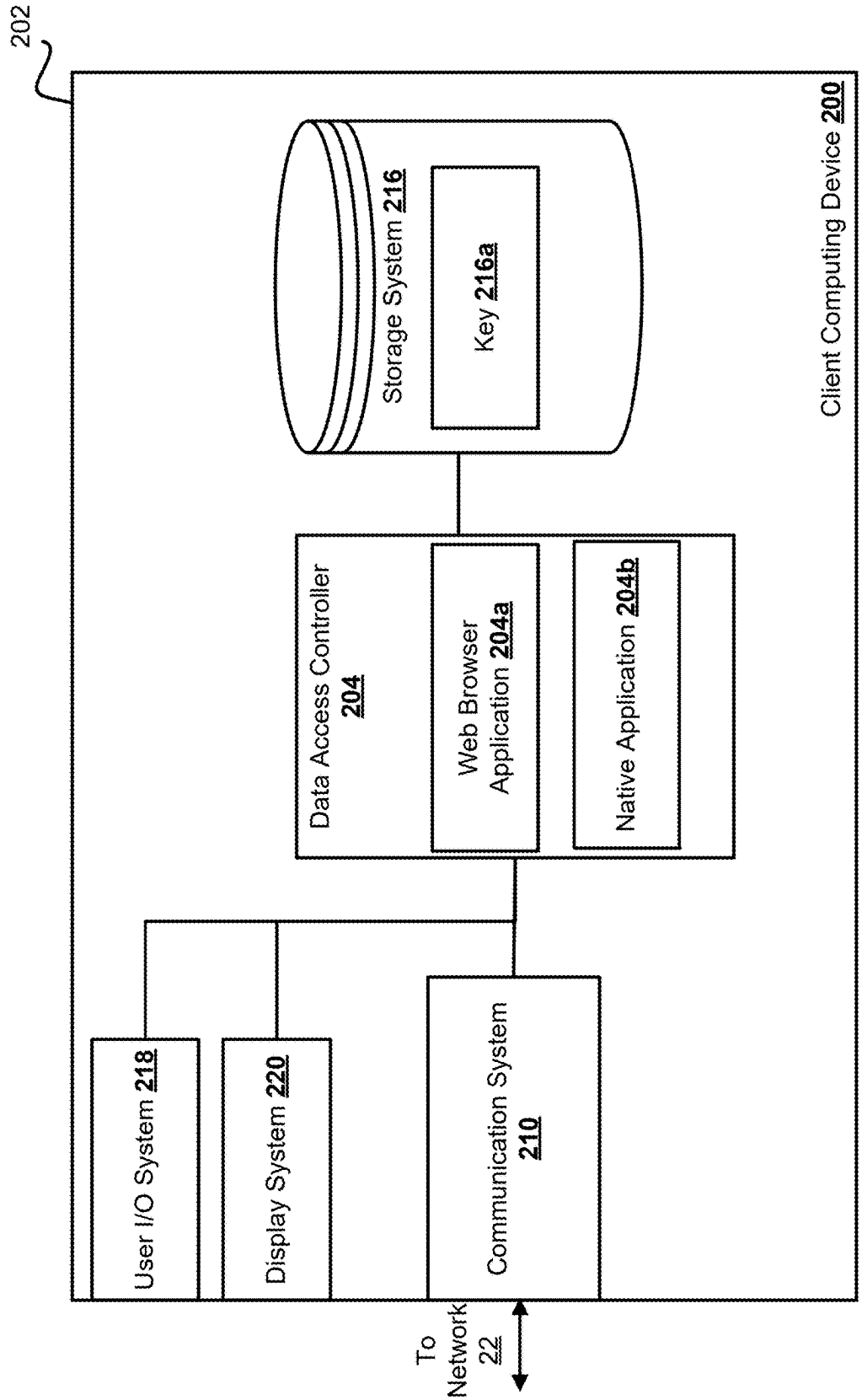

202
Client Computing Device 200
Storage System 216
Key 216a
Data Access Controller 204
Web Browser Application 204a
Native Application 204b
User I/O System 218
Display System 220
Communication System 210
To Network 22

FIG. 2

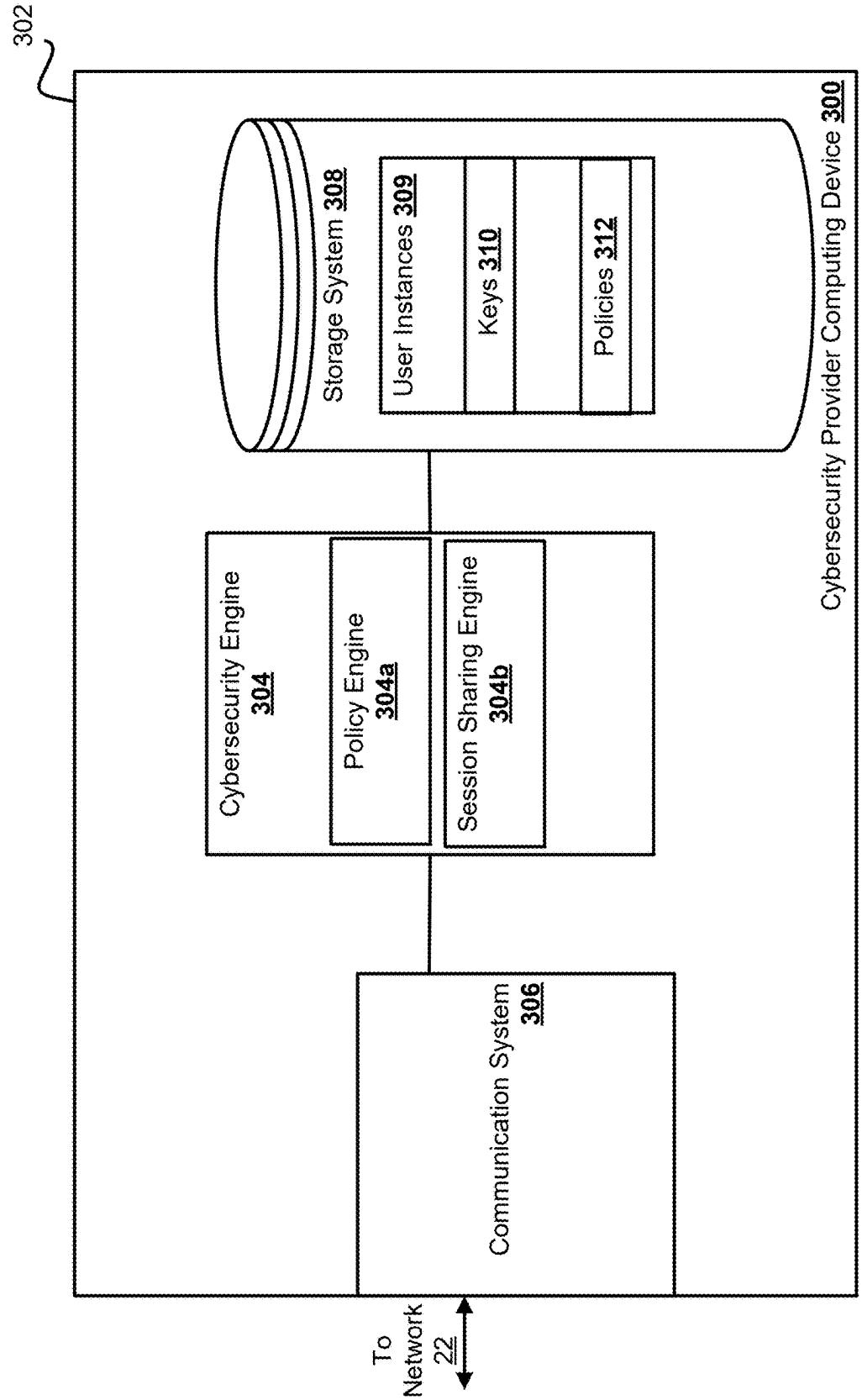

302
Cybersecurity Provider Computing Device 300
Storage System 308
User Instances 309
Keys 310
Policies 312
Cybersecurity Engine 304
Policy Engine 304a
Session Sharing Engine 304b
Communication System 306
To Network 22

FIG. 3

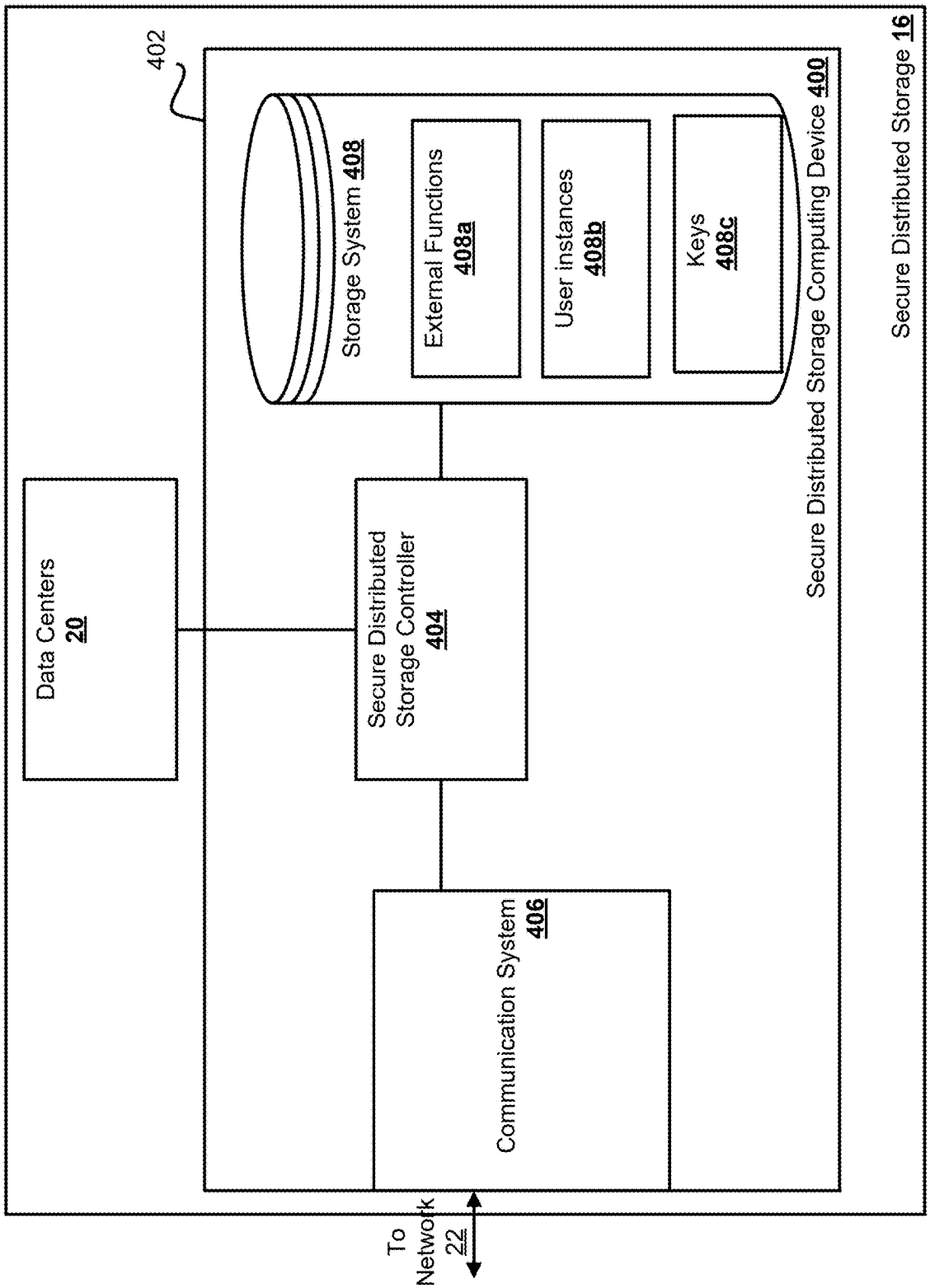

Secure Distributed Storage 16
402
Secure Distributed Storage Computing Device 400
Storage System 408
External Functions 408a
User instances 408b
Keys 408c
Data Centers 20
Secure Distributed Storage Controller 404
Communication System 406
To Network 22

FIG. 4

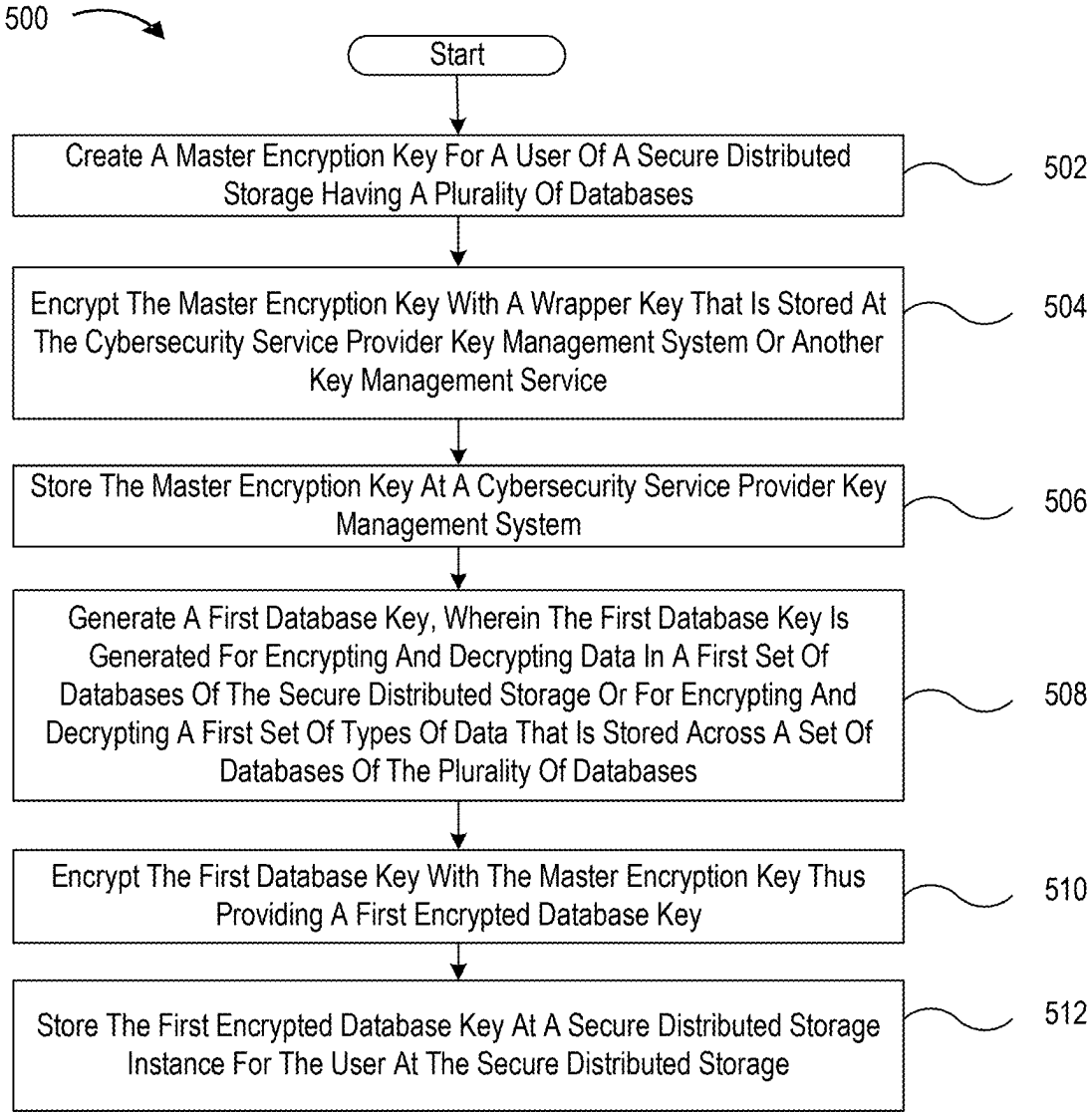

500
Start
Create A Master Encryption Key For A User Of A Secure Distributed Storage Having A Plurality Of Databases
502
Encrypt The Master Encryption Key With A Wrapper Key That Is Stored At The Cybersecurity Service Provider Key Management System Or Another Key Management Service
504
Store The Master Encryption Key At A Cybersecurity Service Provider Key Management System
506
Generate A First Database Key, Wherein The First Database Key Is Generated For Encrypting And Decrypting Data In A First Set Of Databases Of The Secure Distributed Storage Or For Encrypting And Decrypting A First Set Of Types Of Data That Is Stored Across A Set Of Databases Of The Plurality Of Databases
508
Encrypt The First Database Key With The Master Encryption Key Thus Providing A First Encrypted Database Key
510
Store The First Encrypted Database Key At A Secure Distributed Storage Instance For The User At The Secure Distributed Storage
512

FIG. 5

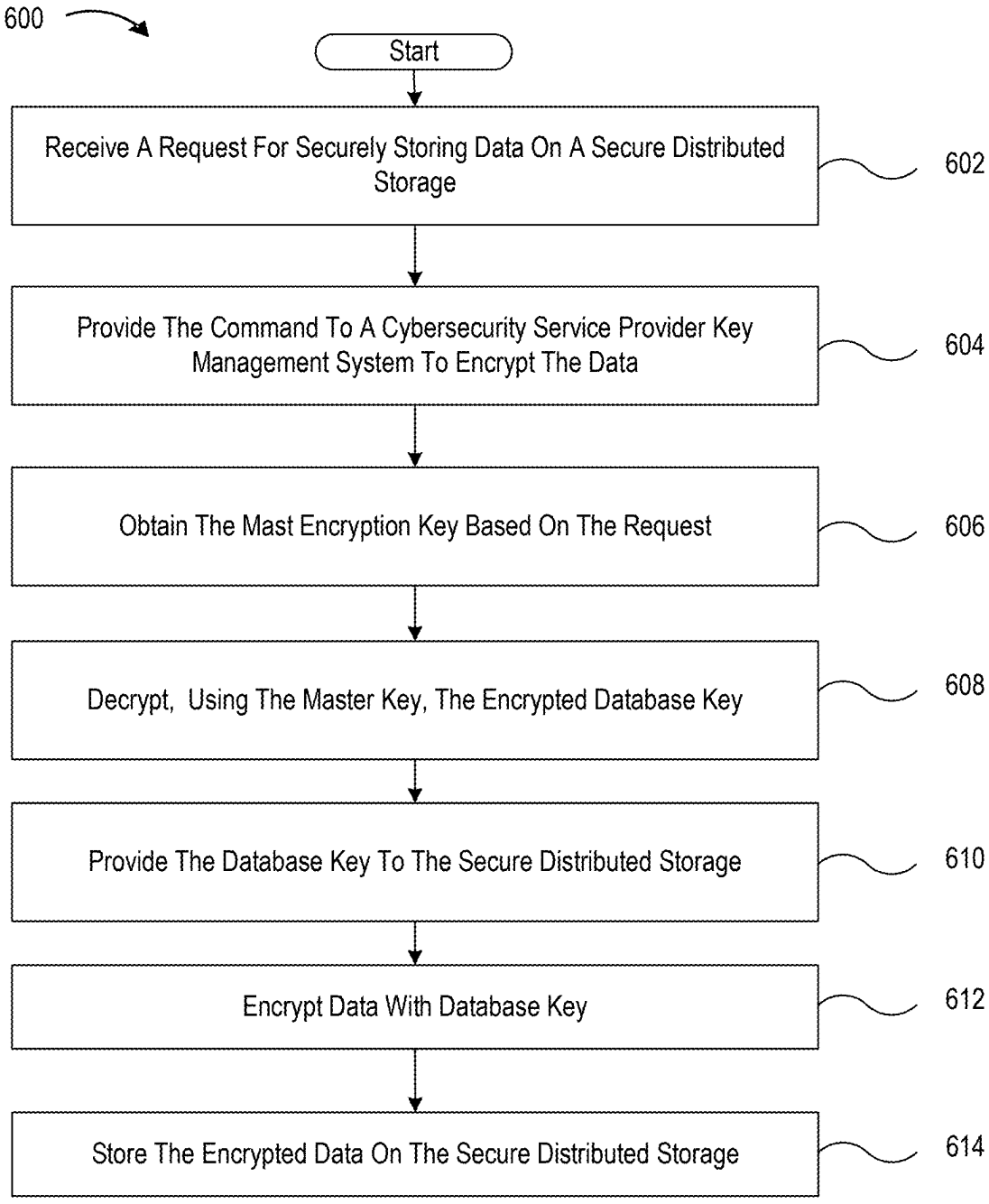

600
Start
Receive A Request For Securely Storing Data On A Secure Distributed Storage
602
Provide The Command To A Cybersecurity Service Provider Key Management System To Encrypt The Data
604
Obtain The Mast Encryption Key Based On The Request
606
Decrypt, Using The Master Key, The Encrypted Database Key
608
Provide The Database Key To The Secure Distributed Storage
610
Encrypt Data With Database Key
612
Store The Encrypted Data On The Secure Distributed Storage
614

FIG. 6

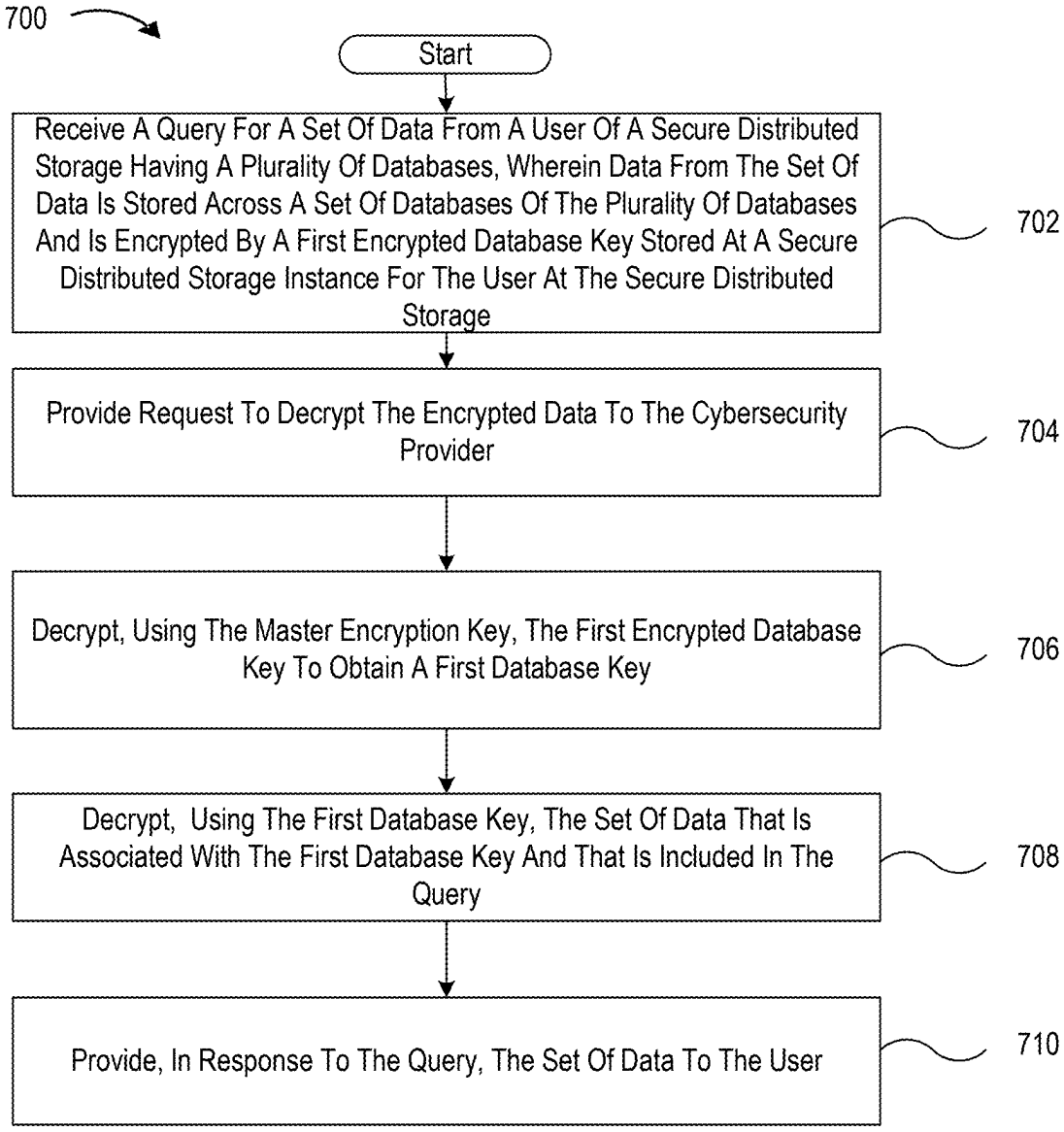

700
Start
Receive A Query For A Set Of Data From A User Of A Secure Distributed Storage Having A Plurality Of Databases, Wherein Data From The Set Of Data Is Stored Across A Set Of Databases Of The Plurality Of Databases And Is Encrypted By A First Encrypted Database Key Stored At A Secure Distributed Storage Instance For The User At The Secure Distributed Storage
702
Provide Request To Decrypt The Encrypted Data To The Cybersecurity Provider
704
Decrypt, Using The Master Encryption Key, The First Encrypted Database Key To Obtain A First Database Key
706
Decrypt, Using The First Database Key, The Set Of Data That Is Associated With The First Database Key And That Is Included In The Query
708
Provide, In Response To The Query, The Set Of Data To The User
710

FIG. 7

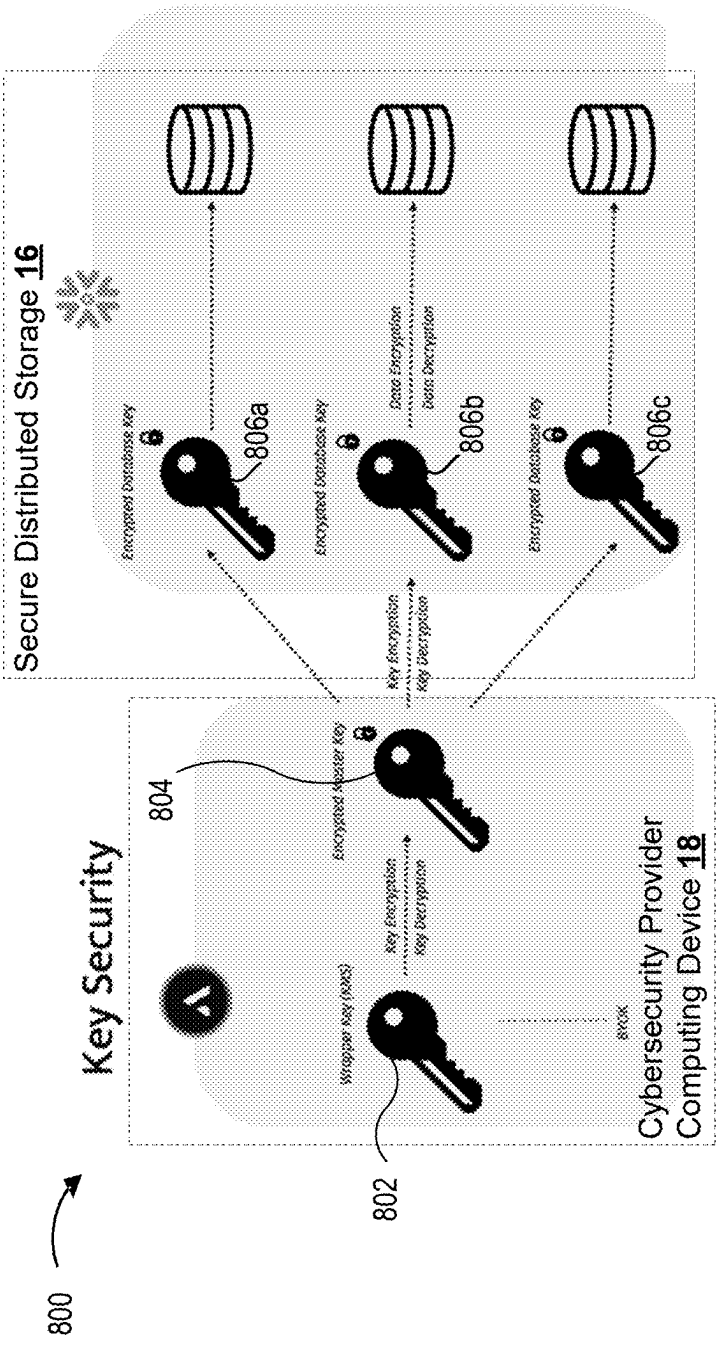

800
Key Security
Cybersecurity Provider Computing Device 18
802
804
Wrapper key (KEK)
Key Encryption
Key Decryption
Encrypted Master Key
Secure Distributed Storage 16
Encrypted Database Key
806a
806b
806c
Data Encryption
Data Decryption

FIG. 8

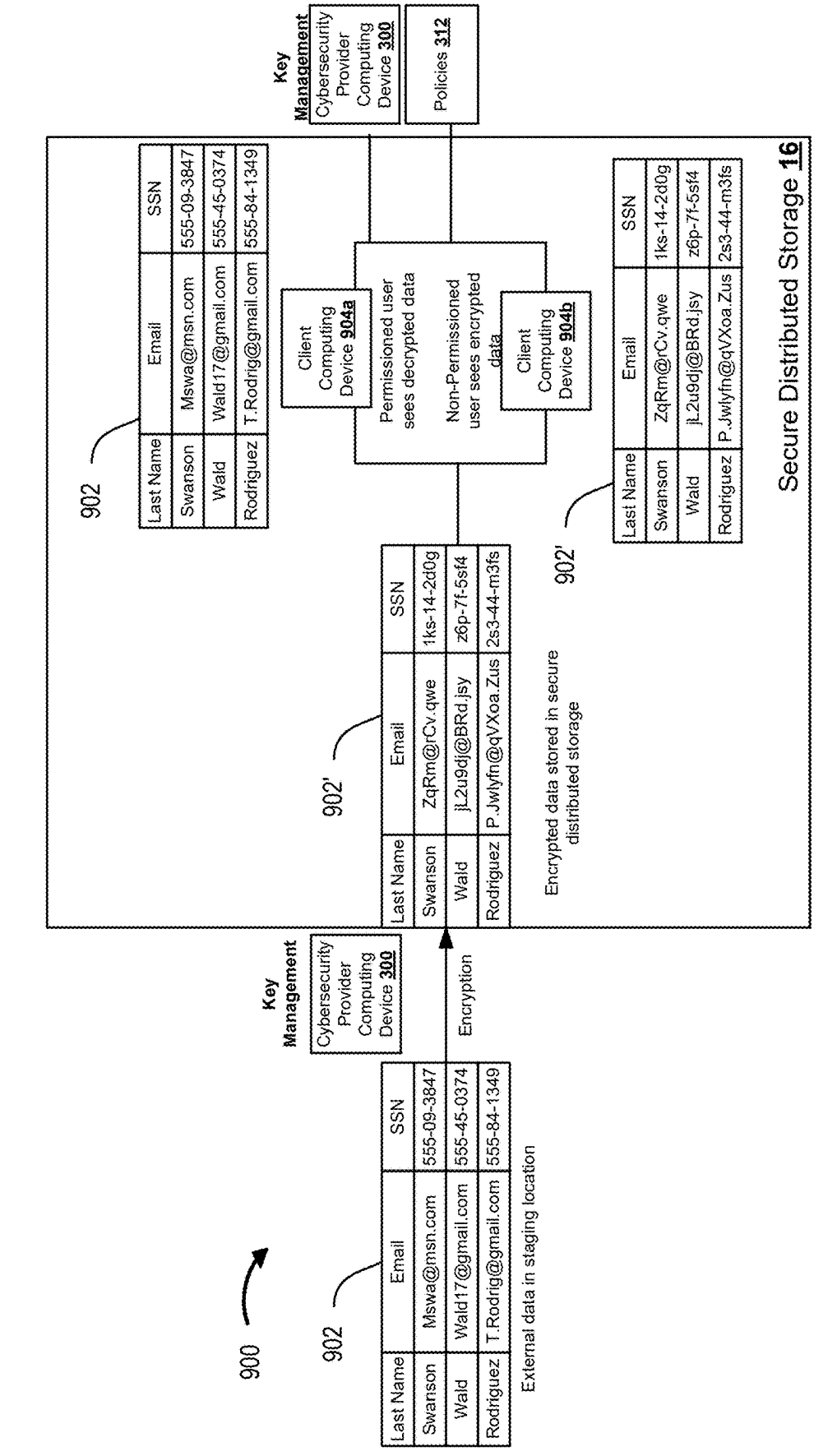

900
902
Last Name | Email | SSN
Swanson | Mswa@msn.com | 555-09-3847
Wald | Wald17@gmail.com | 555-45-0374
Rodriguez | T.Rodrig@gmail.com | 555-84-1349
External data in staging location
Encryption
Key Management
Cybersecurity Provider Computing Device 300
Secure Distributed Storage 16
902'
Last Name | Email | SSN
Swanson | ZqRm@rCv.qwe | 1ks-14-2d0g
Wald | jL2u9dj@BRd.jsy | z6p-7f-5sf4
Rodriguez | P.Jwlyfn@qVXoa.Zus | 2s3-44-m3fs
Encrypted data stored in secure distributed storage
Client Computing Device 904a
Permissioned user sees decrypted data
Non-Permissioned user sees encrypted data
Client Computing Device 904b
Policies 312

FIG. 9

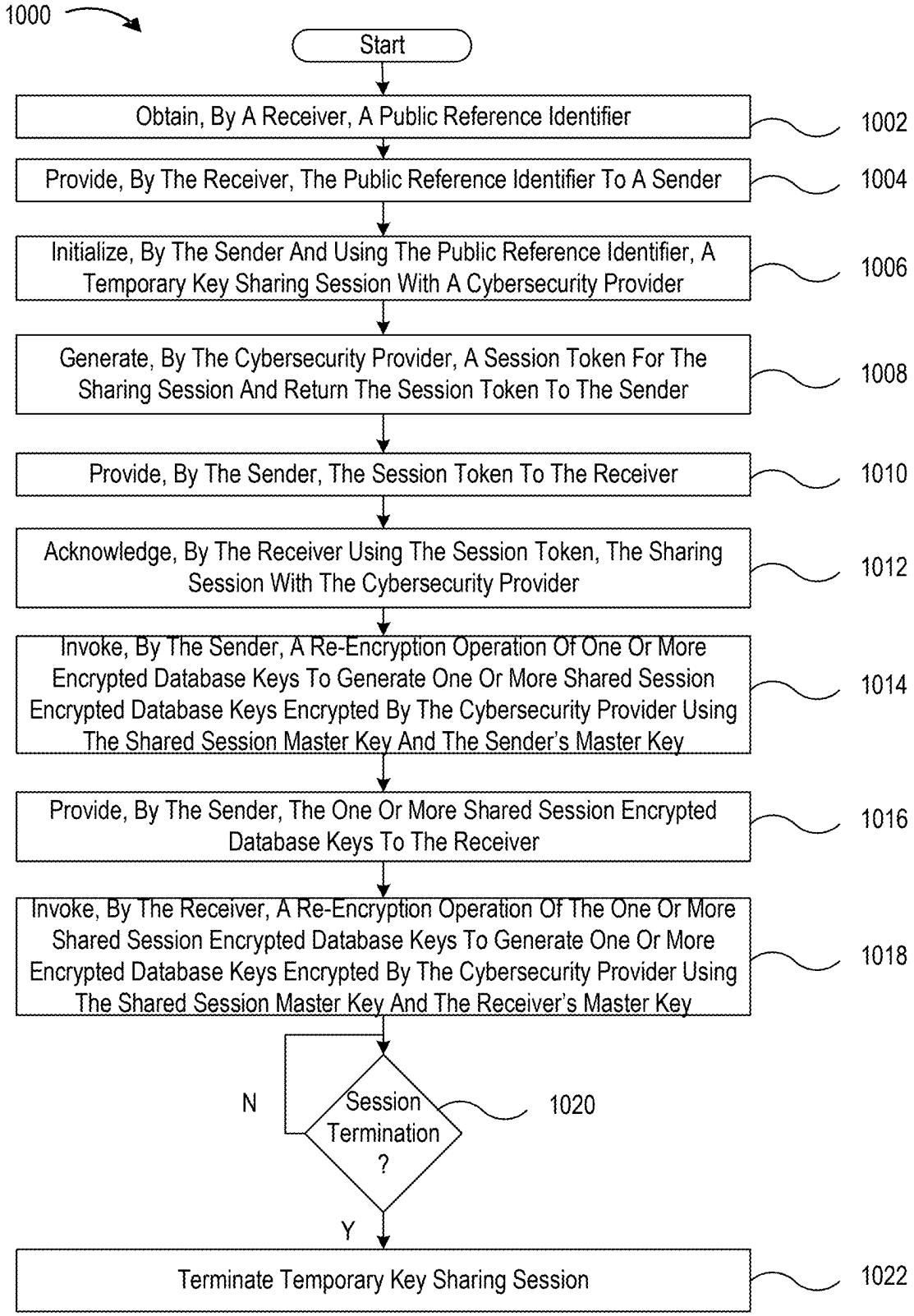

1000
Start
Obtain, By A Receiver, A Public Reference Identifier
1002
Provide, By The Receiver, The Public Reference Identifier To A Sender
1004
Initialize, By The Sender And Using The Public Reference Identifier, A Temporary Key Sharing Session With A Cybersecurity Provider
1006
Generate, By The Cybersecurity Provider, A Session Token For The Sharing Session And Return The Session Token To The Sender
1008
Provide, By The Sender, The Session Token To The Receiver
1010
Acknowledge, By The Receiver Using The Session Token, The Sharing Session With The Cybersecurity Provider
1012
Invoke, By The Sender, A Re-Encryption Operation Of One Or More Encrypted Database Keys To Generate One Or More Shared Session Encrypted Database Keys Encrypted By The Cybersecurity Provider Using The Shared Session Master Key And The Sender's Master Key
1014
Provide, By The Sender, The One Or More Shared Session Encrypted Database Keys To The Receiver
1016
Invoke, By The Receiver, A Re-Encryption Operation Of The One Or More Shared Session Encrypted Database Keys To Generate One Or More Encrypted Database Keys Encrypted By The Cybersecurity Provider Using The Shared Session Master Key And The Receiver's Master Key
1018
N
Session Termination ?
1020
Y
Terminate Temporary Key Sharing Session
1022

FIG. 10

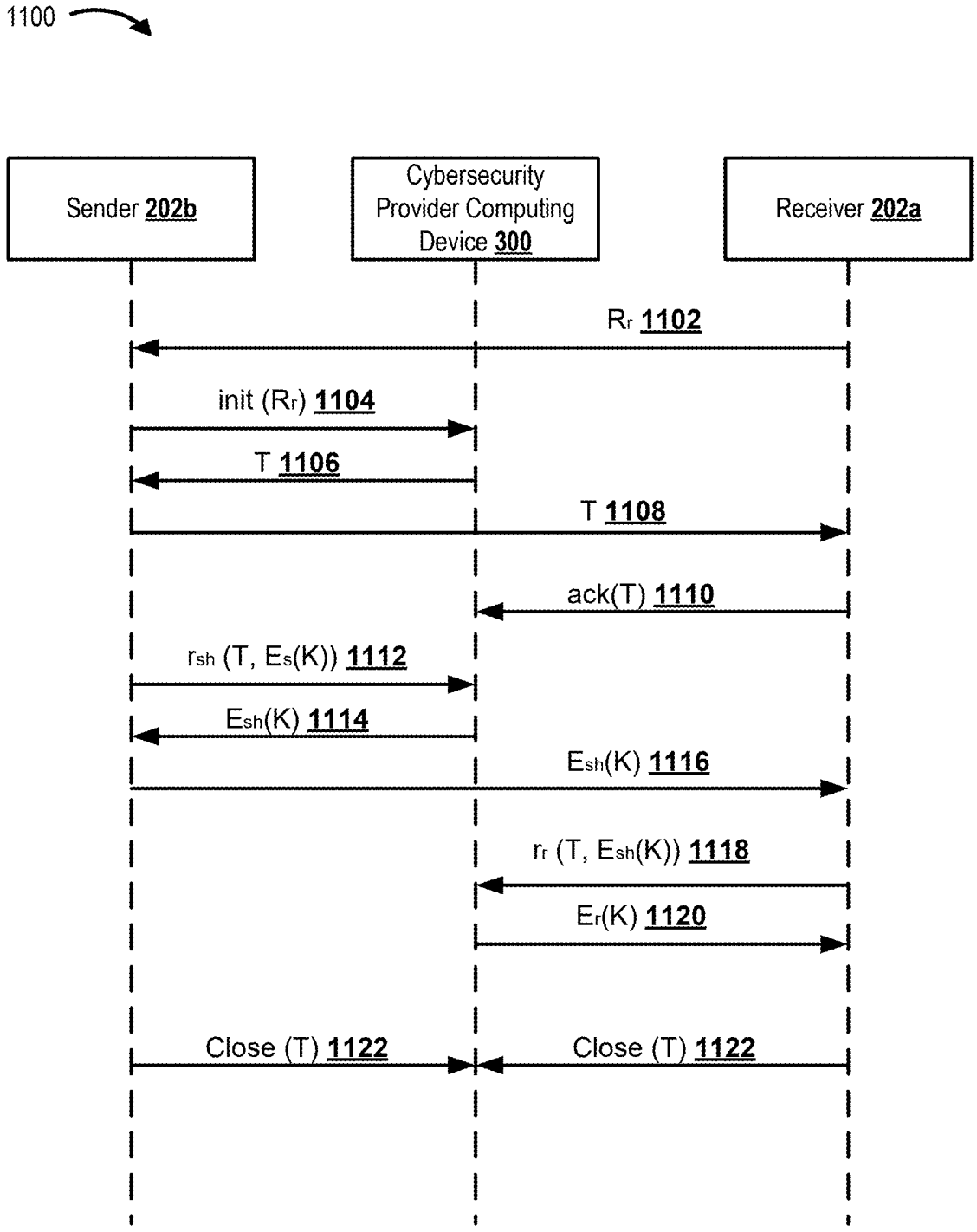

1100
Sender 202b
Cybersecurity Provider Computing Device 300
Receiver 202a
Rr 1102
init (Rr) 1104
T 1106
T 1108
ack(T) 1110
rsh (T, Es(K)) 1112
Esh(K) 1114
Esh(K) 1116
rr (T, Esh(K)) 1118
Er(K) 1120
Close (T) 1122
Close (T) 1122

FIG. 11

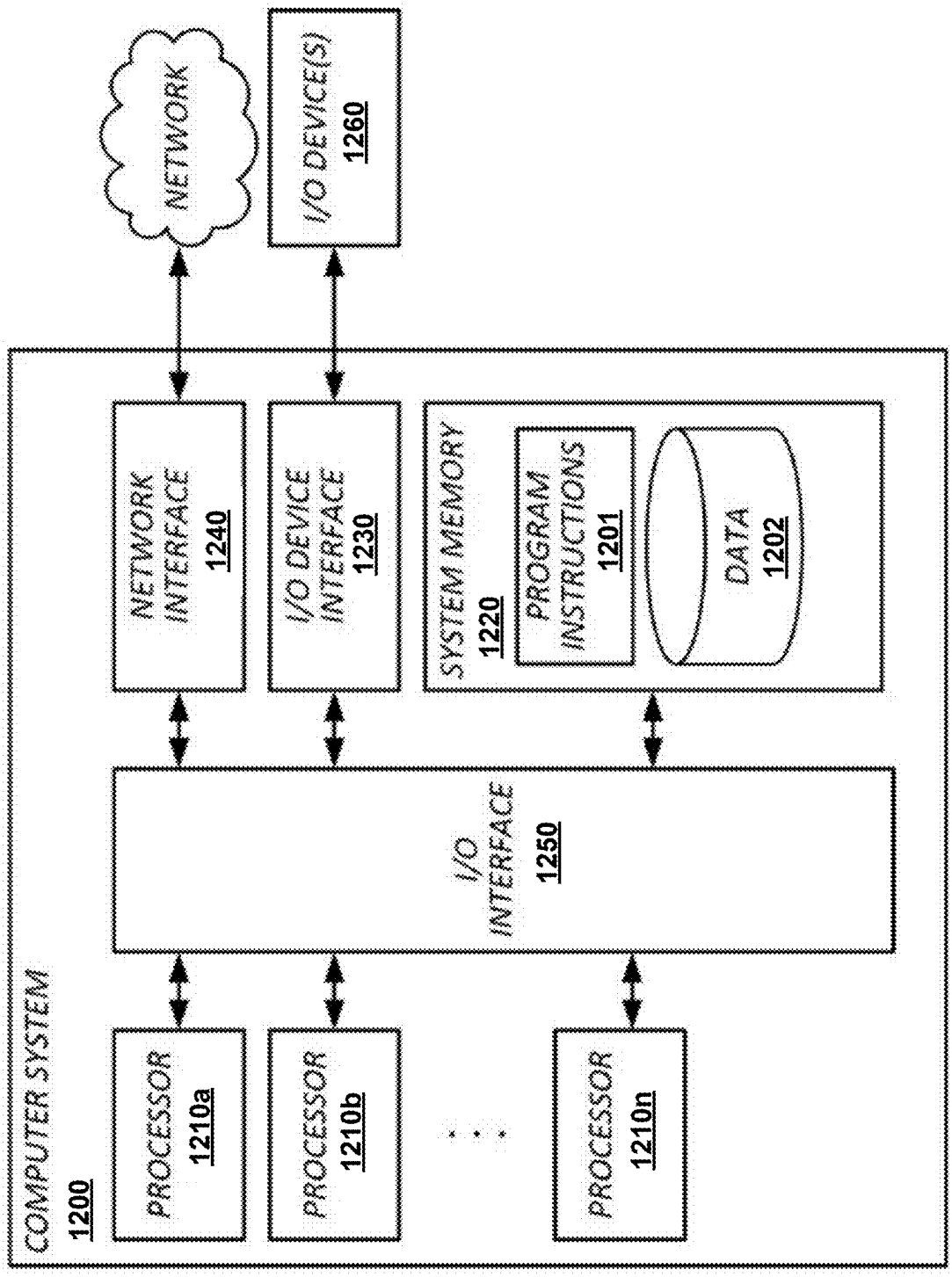

COMPUTER SYSTEM
1200
PROCESSOR
1210a
PROCESSOR
1210b
PROCESSOR
1210n
I/O INTERFACE
1250
NETWORK INTERFACE
1240
I/O DEVICE INTERFACE
1230
SYSTEM MEMORY
1220
PROGRAM INSTRUCTIONS
1201
DATA
1202
NETWORK
I/O DEVICE(S)
1260

FIG. 12

ENCRYPTION KEY MANAGEMENT AND TRANSPARENT DECRYPTION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This patent application is a continuation-in-part of U.S. Non-Provisional patent application Ser. No. 18/755,059, titled "ENCRYPTION KEY MANAGEMENT AND TRANSPARENT DECRYPTION," filed 26 Jun. 2024. U.S. Non-Provisional patent application Ser. No. 18/755,059 claims benefit to provisional application 63/510,205 filed Jun. 26, 2023, titled ENCRYPTION KEY MANAGEMENT AND TRANSPARENT DECRYPTION. The entire contents of the aforementioned patent filings are hereby incorporated by reference for all purposes.

BACKGROUND

1. Field

[0002] The present disclosure relates generally to databases and, more specifically, to encryption key management for encrypting data in a database or a data warehouse and providing transparent decryption when querying the data.

2. Description of the Related Art

[0003] Databases take a variety of forms. Generally, the term "database" refers to an organized collection of data or the system by which access to such data is afforded, depending on the context. Examples include relational databases, such as those first described in the seminal paper "A Relational Model of Data for Large Shared Data Banks" (Codd, Edgar F. (1970), Communications of the ACM. 13 (6): 377-387). More recent examples include object-oriented databases and document-oriented databases. Databases generally include a database management system by which users and other applications access the database, and in some cases, the term "database" is used to refer to this outward facing component, e.g., when referring to operational features of the database.

[0004] In many cases, the security and integrity of the data in the database cannot be trusted. Often, an attacker who has penetrated a computer network will modify or exfiltrate records in a database that are intended to be confidential. Further, in many cases, the attacker may be a credentialed entity within a network, such as a rogue employee, making many traditional approaches to database security inadequate in some cases. Aggravating the risk, in many cases, such an attacker may attempt to mask their activity in a network by deleting access logs stored in datastores.

SUMMARY

[0005] The following is a non-exhaustive listing of some aspects of the present techniques. These and other aspects are described in the following disclosure.

[0006] Some aspects include a process including: creating, with one or more processors, a master encryption key for a user of a secure distributed storage having a plurality of databases; storing, with one or more processors, the master encryption key at a cybersecurity service provider key management system; generating, with one or more processors, a first database key, wherein the first database key is generated for encrypting and decrypting data in a first set of databases of the secure distributed storage or for encrypting and decrypting a first set of types of data that is stored across a set of databases of the plurality of databases; encrypting, with one or more processors, the first database key with the master encryption key thus providing a first encrypted database key; storing, with one or more processors, the first encrypted database key at a secure distributed storage instance for the user at the secure distributed storage; and encrypting, with one or more processors, the master encryption key with a wrapper key that is stored at the cybersecurity service provider key management system or another key management service.

[0007] Some aspects include a process including: receiving, with one or more processors, a query for a set of data from a user of a secure distributed storage having a plurality of databases, wherein data from the set of data is stored across a set of databases of the plurality of databases and is encrypted by a first encrypted database key stored at a secure distributed storage instance for the user at the secure distributed storage; providing, with one or more processors, a request to a cybersecurity service provider key management system for an encrypted master encryption key that is stored at the cybersecurity service provider key management system and that is associated with the user, wherein the request causes the cybersecurity service provider key management system to obtain a wrapper key that is stored at the cybersecurity service provider key management system or another key management service and decrypt the encrypted master encryption key with the wrapper key to obtain a master encryption key; decrypting, with one or more processors and using the master encryption key, the first encrypted database key to obtain a first database key; decrypting, with one or more processors and using the first database key, the set of data that is associated with the first database key and that is included in the query; and providing, with one or more processors and in response to the query, the set of data to the user.

[0008] Some aspects include a process including: receiving, with one or more processors, a query for a set of data from a user of a secure distributed storage having a plurality of databases, wherein data from the set of data is stored across a set of databases of the plurality of databases and is encrypted by a first database key stored at a secure distributed storage instance for the user at the secure distributed storage; determining, with one or more processors and based on a masking policy, that the user has permission to view plaintext of a first portion of the set of data while not having permission to view plaintext of a second portion of the set of data; decrypting, with one or more processors and using the first database key, the first portion of the set of data; and providing, with one or more processors and in response to the query, the set of data to the user, wherein the first portion of the set of data is provided in plaintext while the second portion of the set of data is provided encrypted in cyphertext.

[0009] Some aspects include a tangible, non-transitory, machine-readable medium storing instructions that when executed by a data processing apparatus cause the data processing apparatus to perform operations including any of the above-mentioned processes.

[0010] Some aspects include a system, including: one or more processors; and memory storing instructions that when executed by the processors cause the processors to effectuate operations of any of the above-mentioned processes.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The above-mentioned aspects and other aspects of the present techniques will be better understood when the present application is read in view of the following figures in which like numbers indicate similar or identical elements:

[0012] FIG. **1** is a logical and physical architecture block diagram that shows an example of an encryption key management system in which the present techniques may be implemented in accordance with some embodiments;

[0013] FIG. **2** is a block diagram illustrating an example of a client computing device of the encryption key management system of FIG. **1**, in accordance with some embodiments of the present disclosure;

[0014] FIG. **3** is a block diagram illustrating an example of a cybersecurity provider computing device of the encryption key management system of FIG. **1**, in accordance with some embodiments of the present disclosure;

[0015] FIG. **4** is a block diagram illustrating a secure distributed storage computing device **400** of the secure distributed storage in the encryption key management system of FIG. **1**, in accordance with some embodiments of the present disclosure;

[0016] FIG. **5** is a flowchart that shows an example of a process that generates hierarchical keys used in the encryption key management system of FIG. **1**, in accordance with some embodiments of the present disclosure;

[0017] FIG. **6** is a flowchart that shows an example of a process that uses keys in the encryption key management system to encrypt data in a secure distributed database of FIG. **1**, in accordance with some embodiments of the present disclosure;

[0018] FIG. **7** is a flowchart that shows an example of a process that uses keys in the key management system to decrypt data in a secure distributed database of FIG. **1**, in accordance with some embodiments of the present disclosure;

[0019] FIG. **8** is a block diagram of an example of a key encryption hierarchy for encrypting data in the secure distributed storage of FIG. **1** and during the processes of FIGS. **5-7**, in accordance with some embodiments of the present disclosure;

[0020] FIG. **9** is a block diagram of an example of data encryption and decryption of data with transparent policy-based decryption in the secure distributed storage of FIG. **1** and during the processes of FIGS. **6-7**, in accordance with some embodiments of the present disclosure;

[0021] FIG. **10** is a flowchart that shows an example of a process to share encrypted data between different entities in the encryption key management system of FIG. **1** by creating a key sharing session, in accordance with some embodiments of the present disclosure;

[0022] FIG. **11** is a sequence diagram that shows an example of the process of FIG. **10** to establish a key sharing session, share database keys, and tear down the key sharing session, in accordance with some embodiments of the present disclosure; and

[0023] FIG. **12** is a physical architecture block diagram that shows an example of a computing device by which the above techniques may be implemented.

[0024] While the present techniques are susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and will herein be described in detail. The drawings may not be to scale. It should be understood, however, that the drawings and detailed description thereto are not intended to limit the present techniques to the particular form disclosed, but to the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the present techniques as defined by the appended claims.

DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS

[0025] To mitigate the problems described herein, the inventors had to both invent solutions and, in some cases just as importantly, recognize problems overlooked (or not yet foreseen) by others in the field of cybersecurity, encryption/decryption key management, and encryption key sharing. Indeed, the inventors wish to emphasize the difficulty of recognizing those problems that are nascent and will become much more apparent in the future should trends in industry continue as the inventors expect. Further, because multiple problems are addressed, it should be understood that some embodiments are problem-specific, and not all embodiments address every problem with traditional systems described herein or provide every benefit described herein. That said, improvements that solve various permutations of these problems are described below.

[0026] Users of a secure distributed storage that includes a plurality of databases or a data warehouse service encrypt sensitive data in the secure distributed storage to add a layer of protection against bad actors. These users want to encrypt and decrypt their data but do not want the overhead of managing encryption keys. When dealing with encryption key management, the user often opts to use third-party solutions to manage their keys. This introduces the need to build a solution to access and manage those keys to be able to use them in the encryption and decryption process. Building a solution to access and manage those keys by the user is cumbersome and results in different solutions for each user.

[0027] The systems and methods of the present disclosure provide for encryption key management that includes an interface (e.g., a structured query language (SQL)) for managing encryption keys over individually encrypted data on a partitioned level. The encryption key management system may provide key management to each user that stores data in a relational database or other secure distributed storage. A database key may be a key that is stored on a secure distributed storage's user instance for a user or otherwise associated with the data that it encrypts. The database key may be generated for encrypting and decrypting user data stored in the secure distributed storage, which may be across a set of databases of a plurality of databases included in the secure distributed storage. A plurality of database keys may exist on the user's database instance. For example, a database key may be generated for each individual database in which the user has data stored. In other examples, the database key may be field-based in that the database key may be used as a key across databases for specific data. For example, a database key may be used for encrypting and decrypting social security numbers that are stored on a first set of databases of the plurality of databases while another database key may be used for encryption and decryption of credit card numbers stored on a second set of databases that may include some of the same databases as the first set. The database key may be used to encrypt plaintext data to cyphertext data and decrypt the cyphertext

data to plaintext data. As such, the database key may be symmetrical and, in some embodiments, may not be asymmetrical. The encrypted database key(s) may be stored at a user's instance on the secure distributed storage (e.g., with the data or in a user key store).

[0028] The database key or database keys may be encrypted by a master key that is associated with the user. The master key may encrypt the plaintext of the database key to cyphertext. The master key may be generated by a key management service such Amazon Web Service Key Management Service (AWS KMS) and may be stored by a cybersecurity provider's instance with the key management service or at the cybersecurity provider's computing device. The master key may be encrypted by a wrapper key that may be stored on the cybersecurity service's instance with the key management service or may be provided by the user (e.g., bring your own key BYOK). The wrapper key may be generated by the key management service.

[0029] In various embodiment, the user's secure distributed storage instance or the data stored may include a database tweak that may include a generated tweak that is encrypted by the master_key. When the database_tweak is decrypted, it may be used as input to the encryption/decryption algorithm along with the database key. Database tweaks may be present in format preserving encryption (FPE) algorithms. In addition, the systems and method of the present disclosure may also define cybersecurity_provider_key_id as the identification string used to associate a master key and wrapper key to a user.

[0030] The encryption key management interface may support a set of functions that collectively facilitate the creation, decryption, and rotation of encryption keys and associated tweak values. In one embodiment, the interface includes a function for creating a database key, such as fpe_create_key( ), which generates a new encrypted database key and returns it to the caller. If no master key exists for the user or client at the time of invocation, a master key is automatically generated prior to the creation of the database key. A second function, fpe_create_tweak( ), may be used to generate a corresponding database tweak, which is used in format-preserving encryption algorithms such as FF3-1. Similar to the key creation function, if a master key does not yet exist, the system may generate one before producing the tweak.

[0031] The encryption key management interface may also include a decryption function, fpe_decrypt_key_tweak( ), which decrypts either a database key or tweak. This operation involves decrypting the user's master key using a wrapper key, and then applying the decrypted master key to obtain the plaintext version of the specified key or tweak. Additionally, the encryption key management interface may support key rotation through a function such as fpe_rotate_keys( ), which facilitates the replacement of the existing master key. During this process, a new master key is generated, and all existing database keys and tweaks are decrypted using the old master key (itself decrypted by the wrapper key). These values are then re-encrypted using the new master key, the new master key is encrypted with the wrapper key, and the old master key is securely deleted. This architecture supports dynamic, secure, and auditable key management operations within a distributed encryption system.

[0032] A cybersecurity_provider_key_id may be employed to associate a specific user or client with a corresponding master key. In some embodiments, the cybersecurity_provider_key_id is generated using a hashing function applied to a client identifier or reference string, thereby producing a unique identifier for use in key management operations. The encrypted database key may be generated by the cybersecurity provider using the client's master key, and then returned to the user. Once received, the encrypted database key may be stored within the user's designated database instance, such as a tenant-controlled data warehouse or structured storage system.

[0033] The database key, and in certain configurations, an associated database tweak, may be used as input parameters to a format-preserving encryption algorithm for the encryption and decryption of user data. In order to perform encryption or decryption operations, the user may invoke a decryption function, such as fpe_decrypt_key_tweak( ), which decrypts the encrypted database key or tweak using the user's master key. This approach enables secure, role-based access to encryption keys, while maintaining strong separation between the user environment and the underlying key management infrastructure.

[0034] The partition level may be described herein as a database but could be a schema, a table, a column, or other data storage structure. In various embodiments, the keys may be symmetric keys or may not be asymmetric keys. The secured distributed storage may store external functions, which may include user-defined functions that are stored and executed outside of the secure distributed storage. External functions may make it easier to access external application programming interface (API) services such as geocoders, machine learning models, and other custom code running outside of the database service. This feature eliminates the need to export and reimport data when using third-party services, significantly simplifying a data pipeline. In the key management system of the present disclosure, an external function may be used to make API calls to access the key management system associated with the cybersecurity provider from the secure distributed database. For example, a query to the secure distributed database to access encrypted data may be made by the user. An external function may be used to pass the query context to the cybersecurity provider to check policy permissions for the user and the cybersecurity provider may return to the database provider the level of access the user has for the data, as discussed below. Furthermore, the external functions may trigger key generation, wrapping, unwrapping, and rotation in the cybersecurity provider's backend. The results (e.g., encrypted databased keys or decrypted values) may be passed back to the secure distributed database for storage or immediate use. These operations would be extremely difficult (and risky) to implement directly in the secure distributed database using native SQL or UDFs. External functions make the entire process of secure, policy-aware encryption and decryption inside the secure distributed database safe and seamless by offloading sensitive logic to the cybersecurity provider's trusted infrastructure while keeping the user interaction simple and SQL-native.

[0035] In various embodiments of the present disclosure, users may encrypt sensitive data stored in secure distributed storage to add a layer of protection against bad actors. The user may make a query for the data when the user needs it. The cybersecurity provider may provide an automated policy engine that may provide a signal indicating a level of access during the query based on the policy created by the

user. However, working with encrypted data is cumbersome. For example, a determination of when a user should have access to the plaintext data may need to be made, a user may require access to the decryption algorithm, a user may require access to the encryption keys, the user may be required to manually decrypt the data, or other issues that would be apparent to one of skill in the art in possession of the present disclosure.

[0036] Thus, the systems and methods of the present disclosure may also provide transparent decryption to address these issues. Transparent decryption may allow users to see encrypted or decrypted data based on the policy set at the cybersecurity provider platform by accessing data as the user would if the data was not encrypted. In various embodiments, an external function or other mechanism is used to pass query context to a cybersecurity provider platform from the secure distributed storage. The cybersecurity provider platform may then return what level of access the user has. If the user has permission to see the data in plain text, the masking policy logic triggers decryption over the data, which may be according to the encryption key management, discussed above. The decrypted data is returned to the user in the query results. If the user does not have permission to see the plain text data, the encrypted data is returned to the user in the query results. The encrypted data may maintain the same format as the decrypted data but in cyphertext. This process is not visible to the user, the user simply queries data like they normally would and receives encrypted or decrypted data back.

[0037] In yet other embodiments, the present disclosure may also provide a system and method for secure cryptographic key sharing between distinct entities, each operating independent format-preserving encryption (FPE) environments with separate master key hierarchies. To enable the secure transfer of encrypted data across these distinct cryptographic domains, the present disclosure introduces a temporary, authenticated key sharing session that facilitates controlled key transformation without exposing plaintext key material.

[0038] In operation, a data producer (sender) initiates a session by requesting the creation of a secure context bound to a public reference identifier of a data consumer (receiver). This session is represented by a session token, which uniquely identifies the ephemeral key sharing instance. Once the receiver acknowledges the session using the token, a temporary session-specific master key is established within a secure key management service provided by the cybersecurity provider platform (e.g., ALTR).

[0039] The sender then supplies a set of encrypted data keys, which are initially encrypted under the sender's own FPE master key, to the secure key management service along with the session token. These keys are decrypted within the trusted environment and re-encrypted under the session master key, yielding intermediate shared keys. These shared keys are then transmitted to the receiver. The receiver, in turn, submits the shared keys and session token to the secure key management service, which decrypts the shared keys and re-encrypts them using the receiver's own FPE master key, producing keys compatible with the receiver's encryption domain.

[0040] This session-based transformation ensures that at no point is any raw key material exposed to either party or transmitted in plaintext. Additionally, the session may be time-bound or may be explicitly closed by either party, after which all re-encryption operations associated with the session are disabled. This design ensures confidentiality, integrity, and access isolation in the context of cross-tenant encrypted data sharing, and is particularly suited for multi-tenant cloud data environments such as Snowflake or other secured distributed storage providers.

[0041] FIG. **1** illustrates an example of an encryption key management system **10** in which the present techniques may be implemented. In some embodiments, the encryption key management system **10** is a distributed computing environment implementing a client/server architecture, though other architectures are contemplated, including monolithic architectures executing on a single computing device. In some embodiments, the encryption key management system **10** includes client computing devices **12**, a key management computing device **14**, a secure distributed storage **16**, a cybersecurity provider computing device **18**, and a network **22**, such as the Internet, by which these components may communicate.

[0042] In some embodiments, the client computing devices **12** are desktop computers, laptop computers, in-store kiosks, tablet computers, mobile phones, head-mounted displays, game consoles, set-top boxes or any other computing device that would be apparent to one of skill in the art in possession of the present disclosure, executing an operating system and a web browser or native application in which the described user interfaces are presented. One client computing device **12** is shown, but embodiments may support substantially more concurrent sessions, e.g., more than 100, or more than 1,000 geographically distributed sessions around the US or the world.

[0043] In some embodiments, the key management computing device **14** is a nonblocking web server or application program interface server configured to service multiple concurrent sessions with different client computing devices **12**, for example, implementing a model-view-controller architecture or other design. In some embodiments, the key management computing device **14** may dynamically generate assets, markup language instructions, and scripting language instructions responsive to requests from client computing devices **12** to send user interfaces to, or update user interfaces on, those client computing devices **12**. The user interface may evolve over time (e.g., in a web application), in some cases, displaying new resources (e.g., images and other data) sent from the key management computing device **14** responsive to user inputs to the user interface. In various embodiments the key management computing device **14** may provide cloud services such as Amazon Web Services (AWS) key management service (KMS) for generating and storing encryption keys. As such, the cybersecurity provider of the cybersecurity provider computing device **18** may have a key management service instance at the key management computing device **14**.

[0044] In some embodiments, the cybersecurity provider computing device **18** is a nonblocking web server or application program interface server configured to service multiple concurrent sessions with different client computing devices **12**, for instance implementing a model-view-controller architecture or other design. In some embodiments, the cybersecurity provider computing device **18** may dynamically generate assets, markup language instructions, and scripting language instructions responsive to requests from client computing devices **12** to send user interfaces to, or update user interfaces on, those client computing devices

12. The user interface may evolve over time (e.g., in a web application), in some cases, displaying new resources (e.g., images and other data) sent from the cybersecurity provider computing device **18** responsive to user inputs to the user interface. As discussed above, the cybersecurity provider computing device **18** may have an instance on a key management computing device **14** and may be integrated with the secure distributed storage **16** to provide user instances of a secure key management service platform.

[0045] In some embodiments, the secure distributed storage **16** may include a plurality of data centers **20** each having a plurality of storage compute nodes **20***a* that store at least portion of the data accessed with the client computing devices **12**, in some cases with pointers therebetween stored in one or more of the storage compute nodes **20***a*. In some embodiments, as described below, data may be stored in a manner that abstracts away the secure distributed storage **16** from a workload application through which the data is accessed (e.g., read or written). In some embodiments, data access operations may store or access data in the secure distributed storage **16** with a workload application that is not specifically configured to access data in the secure distributed storage **16**, e.g., one that is configured to operate without regard to whether the secure distributed storage **16** is present, and for which the storage of data in the secure distributed storage **16** is transparent to the workload application storing content in the secure distributed storage **16**.

[0046] Content stored in the secure distributed storage **16** may be created or accessed with a variety of different types of applications, such as monolithic applications or multi-service distributed applications (e.g., implementing a micro-services architecture in which each service is hosted by one of the client computing devices **12**). Examples include email, word processing systems, spreadsheet applications, version control systems, customer relationship management systems, human resources computer systems, accounting systems, enterprise resource management systems, inventory management systems, logistics systems, secure chat computer systems, industrial process controls and monitoring, trading platforms, banking systems, and the like. Such applications that generate or access content in the secure distributed storage **16** for purposes of serving the application's functionality are referred to herein as "workload applications," to distinguish those applications from infrastructure code by which the present techniques are implemented, which is not to suggest that these bodies of code cannot be integrated in some embodiments into a single workload application having the infrastructure functionality. In some cases, several workload applications (e.g., more than 2, more than 10, or more than 50), such as selected among those in the preceding list, may share resources provided by the infrastructure code and functionality described herein.

[0047] In some embodiments, the secure distributed storage **16** may include a collection of data centers **20**, which may be distributed geographically and be of heterogeneous architectures. In some embodiments, the data centers **20** may be various public or private clouds or on-premises data centers for one or more organization-users, such as tenants, of the computing environment **10**. In some embodiments, the data centers **20** may be geographically distributed over the United States, North America, or the world, in some cases with different data centers more than 100 or 1,000 kilometers apart, and in some cases with different data centers **20** in different jurisdictions. In some embodiments, each of the data centers **20** may include a distinct private subnet through which computing devices, such as rack-mounted computing devices in the subnet communicate, for example, via wrap top-of-rack switches within a data center, behind a firewall relative to the network **22**. In some embodiments, each of the data centers **20**, or different subsets of the data centers **20**, may be operated by a different entity, implementing a different security architecture and having a different application program interface to access computing resources, examples including Amazon Web Services™, Azure from Microsoft™, Rack Space™, and Snowflake™. Two different data centers **20** are shown, but embodiments are consistent with, and in commercial implementations likely to include, more data centers, such as more than five, more than 15, or more than 50. In some cases, the data centers may be from the same provider but in different regions.

[0048] In some embodiments, each of the data centers **20** includes a plurality of different hosts exposed by different computational entities, like microkernels, containers, virtual machines, or computing devices executing a non-virtualized operating system. Each host may have an Internet Protocol address on the subnet of the respective data center **20** and may listen to and transmit via a port assigned to an instance of an application described below by which data is stored in a distributed ledger. In some embodiments, each storage compute node **20***a* may correspond to a different network hosts, each network coast having a server that monitors a port, and configured to implement an instance of one of the below-described directed acyclic graphs with hash pointers implementing immutable, tamper-evident distributed ledgers, examples include block chains and related data structures. In some cases, these storage compute nodes **20***a* may be replicated, in some cases across data centers **20**, for example, with three or more instances serving as replicated instances, and some embodiments may implement techniques described below to determine consensus among these replicated instances as to state of stored data. Further, some embodiments may elastically scale the number of such instances based on amount of data stored, amounts of access requests, or the like.

[0049] FIG. **2** illustrates an embodiment of a client computing device **200** that may be the client computing device **12** discussed above with reference to FIG. **1**. In the illustrated embodiment, the client computing device **200** includes a chassis **202** that houses the components of the client computing device **200**. Several of these components are illustrated in FIG. **2**. For example, the chassis **202** may house a processing system and a non-transitory memory system that includes instructions that, when executed by the processing system, cause the processing system to provide a data access controller **204** that is configured to perform the functions of the data access controller or the user computing devices, discussed below. In the specific example illustrated in FIG. **2**, the data access controller **204** is configured to provide one or more of a web browser application **204***a* or a native application **204***b*.

[0050] The chassis **202** may further house a communication system **210** that is coupled to the data access controller **204** (e.g., via a coupling between the communication system **210** and the processing system). The communication system **210** may include software or instructions that are stored on a computer-readable medium and that allow the client com-

puting device **200** to send and receive messages through the communication networks discussed above. For example, the communication system **210** may include a communication interface to provide for communications through the network **22** as detailed above (e.g., first (e.g., long-range) transceiver). In an embodiment, the communication interface may include a wireless antenna that is configured to provide communications with IEEE 802.11 protocols (Wi-Fi), cellular communications, satellite communications, other microwave radio communications or communications. The communication system **210** may also include a communication interface (e.g., the second (e.g., short-range) transceiver) that is configured to provide direct communication with other user computing devices, sensors, storage devices, beacons, and other devices included in the encryption key management system **10** discussed above with respect to FIG. **1**. For example, the communication interface may include a wireless antenna that configured to operate according to wireless protocols such as Bluetooth®, Bluetooth® Low Energy (BLE), near field communication (NFC), infrared data association (IrDA), ANT®, Zigbee®, Z-Wave® IEEE 802.11 protocols (Wi-Fi), or other wireless communication protocols that allow for direct communication between devices.

[0051] The chassis **202** may house a storage device (not illustrated) that provides a storage system **216** that is coupled to the data access controller **204** through the processing system. The storage system **216** may be configured to provide a key store **216***a* (e.g., wrapper keys, BYOK, session token), data, applications, messages, or instructions described in further detail below and used to perform the functions described herein. In various embodiments, the chassis **202** also houses a user input/output (I/O) system **218** that is coupled to the data access controller **204** (e.g., via a coupling between the processing system and the user I/O system **218**). In an embodiment, the user I/O system **218** may be provided by a keyboard input subsystem, a mouse input subsystem, a track pad input subsystem, a touch input display subsystem, a microphone, an audio system, a haptic feedback system, or any other input subsystem. The chassis **202** also houses a display system **220** that is coupled to the data access controller **204** (e.g., via a coupling between the processing system and the display system **220**) and may be included in the user I/O system **218**. In some embodiments, the display system **220** may be provided by a display device that is integrated into the client computing device **200** and that includes a display screen (e.g., a display screen on a laptop/notebook computing device, a tablet computing device, a mobile phone, or wearable device), or by a display device that is coupled directly to the client computing device **200** (e.g., a display device coupled to a desktop computing device by a cabled or wireless connection).

[0052] FIG. **3** depicts an embodiment of a cybersecurity provider computing device **300**, which may be the cybersecurity provider computing device **18** discussed above with reference to FIG. **1**. In the illustrated embodiment, the cybersecurity provider computing device **300** includes a chassis **302** that houses the components of the cybersecurity provider computing device **300**, only some of which are illustrated in FIG. **3**. For example, the chassis **302** may house a processing system (not illustrated) and a non-transitory memory system (not illustrated) that includes instructions that, when executed by the processing system, cause the processing system to provide a cybersecurity engine **304** that is configured to perform the functions of the cybersecurity engines or cybersecurity provider computing devices discussed below. Specifically, the cybersecurity engine **304** may perform the cybersecurity actions (e.g., key encryption/decryption, creation, and storage; policy management, shared key session management; or other cybersecurity functions discussed herein)., Specifically, the cybersecurity engine **304** may include the policy engine **304***a* that processes data requests and returns a policy for how a user is presented data that is requested. The cybersecurity engine **304** may include a session sharing engine **304***b* that may perform secure key sharing and sharing session creation discussed herein.

[0053] The chassis **302** may further house a communication system **306** that is coupled to the cybersecurity engine **304** (e.g., via a coupling between the communication system **306** and the processing system) and that is configured to provide for communication through the network **22** of FIG. **1** as detailed below. The communication system **306** may allow the cybersecurity provider computing device **300** to send and receive messages over the network **108** of FIG. **1**. The chassis **302** may also house a storage device (not illustrated) that provides a storage system **308** that is coupled to the cybersecurity engine **304** through the processing system. The storage system **308** may be configured to store user instances **309** and configured to provide a key store **310** (e.g., wrapper keys, master keys) and policy sets **312** for each user instance **309**. The storage system **308** may include other data or instructions to complete the functionality discussed herein. In various embodiments, the storage system **308** may be provided on the cybersecurity provider computing device **300** or on a database accessible via the communication system **306**. The user instances **309** may be associated with a user instance **408***b* of the user at the secure distributed storage **16**.

[0054] FIG. **4** illustrates an embodiment of a secure distributed storage computing device **400** that may be provided by the secure distributed storage **16** discussed above with reference to FIG. **1**. In the illustrated embodiment, the secure distributed storage computing device **400** includes a chassis **402** that houses the components of the user computing device **400**. Several of these components are illustrated in FIG. **4**. For example, the chassis **402** may house a processing system and a non-transitory memory system that includes instructions that, when executed by the processing system, cause the processing system to provide a secure distributed storage controller **404** that is configured to perform the functions of the secure distributed storage controller or the secure distributed storage computing device, discussed below. For example, the secure distributed storage controller **404** may be a data platform provided by Snowflake®, headquartered in Bozeman, Montana, United States of America, that provides data storage, processing, and analytic solutions on a cloud infrastructure. The data platform may include multiple layers such as database storage, query processing and cloud services.

[0055] The chassis **402** may further house a communication system **406** that is coupled to the secure distributed storage controller **404** (e.g., via a coupling between the communication system **406** and the processing system). The communication system **406** may include software or instructions that are stored on a computer-readable medium and that allow the secure distributed storage computing device **400** to send and receive messages through the communica-

tion networks discussed above. For example, the communication system **406** may include a communication interface to provide for communications through the network **22** as detailed above. The chassis **402** may house a storage device (not illustrated) that provides a storage system **408** that is coupled to the secure distributed storage controller **404** through the processing system. The storage system **408** may be configured to store external functions **408***a*, data, applications, user instances **408***b*, encryption keys **408***c* (e.g., database keys in a keys store), or instructions described in further detail below and used to perform the functions described herein. While a specific example of a secure distributed storage computing device is illustrated, one of skill in the art in possession of the present disclosure will recognize that different configurations may be contemplated.

[0056] FIG. **5** illustrates a flowchart of a method **500**, according to various embodiments. The method **500** may begin at block **502** where a master encryption key for a user of a secure distributed storage having a plurality of databases is created. In an embodiment, at block **502**, the cybersecurity engine **304** of the cybersecurity provider computing device **300** may generate a master encryption key. The cybersecurity engine **304** may communicate with the key management computing device **14** to generate the master encryption key, which may be stored on an instance that the cybersecurity provider for the cybersecurity computing device **300** has on the key management computing device **14** of FIG. **1**. For example, a command may be received to generate a master encryption key for the user.

[0057] In another example of master encryption key generation, a user may interact with an SQL interface provided by the secure distributed storage computing device **400**. The user may request that a database key for data be created by calling an external function such as fpe_create_key( ) function. The external function may call an API of the cybersecurity engine **304** and if no master encryption key exists, the cybersecurity engine **304** may cause the key management computing device **14** to generate a master encryption key before generating the requested database key. Similarly, if an fpe_create_tweak( ) function is called for FF3-1 encryption, a master key may be generated before the database tweak. In FF3-1 and FF3 FPE encryption algorithms, tweaks may be used for further security of the data. A tweak may be an additional alphanumeric string input used alongside the plaintext and database key to enhance security for small domains. The tweak may make it more difficult for attackers to use statistical methods to break the encryption. Different tweak values may produce different outputs for the same database key and data. The original tweak value used for encryption is required to decrypt the data. In some embodiments, the tweak may be protected with the master encryption key. Once the master encryption key is generated, a key identifier may be used to associate the master encryption key to the user. In various embodiments, the key identifier may include an identification string that is generated using a hashing function and a user identifier.

[0058] The method **500** may proceed to block **504** where a master encryption key is encrypted with a wrapper key that is stored at the cybersecurity provider key management system or another key management service. In an embodiment, at block **504**, the cybersecurity engine **304** may wrap or encrypt the master encryption key with a wrapper key. Prior to being stored or after generating and encrypting the database keys with the master encryption key (as discussed below), the master encryption key may be encrypted or wrapped with a wrapper key that is either provided by the user and stored at the client computing device **12**/**200** (e.g., bring your own key (BYOK) such as key **216***a*) or that is stored on the cybersecurity provider's instance on the key management computing device **14** of FIG. **1**. In some embodiments, the wrapper key may generated for the user by the key management service of the key management computing device **14** such as AWS KMS. The wrapper key may be associated with the user via the key identifier that is used to associate the master encryption key to the user.

[0059] The method **500** may proceed to block **506** where the master encryption key is stored at a cybersecurity service provider key management system. In an embodiment, at block **506**, the master encryption key generated may be stored at the user instance **309** of the cybersecurity provider computing device **300** or the user instance **408***b* on the secure distributed storage **16**. In some embodiments, the master encryption key may be stored in cybersecurity service provider's instance at the key management service provided by the key management computing device **14** of FIG. **1**.

[0060] The method **500** may proceed to block **508** where a database key is generated for encrypting and decrypting data in a set of databases of the secure distributed storage or for encrypting and decrypting a set of types of data that is stored across a set of databases of the plurality of databases. In an embodiment, at block **508**, a database key may be generated for encrypting and decrypting data stored in the secured distributed storage **16**. As discussed above, the user may request that a database key for data be created by calling an fpe_create_key( ) function. The cybersecurity engine **304** may receive the function call from the secure distributed storage computing device **400** and communicate with the key management service of the key management computing device **14** to generate the database key. Similarly, a tweak may be generated as well for FF3-1 encryption. As discussed above, the user may request that a database key for data be created by calling an fpe_create_tweak( ) function. The cybersecurity engine **304** may receive the function call and communicate with the key management service of the key management computing device **14** to generate the tweak. The database key and, in some embodiments, the tweak are used as input to the encryption algorithm (e.g., an FPE encryption algorithm) to encrypt and decrypt the data. In some embodiments, the database key may be associated with a type of data. For example, the database key may be associated with a set of telephone numbers, a set of social security numbers, a set of names, a set of addresses, a set of email addresses, a set of credit card numbers, a set of account numbers, or other data types that would be apparent to one of skill in the art in possession of the present disclosure. In other embodiment, the database key may be associated with a set of data that may have more than one type of data.

[0061] The method **500** may proceed to block **510** where the first database key is encrypted with the master encryption key, thus providing an encrypted database key. In an embodiment, at block **510**, the cybersecurity engine **304** may encrypt the database key with the master encryption key that is associated with the user that requested the creation of the database key. The key identifier may be obtained from a user identifier and used to identify the master key. The master key is retrieved and decrypted (e.g.,

unwrapped) with the wrapper key, and then the master key is used only in memory to encrypt the database key.

[0062] The method **500** may then proceed to block **512** where the encrypted database key is stored at a secure distributed storage instance for the user at the secure distributed storage. In an embodiment, at block **512**, the cybersecurity engine **304** may provide the encrypted database key to the secure distributed storage controller **404** via the network **22**. The secure distributed storage controller **404** may store the database key at the user instance **408***b* for the user associated with the database key. Similarly, in embodiments, where a tweak is used, the cybersecurity engine **304** may provide the encrypted tweak to the secure distributed storage controller **404** via the network **22**. The secure distributed storage controller **404** may store the tweak at the user instance **408***b* for the user associated with the tweak. In some embodiments, the encrypted database keys or tweaks may be associated with the data by links or pointers. In other embodiments, the encrypted databased keys or tweaks may be stored alongside or indexed to the data.

[0063] FIG. **6** illustrates a flowchart of a method **600** for encrypting data that is stored on secure distributed storage, according to various embodiments of the present disclosure. The method **600** may begin at block **602** where a command is received for securely storing data on a secure distributed storage. In an embodiment, at block **602**, the secure distributed storage controller **404** may receive a request to store data on the secure distributed storage **16**. The request may include a user identifier and the data that is to be stored. In some embodiments, the data may include various types of data (e.g., a set of telephone numbers, a set of social security numbers, a set of names, a set of addresses, a set of email addresses, a set of credit card numbers, a set of account numbers, or other data types that would be apparent to one of skill in the art in possession of the present disclosure). The request may identify whether the data is to be stored as a set with a particular database key or with various database keys associated with respective type of data (e.g., a database key for social security numbers and a different database key for credit card numbers). In other embodiments, policies **312** as to how the data is to be partitioned and encrypted may be stored at the secure distributed storage computing device **400** in the user instance **408** or at the user instance **309** at the cybersecurity provider computing device **300**. Partitioning by key is often based on policy or key labels, not hardcoded in user requests. The association between data types and keys may be determined by policy enforcement logic, not only by user selection.

[0064] The method **600** may proceed to block **604** where the request to encrypt data is passed to the cybersecurity service provider. In an embodiment, at block **604**, the secure distributed storage controller **404** may use an external function **408***a* to pass the request to the cybersecurity engine **304**. As discussed herein, the external function may be a user-defined function that is stored and executed outside of the secure distributed storage controller **404**. The external function may make it easier to access external API services running outside of the secure distributed storage controller **404** and may eliminate the need to export and reimport data using third-party services, thus simplifying data pipelines. As such, the external function may make an API call to the cybersecurity engine **304** and provide the request, any encrypted database keys associated with the request, a user identifier, a BYOK or other information that may be used to decrypt the encrypted database key. The encrypted database keys themselves may not be necessarily passed in every request. They may already reside in the storage system **308** and be referenced via key labels or metadata.

[0065] The method **600** may proceed to block **606** where the master encryption key is obtained based on the request. In an embodiment, at block **606**, the cybersecurity engine **304** may obtain a master encryption key associated with a key identifier included in the request. The master encryption key may be stored and wrapped in the user instance **309** for the user. The wrapper key associated with the key identifier may be obtained and used to decrypt or unwrap the master encryption key. In other embodiments, database keys may have not been created for the data and the cybersecurity engine **304** may generate the database key or, if not created, generate the master key according to the method **500** of FIG. **5**. Database key creation and master key generation can be triggered automatically as part of the FPE function call sequence (fpe_create_key, etc.), so the user may not explicitly request key creation.

[0066] The method **600** may proceed to block **608** where the encrypted database key is decrypted with the master encryption key. In an embodiment, at block **608**, the cybersecurity engine **304** may decrypt the encrypted database key or keys with the master encryption key. The cybersecurity engine **304** may provide the master key and the encrypted database key as inputs into the encryption algorithm that was used to encrypt the database key(s). The encryption algorithm may output the decrypted database key. Similarly, an encrypted tweak may be decrypted with the master key.

[0067] The method **600** may proceed to block **610** where the database key is returned to the secure distributed storage. In an embodiment, at block **610**, the database key may be returned to the secure distributed storage computing device **400**. For example, in response to the API call via the external function, the cybersecurity engine **304** may return the one or more database keys used to encrypt the data to the secure distributed storage computing device **400**. Likewise, if a database tweak was decrypted by cybersecurity engine **304**, the database tweak may be returned to the secure distributed storage session of data storing.

[0068] The method **600** may proceed to block **612** where the data is encrypted with the database key. In an embodiment, at block **612**, the secure distributed storage engine **404** may use an encryption algorithm with the database key to encrypt at least a portion of the data. Other database keys may encrypt other portions of the data. For example, one or more database keys may be used for a type of data while one or more other database keys may be used to encrypt another type of data. Associations between the database keys and the data may be stored at the secure distributed storage computing device **400**. In some embodiments, a database key and a decrypted tweak may be used to encrypt the data using an FPE encryption algorithm (e.g., FF3-1). In some embodiments, the encryption of the data may be performed on a client application layer or by the secure distributed storage controller **404** via stored procedures or UDFs that have access to an encryption algorithm's libraries (e.g., FPE libraries). The plaintext keys or tweaks may never persist at the secure distributed storage system **400** as they may only be used transiently within memory during encryption of the data. Thus, when encryption is performed by the secure distributed storage engine, the plaintext database key/tweak is held only in volatile memory and never persisted. In some

embodiments, the data may be encrypted by the database key by the cybersecurity engine **304** and the encrypted data may be passed to the secure distributed storage engine **404** for storage.

[0069] The method **600** may proceed to block **614** where the encrypted data is stored at the secure distributed storage. In an embodiment, at block **614**, the encrypted data may be stored by the secure distributed storage engine **404** at the secure distributed storage **16**. The encrypted data may be stored across various datacenters **20** and storage compute nodes **20***a*. Using an FPE algorithm, the result of the encryption in block **612** is cyphertext that retains the original format (e.g., fixed-length strings, digit-only fields), which may be written to a table provided by the secure distributed storage **16**. Encrypted data written back to the storage layer may retain referential integrity with unencrypted tables.

[0070] FIG. **7** illustrates a flowchart of a method **700** for decrypting data that is stored in secure distributed storage, according to various embodiments of the present disclosure. The method **700** may include block **702** where a query for a set of data is received from a user of a secure distributed storage. In an embodiment at block **702**, the user, via the user computing device **12**/**200**, may send a query to the secured distributed storage computing device **400** to obtain a set of data. For example, the user or an application on the client computing device **12**/**200** may run an SQL statement like "SELECT cybersecurityservice_fpe_decrypt_column (encrypted_value, encrypted_key, encrypted_tweak) FROM secure_table;." Data from the set of data may be stored across a set of databases of the plurality of databases. The set of data may be encrypted and associated with one or more database keys that may be stored at a secure distributed storage instance for the user at the secure distributed storage computing device **400**. As discussed above, the data may be encrypted by type, by user, other parameters, or a combination of parameters. The encrypted value, the encrypted key, and in some instances the encrypted tweak may be stored in columns of the same or related tables.

[0071] In some embodiments, the query may be made to the secure distributed storage computing device **400** for data from a table (e.g., SQL statement: SELECT ssn, name FROM customer_data;). The user or application making the query may or may not know whether the data is encrypted or not. The data or a portion of the data may be associated with a masking policy. The secure distributed storage controller **404** may call an external function **408***a* (e.g., cybersecurityservice_check_policy) to ask the policy engine **304***a* if the user associated with the request is authorized to view the decrypted data. The policy engine **304***a* may determine whether the user is authorized to access the data based on a user identifier, a user's role, a field or a resource the user is accessing, or other information associated with the data or user. If the user is permitted to view the data, the policy engine **304***a* may indicate the permission to the secure distributed storage controller **404**. If the user is not permitted to view the data, the policy engine **304***a* may indicate the lack of permission to the secure distributed storage controller **404**. The masking policy at the secure distributed storage controller **404** may return the encrypted value as-is (e.g., still in format-preserved ciphertext). If the user is authorized, then masking policy may cause the secure distributed storage controller **404** to proceed to block **704**.

[0072] The method **700** may proceed to block **704** where a request to decrypt the data is provided to the cybersecurity provider computing device. In an embodiment, at block **704**, the secure distributed storage controller **404** may use an external function **408***a* to pass the request to the cybersecurity engine **304** to decrypt the data. As discussed herein, the external function **408***a* may be a user-defined function that is stored and executed outside of the secure distributed storage controller **404**. The external function **408***a* may make it easier to access external API services running outside of the secure distributed storage controller **404** and may eliminate the need to export and reimport data using third-party services, thus simplifying data pipelines. As such, the external function **408***a* may make an API call to the cybersecurity engine **304** and provide the request, any encrypted database keys or tweaks associated with the request, a user identifier, a BYOK, the encrypted data, or other information that may be used to decrypt encrypted database key.

[0073] In an embodiment, at block **704**, the request may cause the cybersecurity engine **304** to obtain a wrapper key that is stored at the cybersecurity provider computing device **300** in the key store **310** or another key management service (e.g., key management computing device **14** (e.g., AWS KMS) or other cloud KMS service if BYOK is used) and decrypt the encrypted master encryption key with the wrapper key to obtain a master encryption key.

[0074] The method **700** may proceed to block **706** where the first encrypted database key is decrypted, using the master encryption key, to obtain a first database key. In an embodiment, at block **706**, the cybersecurity engine **304** may decrypt the encrypted database key with the master key. Similarly, if an encrypted tweak is provided in the request, the encrypted tweak may be decrypted by the master key. The database key or the tweak may be in plaintext only within the cybersecurity provider computing device's **300** trusted memory and not stored.

[0075] The method **700** may proceed to block **708** where the set of data that is associated with the first database key and that is included in the query is decrypted, using the first database key. In an embodiment, at block **708**, the cybersecurity engine **304** may include an encryption/decryption algorithm that was used to encrypt the data. The cybersecurity engine **304** may decrypt the encrypted data with the database key and encryption/decryption algorithm. In some embodiments, the tweak may also be used with the database key and the encryption/decryption algorithm to decrypt the encrypted data. For example, the cybersecurity engine **304** may use the decrypted database key and tweak to perform format-preserving decryption using an FPE algorithm (e.g., FF3-1). The data may be provided in its original plaintext form, maintaining the format and length constraints of the encrypted value.

[0076] The method **700** may proceed to block **710** where the set of data, requested in the query, is provided to the user. In an embodiment, at block **710**, the cybersecurity engine **304** may provide the data identified in the request to the secure distributed storage controller **404**. The secure distributed storage controller **404** may provide the data to the client computing device **200** in response to the request. All decrypted database keys, the master key, or any tweaks may be discarded from memory after the decryption operation.

[0077] In some embodiments, the system provides a method for securely rotating a master key associated with a client or tenant within the multi-tenant data security platform. The rotation process begins when a client computing

device **12**/**200** initiates a master key rotation request, typically through a function call such as cybersecurityservice_fpe_rotate_keys( ). This request is executed within the secured distributed storage **16** such as a cloud-hosted data environment (e.g., Snowflake) and transmitted via a secure external function to the cybersecurity provider computing device **300**.

[0078] Upon receiving the request, the cybersecurity engine **304** may identify the client through a unique identifier (e.g., cybersecurityservice_key_id) and retrieves the corresponding master key, which may be typically encrypted or "wrapped" using a higher-level key such as a wrapper key residing in the key management computing device **14** (e.g., AWS KMS) or in a BYOK model). The cybersecurity engine **304** may then decrypt the current master key using the wrapper key within its secure, isolated execution environment. Once the current master key is available in memory, the cybersecurity engine **304** generates a new cryptographically secure master key according to the master key generation discussed above. This new master key may be wrapped using the appropriate wrapper key to ensure it is protected before being stored or used in further operations.

[0079] The cybersecurity engine **304** may then proceed to locate all database encryption keys and associated tweak values that were originally encrypted using the old master key. For each such key or tweak, the cybersecurity engine **304** may perform a rewrapping process where the object is decrypted using the old master key and then re-encrypted using the new master key. This operation may be executed iteratively across a set of key records associated with the client and can be coordinated with metadata or indexing mechanisms to ensure completeness and traceability.

[0080] Once all relevant keys and tweaks have been successfully re-encrypted with the new master key, the cybersecurity engine **304** may update the client's key registry to mark the new master key as the active encryption root. The old master key may then be securely deleted from storage or memory, or optionally archived with expiration metadata if compliance policies require retention. The completion of the key rotation process may be communicated to the client computing device **12**.

[0081] FIG. **8** illustrates the cryptographic key hierarchy and flow **800** involved in cybersecurity provider's secure encryption key management system for the secure distributed storage **16**, as previously described. The illustration effectively separates the trust boundary between the cybersecurity provider's secure key management system instance (on the left) and a user's secure distributed environment (on the right), showcasing how keys are securely generated, encrypted, stored, and used without ever exposing plaintext key material to untrusted environments.

[0082] On the cybersecurity provider's side, the wrapper key **802** may reside in the key management computing device **14**. In Bring-Your-Own-Key (BYOK) scenarios, this wrapper key **802** may be managed and owned by the client at the client computing device **12**. The wrapper key **802** may be used to encrypt and decrypt the master key **804**, which may be generated and stored by the cybersecurity provider (e.g., via the key management service (e.g., AWS KMS). The master key **804** may act as a central encryption authority, used to encrypt and decrypt individual database keys **806***a*, **806***b*, or up to **806***c*. These encrypted database keys **806***a*, **806***b*, or up to **806***c* are then securely transferred and stored in the client's secure distributed storage environment, as shown in the right-hand section of FIG. **8**. Once in the secure distributed storage, each encrypted database keys **806***a*, **806***b*, or up to **806***c* is tied to a specific dataset or partition (e.g., a table or schema), and is used to encrypt and decrypt data at query time.

[0083] FIG. **9** illustrates a block diagram of transparent decryption **900** discussed above. Transparent decryption may allow users to see encrypted or decrypted data based on the policy set at the policy engine **304***a* of the cybersecurity engine **304** at the cybersecurity provider computing device **300** by accessing data as the user would if the data was not encrypted. In various embodiments, an external function or other mechanism is used to pass query context to the policy engine **304***a* from the secure distributed storage **16**. The policy engine **304***a* may then return what level of access the user has. If the user has permission to see the data in plain text, a masking policy logic triggers decryption over the data, which may be according to the encryption key management discussed above. The decrypted data is returned to the user in the query results. If the user does not have permission to see the plain text data, the encrypted data is returned to the user in the query results. This process is not visible to the user, the user simply queries data like they normally would and gets encrypted or decrypted data back. The encrypted and decrypted data may include the format of the data (e.g., character length and pattern).

[0084] In the illustrated example, the "Email" and the "SSN" columns of the table **902** may be encrypted by the cybersecurity provider computing device **300** while the "Last Name" column is not encrypted. Table **902**'illustrates the encrypted columns. A first user that is associated with a client computing device **904***a* may make a request for table **902** and a second user that is associated with a client computing device **904***b* may also make a request for the table **902**. The secure distributed storage **16** may query the cybersecurity provider computing device **300** to check the policies **312** to determine whether the first user or the second user have rights in viewing the encrypted data. The cybersecurity provider computing device **300** using the policies **312** may determine that the first user has permission while the second user does not and return the table **902** to the client computing device **904***a* and return the table **902'** to the client computing device **904***b*. In other examples, the second user may have permission to view "Email" but not the "SSN." As such, the secured distributed storage **16** may return decrypted versions of the "Email" column and encrypted versions of the "SSN"column.

[0085] FIG. **10** illustrates a flowchart of a method **1000** for secure encrypted cryptographic key sharing via temporary sessions between two independent computing entities, each operating within separate encryption domains, according to various embodiments of the present disclosure. The method **1000** utilizes a temporary, authenticated key sharing session managed by the cybersecurity provider computing device **300**. The cybersecurity provider computing device's **300** FPE key sharing method may enable the use case where a data producer and cybersecurity provider's customer wishes to share encrypted data with a consumer who is also a cybersecurity provider's customer. Using this method **1000**, a producer can share the data encryption keys with the consumer so that each party holds their own key to decrypt the FPE data using independent cybersecurity provider deployments. The cybersecurity provider's FPE key management may use a key-wrapping scheme; data keys are

encrypted at rest in a client's secure distributed storage account and only decrypted at query-time by a master key held by the cybersecurity provider (or held by the client in the case of a bring-your-own-key deployment). Given that two parties have separate FPE deployments and master keys, the data keys to share must be reencrypted from one master key to another. This is facilitated by establishing a secure temporary sharing session that has a common master key that both parties have access to, and then reencrypting one or more data keys against the session to securely share them outside of a secure communication medium. Before establishing a session, both parties must have a cybersecurity provider instance set up on their secure distributed storage accounts as well as a fully-initialized encryption deployment (e.g., master key is generated). Unless otherwise qualified, all SQL commands may be made with the current database set to the caller's FPE integration database and the current schema set to "key_sharing_handler."

[0086] The method **1000** may begin at block **1002** where a first client computing device that operates as a receiver obtains a public reference identifier. In an embodiment, at block **1002**, a user of a first client computing device **200***a* may make a request for a public reference identifier at the secure distributed storage controller **404**. For example, the user may invoke a function call within the secure distributed storage **16** (e.g., get_public_ref_id( )). The public reference identifier may be a universally unique identifier (UUID).

[0087] The method **1000** may proceed to block **1004** where the first client computing device provides the public reference identifier to a second client computing device. In an embodiment, at block **1004**, the first client computing device **200***a* may send or transmit the public reference identifier to a second client computing device **200***b*. The transmission may be over a secure communication channel, such as encrypted email or a secure file transfer mechanism.

[0088] The method **1000** may proceed to block **1006** where the second client computing device that operates as a sender initializes a temporary key sharing session by invoking a session initialization command. In an embodiment, at block **1006**, the second client computing device **200***b* may initialize a temporary key sharing session with the cybersecurity provider computing device **300**. The temporary key sharing session may be initiated with a session initialization command (e.g., sender_intialize_key_sharing_session) that includes the receiver's public reference identifier and a session time-to-live (TTL) parameter. Specifically, the session sharing engine **304***b* may obtain the initialization of the temporary key sharing session.

[0089] The method **1000** may proceed to block **1008** where a session token is generated and returned to the second client computing device. In an embodiment, at block **1008**, the session sharing engine **304***b* of the cybersecurity provider computing device **300** may generate a session token. By generating a session token, the session sharing engine **304***b* may establish a loosely-bound sharing session that can only be acknowledged by the receiver (e.g., identified by the public reference identifier). The session sharing engine **304***b* may generate sharing session master key according to master key generation discussed above. The session sharing engine **304***b* may return the session token to the second client computing device **200***b*. The session master key may be internal to the cybersecurity provider computing device **300** and is not visible to either party of the temporary key sharing session.

[0090] The method **1000** may proceed to block **1010** where the second client computing device provides the session token to the first client computing device. In an embodiment, at block **1010**, the second client computing device **200***b* may send or transmit the session token to the client computing device **200***a*. The transmission may be over a secure communication channel, such as encrypted email or a secure file transfer mechanism. The first client computing device **200***a*/receiver may store the session token in a secure location such as a key store **216***a*.

[0091] The method **1000** may proceed to block **1012** where the first client computing device acknowledges the sharing session. In an embodiment, at block **1012**, the first client computing device **200***a* may acknowledge the sharing session with the session sharing engine **304***b*. The first client computing device **200***a* may invoke an acknowledgement procedure (e.g., receiver_acknowledge_key_sharing_session) using the session token. Upon a successful acknowledgement, the sharing session may become mutually bound and authenticated between the sender and the receiver.

[0092] After the shared session is established, the method **1000** may proceed to block **1014** where the second client computing device invokes a re-encryption operation of one or more encrypted database keys. In an embodiment, at block **1014**, the second client computing device **200***b* may identify one or more database keys to provide to the first client computing device **200***a*. For example, the one or more database keys may be associated with (e.g., used to encrypt) particular encrypted data that the sender wants to share with the receiver. The second client computing device **200***b* may call the session sharing engine **304***b* with the session token and one or more encrypted database keys. The cybersecurity engine **304** decrypts the encrypted database key with the master key according to methods discussed above (e.g., using a wrapper key to decrypt the master key, etc.). The session sharing engine **304***b* may then encrypt those decrypted database keys with the sharing session master key to generate one or more shared session encrypted database keys and provide the shared session encrypted database keys back to the sender (e.g., second client computing device **200***b*). As discussed above, the cybersecurity engine **304** may integrate FPE. As such, encryption may be performed using a key and a related tweak value, both of which are persisted in ciphertext. It should be understood that encrypting and decrypting a database key in method **1000** is a generalization for operating on one or more pairs of keys and tweaks as opposed to a single value.

[0093] The method **1000** may proceed to block **1016** where the second client computing device sends the one or more shared session encrypted database keys to the first client computing device. In an embodiment, at block **1016**, the second client computing device **200***b* may send or transmit the shared session encrypted database keys to the client computing device **200***a*. The sender may optionally modify associated key labels or metadata to conform to external naming conventions or to prevent leakage of internal information. The transmission may be over a secure communication channel, such as encrypted email or a secure file transfer mechanism. The first client computing device **200***a*/receiver may store the shared session encrypted database keys in a secure location such as the key store **216***a*.

[0094] The method **1000** may proceed to block **1018** where the first client computing device invokes a re-encryption function on the shared session encrypted database keys.

In an embodiment, at block **1018**, the first client computing device **200***a* may invoke a second re-encryption function (e.g., receiver_reencrypt_into_client_keychain) with the session sharing engine **304***b* using the session encrypted database keys and the session token. The session sharing engine **304***b* may decrypt the shared session encrypted database keys with the session master key that is identified by the session token and re-encrypt the session keys under the receiver's own master key, thereby generating usable key material within the receiver's trust domain. As such, the encrypted database key may be added to the receiver's key store **310** in that user instance **309**.

[0095] The method **1000** may proceed to decision block **1020** where it is determined whether a session termination condition is present. In an embodiment, at decision block **1020**, the session sharing engine **304***b* may determine whether a session termination condition is present. For example, the session sharing engine **304***b* may determine whether the TTL condition is satisfied such that the amount of time that the shared session is allowed to be open has lapsed. In other embodiments, the session sharing engine **304***b* may monitor the first client computing device **200***a* or the second client computing device **200***b* for any close session messages. For example, the receiver or the sender may run "call close_key_sharing_session(<session token>)." If, at decision block **1020**, a session termination condition is not present, the method **1000** may continue to monitor for a session termination condition.

[0096] If the session termination condition is present, then the method **1000** may proceed to block **1022** where the shared session is terminated. In an embodiment, at block **1022**, the session sharing engine **304***b* may tear down or close the session such that no re-encryption will be allowed and the shared session will be inaccessible by the sender and the receiver. An appropriate message may be returned to either the sender or the receiver if a call to re-encrypt is received.

[0097] FIG. **11** illustrates a message sequence diagram **1100** illustrating an example of method **1000**. In an embodiment, the secure key sharing process of method **1000** is illustrated by the message sequence diagram **1100** that details the interactions between a sender **200***b*, a receiver **200***a*, and the cybersecurity provider computing device **300**. The process begins when the receiver **200***a* generates and transmits a public reference identifier "Rr" to the sender **200***b*, at step **1102**. The sender **200***b* uses the public reference identifier Rr to initialize a key sharing session by invoking an initialization function with the secure platform, at step **1104**. In response, the platform generates a session token "T" that uniquely identifies the key sharing session and returns the session token T to the sender **200***b*, at step **1106**. This session token T is transmitted by the sender **200***b* to the receiver **200***a*, at step **1108**. The receiver **200***a* then uses the session token T to acknowledge the session with the secure platform (ack(T)), which binds the session to both participants and authorizes subsequent operations, at step **1110**. The acknowledgement completes the initial phase of session creation.

[0098] Once the session is active, the sender **200***b* proceeds to initiate key sharing by supplying the session token T and an encrypted database key Es(K). (specifically, a database key previously encrypted using the sender's own FPE master key), at step **1112**. The cybersecurity provider computing device **300** decrypts this input database key and re-encrypts it using the session's temporary master key, resulting in an intermediate, shareable encrypted database key Esh(K) that is returned to the sender **200***b*, at step **1114**. This shareable encrypted database key Esh(K) is then transmitted from the sender **200***b* to the receiver **200***a*, at step **1116**.

[0099] Upon receiving the shareable encrypted database key Esh(K), the receiver **200***a* submits the shareable encrypted database key Esh(K) and the session token T to the cybersecurity provider computing device **300**, requesting re-encryption into the receiver's own cryptographic domain, at step **1118**. The cybersecurity provider computing device **300** again encrypts the shareable encrypted database key Esh(K) using the session master key and re-encrypts it using the receiver's FPE master key. The final output is a database key Er(K) encrypted under the receiver's key hierarchy, which is then sent to the receiver **200***a* and stored in the receiver's secure key table for subsequent use, at step **1120**. At the conclusion of the process, at least one of the sender or the receiver may terminate the session by invoking a session closure function, which renders the shared session inactive and prevents further re-encryption operations, at step **1122**. The entire protocol ensures that no raw key material is exposed to either party, while enabling cryptographically isolated systems to securely exchange usable encryption keys through a transient, authenticated context. As noted above, FPE encryption may be performed using a key and a related tweak value, both of which are persisted in ciphertext. It should be understood that encrypting and decrypting a database key K is a generalization for operating on one or more pairs of keys or tweaks as opposed to a single value.

[0100] Thus, the systems and methods of the present disclosure provide a comprehensive framework for secure, scalable, and policy-aware encryption key management and data access control within distributed cloud data environments. Through the use of hierarchical key structures, external function integration, and a temporary session-based key sharing protocol, the disclosed systems and methods enable cryptographically isolated entities to securely exchange encryption keys without exposing raw key material or compromising trust boundaries. The incorporation of format-preserving encryption further allows sensitive data to be protected without altering its structure, thereby preserving schema integrity and application compatibility. Transparent decryption mechanisms, governed by real-time access policies, offer seamless user experiences while enforcing granular data access restrictions. Collectively, these innovations deliver significant technical advantages including reduced key exposure risk, improved regulatory compliance, operational scalability across multi-tenant environments, and simplified integration into existing data workflows. While specific embodiments and examples have been described for illustrative purposes, the scope of the invention encompasses any variations, modifications, and equivalents without departing from the scope of the present disclosure.

[0101] FIG. **12** is a diagram that illustrates an exemplary computing system **1000** in accordance with embodiments of the present technique. Various portions of systems and methods described herein, may include or be executed on one or more computer systems similar to computing system **1200**. Further, processes and modules described herein may be executed by one or more processing systems similar to that of computing system **1200**.

[0102] Computing system **1200** may include one or more processors (e.g., processors **1210***a*-**1210***n*) coupled to system memory **1220**, an input/output I/O device interface **1230**, and a network interface **1240** via an input/output (I/O) interface **1250**. A processor may include a single processor or a plurality of processors (e.g., distributed processors). A processor may be any suitable processor capable of executing or otherwise performing instructions. A processor may include a central processing unit (CPU) that carries out program instructions to perform the arithmetical, logical, and input/output operations of computing system **1200**. A processor may execute code (e.g., processor firmware, a protocol stack, a database management system, an operating system, or a combination thereof) that creates an execution environment for program instructions. A processor may include a programmable processor. A processor may include general or special purpose microprocessors. A processor may receive instructions and data from a memory (e.g., system memory **1220**). Computing system **1200** may be a uni-processor system including one processor (e.g., processor **1210***a*), or a multi-processor system including any number of suitable processors (e.g., **1210***a*-**1210***n*). Multiple processors may be employed to provide for parallel or sequential execution of one or more portions of the techniques described herein. Processes, such as logic flows, described herein may be performed by one or more programmable processors executing one or more computer programs to perform functions by operating on input data and generating corresponding output. Processes described herein may be performed by, and apparatus can also be implemented as, special purpose logic circuitry, e.g., an FPGA (field programmable gate array) or an ASIC (application specific integrated circuit). Computing system **1200** may include a plurality of computing devices (e.g., distributed computer systems) to implement various processing functions.

[0103] I/O device interface **1230** may provide an interface for connection of one or more I/O devices **1260** to computer system **1200**. I/O devices may include devices that receive input (e.g., from a user) or output information (e.g., to a user). I/O devices **1260** may include, for example, graphical user interface presented on displays (e.g., a cathode ray tube (CRT) or liquid crystal display (LCD) monitor), pointing devices (e.g., a computer mouse or trackball), keyboards, keypads, touchpads, scanning devices, voice recognition devices, gesture recognition devices, printers, audio speakers, microphones, cameras, or the like. I/O devices **1260** may be connected to computer system **1200** through a wired or wireless connection. I/O devices **1260** may be connected to computer system **1200** from a remote location. I/O devices **1260** located on remote computer system, for example, may be connected to computer system **1200** via a network and network interface **1240**.

[0104] Network interface **1240** may include a network adapter that provides for connection of computer system **1200** to a network. Network interface may **1240** may facilitate data exchange between computer system **1200** and other devices connected to the network. Network interface **1240** may support wired or wireless communication. The network may include an electronic communication network, such as the Internet, a local area network (LAN), a wide area network (WAN), a cellular communications network, or the like.

[0105] System memory **1220** may be configured to store program instructions **1200** or data **1210**. Program instructions **1200** may be executable by a processor (e.g., one or more of processors **1210***a*-**1210***n*) to implement one or more embodiments of the present techniques. Instructions **1200** may include modules of computer program instructions for implementing one or more techniques described herein with regard to various processing modules. Program instructions may include a computer program (which in certain forms is known as a program, software, software application, script, or code). A computer program may be written in a programming language, including compiled or interpreted languages, or declarative or procedural languages. A computer program may include a unit suitable for use in a computing environment, including as a stand-alone program, a module, a component, or a subroutine. A computer program may or may not correspond to a file in a file system. A program may be stored in a portion of a file that holds other programs or data (e.g., one or more scripts stored in a markup language document), in a single file dedicated to the program in question, or in multiple coordinated files (e.g., files that store one or more modules, sub programs, or portions of code). A computer program may be deployed to be executed on one or more computer processors located locally at one site or distributed across multiple remote sites and interconnected by a communication network.

[0106] System memory **1220** may include a tangible program carrier having program instructions stored thereon. A tangible program carrier may include a non-transitory computer readable storage medium. A non-transitory computer readable storage medium may include a machine readable storage device, a machine readable storage substrate, a memory device, or any combination thereof. Non-transitory computer readable storage medium may include non-volatile memory (e.g., flash memory, ROM, PROM, EPROM, EEPROM memory), volatile memory (e.g., random access memory (RAM), static random access memory (SRAM), synchronous dynamic RAM (SDRAM)), bulk storage memory (e.g., CD-ROM and/or DVD-ROM, hard-drives), or the like. System memory **1220** may include a non-transitory computer readable storage medium that may have program instructions stored thereon that are executable by a computer processor (e.g., one or more of processors **1210***a*-**1210***n*) to cause the subject matter and the functional operations described herein. A memory (e.g., system memory **1220**) may include a single memory device and/or a plurality of memory devices (e.g., distributed memory devices). Instructions or other program code to provide the functionality described herein may be stored on a tangible, non-transitory computer readable media. In some cases, the entire set of instructions may be stored concurrently on the media, or in some cases, different parts of the instructions may be stored on the same media at different times.

[0107] I/O interface **1250** may be configured to coordinate I/O traffic between processors **1210***a*-**1210***n*, system memory **1220**, network interface **1240**, I/O devices **1260**, and/or other peripheral devices. I/O interface **1250** may perform protocol, timing, or other data transformations to convert data signals from one component (e.g., system memory **1220**) into a format suitable for use by another component (e.g., processors **1210***a*-**1210***n*). I/O interface **1250** may include support for devices attached through various types of peripheral buses, such as a variant of the

Peripheral Component Interconnect (PCI) bus standard or the Universal Serial Bus (USB) standard.

[0108] Embodiments of the techniques described herein may be implemented using a single instance of computer system **1200** or multiple computer systems **1200** configured to host different portions or instances of embodiments. Multiple computer systems **1200** may provide for parallel or sequential processing/execution of one or more portions of the techniques described herein.

[0109] Those skilled in the art will appreciate that computer system **1200** is merely illustrative and is not intended to limit the scope of the techniques described herein. Computer system **1200** may include any combination of devices or software that may perform or otherwise provide for the performance of the techniques described herein. For example, computer system **1200** may include or be a combination of a cloud-computing system, a data center, a server rack, a server, a virtual server, a desktop computer, a laptop computer, a tablet computer, a server device, a client device, a mobile telephone, a personal digital assistant (PDA), a mobile audio or video player, a game console, a vehicle-mounted computer, or a Global Positioning System (GPS), or the like. Computer system **1200** may also be connected to other devices that are not illustrated, or may operate as a stand-alone system. In addition, the functionality provided by the illustrated components may in some embodiments be combined in fewer components or distributed in additional components. Similarly, in some embodiments, the functionality of some of the illustrated components may not be provided or other additional functionality may be available.

[0110] Those skilled in the art will also appreciate that while various items are illustrated as being stored in memory or on storage while being used, these items or portions of them may be transferred between memory and other storage devices for purposes of memory management and data integrity. Alternatively, in other embodiments some or all of the software components may execute in memory on another device and communicate with the illustrated computer system via inter-computer communication. Some or all of the system components or data structures may also be stored (e.g., as instructions or structured data) on a computer-accessible medium or a portable article to be read by an appropriate drive, various examples of which are described above. In some embodiments, instructions stored on a computer-accessible medium separate from computer system **1200** may be transmitted to computer system **1200** via transmission media or signals such as electrical, electromagnetic, or digital signals, conveyed via a communication medium such as a network or a wireless link. Various embodiments may further include receiving, sending, or storing instructions or data implemented in accordance with the foregoing description upon a computer-accessible medium. Accordingly, the present techniques may be practiced with other computer system configurations.

[0111] In block diagrams, illustrated components are depicted as discrete functional blocks, but embodiments are not limited to systems in which the functionality described herein is organized as illustrated. The functionality provided by each of the components may be provided by software or hardware modules that are differently organized than is presently depicted, for example such software or hardware may be intermingled, conjoined, replicated, broken up, distributed (e.g. within a data center or geographically), or otherwise differently organized. The functionality described herein may be provided by one or more processors of one or more computers executing code stored on a tangible, non-transitory, machine readable medium. In some cases, notwithstanding use of the singular term "medium," the instructions may be distributed on different storage devices associated with different computing devices, for instance, with each computing device having a different subset of the instructions, an implementation consistent with usage of the singular term "medium" herein. In some cases, third party content delivery networks may host some or all of the information conveyed over networks, in which case, to the extent information (e.g., content) can be said to be supplied or otherwise provided, the information may provided by sending instructions to retrieve that information from a content delivery network.

[0112] The reader should appreciate that the present application describes several independently useful techniques. Rather than separating those techniques into multiple isolated patent applications, applicants have grouped these techniques into a single document because their related subject matter lends itself to economies in the application process. But the distinct advantages and aspects of such techniques should not be conflated. In some cases, embodiments address all of the deficiencies noted herein, but it should be understood that the techniques are independently useful, and some embodiments address only a subset of such problems or offer other, unmentioned benefits that will be apparent to those of skill in the art reviewing the present disclosure. Due to costs constraints, some techniques disclosed herein may not be presently claimed and may be claimed in later filings, such as continuation applications or by amending the present claims. Similarly, due to space constraints, neither the Abstract nor the Summary of the Invention sections of the present document should be taken as containing a comprehensive listing of all such techniques or all aspects of such techniques.

[0113] It should be understood that the description and the drawings are not intended to limit the present techniques to the particular form disclosed, but to the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the present techniques as defined by the appended claims. Further modifications and alternative embodiments of various aspects of the techniques will be apparent to those skilled in the art in view of this description. Accordingly, this description and the drawings are to be construed as illustrative only and are for the purpose of teaching those skilled in the art the general manner of carrying out the present techniques. It is to be understood that the forms of the present techniques shown and described herein are to be taken as examples of embodiments. Elements and materials may be substituted for those illustrated and described herein, parts and processes may be reversed or omitted, and certain features of the present techniques may be utilized independently, all as would be apparent to one skilled in the art after having the benefit of this description of the present techniques. Changes may be made in the elements described herein without departing from the spirit and scope of the present techniques as described in the following claims. Headings used herein are for organizational purposes only and are not meant to be used to limit the scope of the description.

[0114] As used throughout this application, the word "may" is used in a permissive sense (i.e., meaning having the potential to), rather than the mandatory sense (i.e.,

meaning must). The words "include", "including", and "includes" and the like mean including, but not limited to. As used throughout this application, the singular forms "a," "an," and "the" include plural referents unless the content explicitly indicates otherwise. Thus, for example, reference to "an element" or "a element" includes a combination of two or more elements, notwithstanding use of other terms and phrases for one or more elements, such as "one or more." The term "or" is, unless indicated otherwise, non-exclusive, i.e., encompassing both "and" and "or." Terms describing conditional relationships, e.g., "in response to X, Y," "upon X, Y,", "if X, Y," "when X, Y," and the like, encompass causal relationships in which the antecedent is a necessary causal condition, the antecedent is a sufficient causal condition, or the antecedent is a contributory causal condition of the consequent, e.g., "state X occurs upon condition Y obtaining" is generic to "X occurs solely upon Y" and "X occurs upon Y and Z." Such conditional relationships are not limited to consequences that instantly follow the antecedent obtaining, as some consequences may be delayed, and in conditional statements, antecedents are connected to their consequents, e.g., the antecedent is relevant to the likelihood of the consequent occurring. Statements in which a plurality of attributes or functions are mapped to a plurality of objects (e.g., one or more processors performing steps A, B, C, and D) encompasses both all such attributes or functions being mapped to all such objects and subsets of the attributes or functions being mapped to subsets of the attributes or functions (e.g., both all processors each performing steps A-D, and a case in which processor **1** performs step A, processor **2** performs step B and part of step C, and processor **3** performs part of step C and step D), unless otherwise indicated. Further, unless otherwise indicated, statements that one value or action is "based on" another condition or value encompass both instances in which the condition or value is the sole factor and instances in which the condition or value is one factor among a plurality of factors. Unless otherwise indicated, statements that "each" instance of some collection have some property should not be read to exclude cases where some otherwise identical or similar members of a larger collection do not have the property, i.e., each does not necessarily mean each and every. Limitations as to sequence of recited steps should not be read into the claims unless explicitly specified, e.g., with explicit language like "after performing X, performing Y," in contrast to statements that might be improperly argued to imply sequence limitations, like "performing X on items, performing Y on the X'ed items," used for purposes of making claims more readable rather than specifying sequence. Statements referring to "at least Z of A, B, and C," and the like (e.g., "at least Z of A, B, or C"), refer to at least Z of the listed categories (A, B, and C) and do not require at least Z units in each category. Unless specifically stated otherwise, as apparent from the discussion, it is appreciated that throughout this specification discussions utilizing terms such as "processing," "computing," "calculating," "determining" or the like refer to actions or processes of a specific apparatus, such as a special purpose computer or a similar special purpose electronic processing/computing device.

[0115] In this patent, certain U.S. patents, U.S. patent applications, or other materials (e.g., articles) have been incorporated by reference. The text of such U.S. patents, U.S. patent applications, and other materials is, however, only incorporated by reference to the extent that no conflict exists between such material and the statements and drawings set forth herein. In the event of such conflict, the text of the present document governs.

[0116] The present techniques will be better understood with reference to the following enumerated embodiments:

[0117] Clause 1. A tangible, non-transitory, machine-readable medium storing instructions that, when executed by one or more processors, effectuate operations comprising: generating, by one or more processors, a master encryption key associated with a user of a secure distributed storage comprising a plurality of databases; encrypting, by one or more processors, the master encryption key with a wrapper key that is stored at a key management system associated with a cybersecurity provider; generating, by one or more processors, a database key for encrypting and decrypting data stored in one or more databases of the secure distributed storage; encrypting, by one or more processors, the database key using the master encryption key, thereby generating an encrypted database key; and storing, by one or more processors, the encrypted database key in association with the user at the secure distributed storage.

[0118] Clause 2. The machine-readable medium of clause 1, wherein the operations further comprise, in response to a query to access encrypted data: retrieving the encrypted database key from the secure distributed storage and decrypting the encrypted database key using the master encryption key; and using the decrypted database key to decrypt the encrypted data stored in the secure distributed storage.

[0119] Clause 3. The machine-readable medium of clause 2, wherein the operations further comprise: decrypting the encrypted data using the decrypted database key and returning a plaintext result to the user in response to the query.

[0120] Clause 4. The machine-readable medium of clause 2, wherein the operations further comprise: determining, based on a masking policy evaluated by a policy engine, whether the decrypted data is returned in plaintext or encrypted form.

[0121] Clause 5. The machine-readable medium of clause 4, wherein the masking policy is based on at least one of a user identifier, a user role, a data field being accessed, or a resource associated with the user.

[0122] Clause 6. The machine-readable medium of clause 1, wherein the master encryption key is decrypted using the wrapper key prior to decrypting the encrypted database key.

[0123] Clause 7. The machine-readable medium of clause 1, wherein the wrapper key is provided by the user and is stored at a client computing device in a bring-your-own-key (BYOK) configuration.

[0124] Clause 8. The machine-readable medium of clause 1, wherein the database key is generated in response to a function call made through a structured query language (SQL) interface of the secure distributed storage.

[0125] Clause 9. The machine-readable medium of clause 8, wherein the function call is executed via an external function interface that transmits a request to the cybersecurity provider.

[0126] Clause 10. The machine-readable medium of clause 1, wherein the database key is used with a format-preserving encryption algorithm to encrypt and decrypt data.

[0127] Clause 11. The machine-readable medium of clause 10, wherein the format-preserving encryption algorithm is FF3-1.

[0128] Clause 12. The machine-readable medium of clause 10, wherein the operations further comprise: using a tweak value in conjunction with the database key as input to the format-preserving encryption algorithm.

[0129] Clause 13. The machine-readable medium of clause 12, wherein the operations further comprise: decrypting the tweak value using the master encryption key before using the tweak value as input to the format-preserving encryption algorithm.

[0130] Clause 14. The machine-readable medium of clause 1, wherein the database key is associated with a particular type of data selected from the group consisting of social security numbers, credit card numbers, telephone numbers, email addresses, names, and addresses.

[0131] Clause 15. The machine-readable medium of clause 1, wherein the database key is associated with data stored across multiple databases or across multiple fields within a database.

[0132] Clause 16. The machine-readable medium of clause 1, wherein the encrypted database key is stored in a key store in a user instance associated with the secure distributed storage.

[0133] Clause 17. The machine-readable medium of clause 1, wherein the decrypted database key is held only in transient memory of a cybersecurity provider computing device during encryption or decryption operations.

[0134] Clause 18. The machine-readable medium of clause 1, wherein the operations further comprise: in response to a request to share the encrypted database key with a second encryption domain, invoking a first re-encryption operation to re-encrypt the encrypted database key using a session master key associated with a temporary key sharing session; transmitting the re-encrypted database key to the second encryption domain; and invoking a second re-encryption operation to re-encrypt the re-encrypted database key using a second master encryption key associated with the second encryption domain.

[0135] Clause 19. The machine-readable medium of clause 1, wherein the encrypted data returned to an unauthorized user is in ciphertext but maintains the format of the original data.

[0136] Clause 20. A method, comprising: generating, by one or more processors, a master encryption key associated with a user of a secure distributed storage comprising a plurality of databases; encrypting, by one or more processors, the master encryption key with a wrapper key that is stored at a key management system associated with a cybersecurity provider; generating, by one or more processors, a database key for encrypting and decrypting data stored in one or more databases of the secure distributed storage; encrypting, by one or more processors, the database key using the master encryption key, thereby generating an encrypted database key; and storing, by one or more processors, the encrypted database key in association with the user at the secure distributed storage.

What is claimed is:

1. A tangible, non-transitory, machine-readable medium storing instructions that, when executed by one or more processors, effectuate operations comprising:

generating, by one or more processors, a master encryption key associated with a user of a secure distributed storage comprising a plurality of databases;

encrypting, by one or more processors, the master encryption key with a wrapper key that is stored at a key management system associated with a cybersecurity provider;

generating, by one or more processors, a database key for encrypting and decrypting data stored in one or more databases of the secure distributed storage;

encrypting, by one or more processors, the database key using the master encryption key, thereby generating an encrypted database key; and

storing, by one or more processors, the encrypted database key in association with the user at the secure distributed storage.

2. The machine-readable medium of claim **1**, wherein the operations further comprise, in response to a query to access encrypted data:

retrieving the encrypted database key from the secure distributed storage and decrypting the encrypted database key using the master encryption key; and

using the decrypted database key to decrypt the encrypted data stored in the secure distributed storage.

3. The machine-readable medium of claim **2**, wherein the operations further comprise:

decrypting the encrypted data using the decrypted database key and returning a plaintext result to the user in response to the query.

4. The machine-readable medium of claim **2**, wherein the operations further comprise:

determining, based on a masking policy evaluated by a policy engine, whether the decrypted data is returned in plaintext or encrypted form.

5. The machine-readable medium of claim **4**, wherein the masking policy is based on at least one of a user identifier, a user role, a data field being accessed, or a resource associated with the user.

6. The machine-readable medium of claim **1**, wherein the master encryption key is decrypted using the wrapper key prior to decrypting the encrypted database key.

7. The machine-readable medium of claim **1**, wherein the wrapper key is provided by the user and is stored at a client computing device in a bring-your-own-key (BYOK) configuration.

8. The machine-readable medium of claim **1**, wherein the database key is generated in response to a function call made through a structured query language (SQL) interface of the secure distributed storage.

9. The machine-readable medium of claim **8**, wherein the function call is executed via an external function interface that transmits a request to the cybersecurity provider.

10. The machine-readable medium of claim **1**, wherein the database key is used with a format-preserving encryption algorithm to encrypt and decrypt data.

11. The machine-readable medium of claim **10**, wherein the format-preserving encryption algorithm is FF3-1.

12. The machine-readable medium of claim **10**, wherein the operations further comprise:

using a tweak value in conjunction with the database key as input to the format-preserving encryption algorithm.

13. The machine-readable medium of claim **12**, wherein the operations further comprise:

decrypting the tweak value using the master encryption key before using the tweak value as input to the format-preserving encryption algorithm.

14. The machine-readable medium of claim **1**, wherein the database key is associated with a particular type of data selected from the group consisting of social security numbers, credit card numbers, telephone numbers, email addresses, names, and addresses.

15. The machine-readable medium of claim **1**, wherein the database key is associated with data stored across multiple databases or across multiple fields within a database.

16. The machine-readable medium of claim **1**, wherein the encrypted database key is stored in a key store in a user instance associated with the secure distributed storage.

17. The machine-readable medium of claim **1**, wherein the decrypted database key is held only in transient memory of a cybersecurity provider computing device during encryption or decryption operations.

18. The machine-readable medium of claim **1**, wherein the operations further comprise:

in response to a request to share the encrypted database key with a second encryption domain, invoking a first re-encryption operation to re-encrypt the encrypted database key using a session master key associated with a temporary key sharing session;

transmitting the re-encrypted database key to the second encryption domain; and

invoking a second re-encryption operation to re-encrypt the re-encrypted database key using a second master encryption key associated with the second encryption domain.

19. The machine-readable medium of claim **1**, wherein the encrypted data returned to an unauthorized user is in ciphertext but maintains the format of the original data.

20. A method, comprising:

generating, by one or more processors, a master encryption key associated with a user of a secure distributed storage comprising a plurality of databases;

encrypting, by one or more processors, the master encryption key with a wrapper key that is stored at a key management system associated with a cybersecurity provider;

generating, by one or more processors, a database key for encrypting and decrypting data stored in one or more databases of the secure distributed storage;

encrypting, by one or more processors, the database key using the master encryption key, thereby generating an encrypted database key; and

storing, by one or more processors, the encrypted database key in association with the user at the secure distributed storage.

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