Managed Information: A New Abstraction Mechanism for Handling Information in Software-as-a-Service

DAVID H. LORENZ, Open University of Israel, Israel
BOAZ ROSENAN, University of Haifa, Israel

Management of information is an important aspect of every application. This includes, for example, protecting user data against breaches (like the one reported in the news about 50 million Facebook profiles being harvested for Cambridge Analytica), complying with data protection laws and regulations (like EU’s new General Data Protection Regulation), coping with large databases, and retaining user data across software versions. Today, every application needs to cope with such concerns by itself and on its own.

In this paper we introduce Managed Information (MI), an abstraction mechanism for managing extra-functional data related concerns, similar to how managed memory today abstracts away many memory related concerns. MI limits the access applications have to user data, which, in return, relieves them from responsibility over it. This is achieved by hosting them on a Managed Information Platform (MIP), and implementing their logic in a language that supports MI. As evidence for the feasibility of MI we describe the design and implementation of such a platform. For demonstration of MI, we describe a simple social network application built with it. The implementation is open source.

Additional Key Words and Phrases: Managed Languages, Domain Specific Languages (DSLs), Application Security, Clojure

1 INTRODUCTION

Abstraction is a key concept in software. Being able to abstract away aspects of software has been an enabler to many advancements in the field of Software Engineering and to the construction of complex software systems [Jackson 2016]. Choosing the right level of abstraction presents a trade-off in designing the architecture of the software system. On the one hand, the higher the level of abstraction is, the more aspects it will abstract away but the more rigid it becomes. On the other hand, the lower the level of abstraction is, the more control it provides over the end result but the more effort it requires of its consumer.

As an example, an Instruction Set Architecture (ISA) (e.g., Intel’s x86 family) is commonly thought of as the lowest level of abstraction available to software. It abstracts away concerns handled by the hardware, such as register forwarding and memory address translation. Meanwhile, it leaves many other aspects for programmers and compilers consuming this abstraction to deal with on their own. For example, this abstraction treats memory as a flat array of cells. It does not define how memory is to be structured, and how allocations are made.

As another example, a virtual machine (e.g., the Java Virtual Machine (JVM)) often provides a higher level of abstraction, treating memory as a graph of objects pointing to one another. This higher level of abstraction allows memory to be managed (e.g., the Java [Arnold and Gosling 1996] language with managed memory and garbage collection). By defining what objects are and how they reference each other, the abstraction can take ownership over memory deallocation, and provide better guarantees of memory safety,
such as protection against buffer overruns. This increased level of abstraction comes at a price. Programs written over the JVM lose the ability to access memory directly, and also lose fine-grained control over run-time, as the garbage collector can kick in at any time.

Computer programs can also define abstractions. *Content Management Systems (CMSs)*, such as WordPress, Drupal, or MediaWiki, for example, abstract away many of the common concerns related to building and serving websites, while allowing their users to concentrate on the contents they wish to present. Like every abstraction, this too comes at the price of control. CMSs typically allow content to be freely edited, but give very little control over functionality. For example, users creating blogs over WordPress can customize their blogs with predefined options programmed into WordPress, but have no way of creating new social features without breaking the abstraction level, implementing them using *PHP* [Lerdorf et al. 2002] code.

### 1.1 Abstracting Information

Our work is concerned with the level of abstraction available for handing information in software. By information we refer generally to data-related concerns that are extra-functional in nature but nonetheless addressed individually by every application separately. Some concerns relate to the amount of information applications need to handle, and to the challenges in maintaining efficiency and availability while handling large amounts of data. Other concerns relate to securing information and to regulation regarding the integrity and confidentiality of the information stored.

The lack of sufficient abstractions for information intensive software is especially evident in today’s *Software as a Service* (Saas) applications [Buxmann et al. 2008; Turner et al. 2003]. In terms of information, Saas applications are “unmanaged.” Each application is responsible on its own for properly protecting user data, and for proofing itself against known vulnerabilities. Saas applications have to handle data denormalization and data migration. And there are data protection regulations to which each application needs to comply.

To mitigate this problem, we contribute in this paper an abstraction mechanism named Managed Information (MI). This abstraction allows for Saas applications to be implemented, while the following five concerns regarding the management of information are abstracted away:

- **Access Control** In Saas, access control is coupled with authorization. MI provides a separation, where authorization is owned by the application, and access control is abstracted away.

- **Vulnerabilities** Security vulnerabilities can be found anywhere in the software, and therefore, protecting against them involves all developers. MI makes vulnerabilities in the application code irrelevant by guaranteeing that the information remains secure even if the application itself acts on behalf of an attacker.

- **Denormalization** To handle large amounts of information, Saas application developers are often required to denormalize their data, by maintaining redundant representations of it. This redundancy adds complexity to the implementation, and is prone to bugs. MI allows for denormalization to be abstracted away. The application only defines the relations that need to be maintained.

- **Software Evolution** There is a tension between the desire for the application to evolve, and the need to retain old data, along with assumptions made on it. With MI the software may evolve as its developers desire, while information is retained with its integrity and confidentiality assumptions unchanged.
Regulatory Compliance: Regulators are becoming more and more involved in management of information. GDPR [EU 2016] is one example of regulation that states what rights users must be given over information they contribute. MI provides a way to implement features required for regulatory compliance in an application agnostic manner. This allows applications to comply with such regulations without taking any specific actions.

1.2 Conceptual Contribution
The main research question addressed in this work is one of feasibility [Shaw 2002]: is it possible at all to accomplish a level of abstraction that supports MI? If so, to what extent these five concerns or others could be managed in MI? To that end, we present a conceptual framework for MI. To validate the concept of MI we implemented a fully functional, open source, proof-of-concept MI platform for SaaS applications. With respect to the 5 concerns listed above, our proof-of-concept implementation validates the feasibility of MI. We also provide a demonstration of how MI works on TweetMI, a Twitter-like example, which is simple yet representative of complex social network SaaS applications in reality.

2 Conceptual Framework
In the knowledge hierarchy [Rowley 2007], also known as the Data/Information/Knowledge/Wisdom (DIKW) hierarchy, information resides directly on top of the foundation of data. Data refers to raw observations, whereas information refers to meaning logically inferred from data or from processed data. In these terms, Managed Information (MI) abstracts over information, i.e., the meaning—not just the form—of data.

From a programming perspective, MI relieves the application developer of most of the responsibility over user data. Through the use of abstraction, MI lets the application programmer decouple the application logic from the data, similar to how a garbage collector frees the programmer from most of the responsibility over memory management. Indeed, with MI eight out of the nine application-level vulnerabilities listed in the 2017’s OWASP Top 10 [van der Stock et al. 2017] would be abstracted away by the language implementation (Sect. 5.2).

From a data management perspective, MI is an abstraction mechanism that subsumes and supersedes that of a Database Management System (DBMS). In traditional applications, a DBMS is often used as the primary abstraction over the state of the application, i.e., its data. While a DBMS abstracts away the nuts and bolts of how data is stored and retrieved, it manages only the data’s bits and structure and not its implied information.

We explain the MI abstraction in three steps (corresponding to Sections 2.1 to 2.3).

2.1 From Data to Information
The first step allows for denormalization and data migration to be decoupled from the application logic. This is achieved by lifting the repository from handling data to handling information by associating the data with logic capable of answering questions regarding it. An Application Platform (AP) capable of answering questions regarding the data becomes a repository for information:

Definition 1 (AP). An Application Platform is software that provides the following operations:

1. Create, Read, Update and Delete (CRUD) data.
(2) Create, Update and Delete logic, which defines how questions and data translate into answers.
(3) Perform queries: given a question, provide an answer based on the logic and the data.

Similarly to a DBMS, an AP supports storage and retrieval of data. However, unlike a DBMS, an AP also stores logic which effectively gives the data meaning. A DBMS, in contrast, stores the data without any interpretation, i.e., the queries answered by a DBMS refer to the data symbolically (e.g., fields in tables) rather than to the meaning it represents.

2.2 From Unmanaged to Managed Information

The second step allows for access control to be decoupled from the application logic. This is achieved by adding an ownership model to the Managed Information Platform (MIP), giving each piece of data an owner and an intended audience:

**Definition 2 (MIP).** A Managed Information Platform is an AP that meets the following additional requirements:

(4) Data is attributed to users. Any user can perform any CRUD operation on data, as long as the data is attributed to that user.

(5) Users and logic can specify whose data and logic to trust. Untrusted data and logic is not taken into consideration.

(6) Users who create data can specify who can read it. Queries made by a user only consider data that user is allowed to read.

In Def. 2 a MIP is an AP that also addresses data integrity (Reqs. 4 and 5) and data confidentiality (Req. 6). Data stated by a user is always accompanied by (at least) two pieces of information: (I) an attribution to the user who created the data, and (II) the specification of who can read this data. Mathematically, both can be represented as sets of users. We therefore call the attribution of a piece of data (fact)—its writers-set, and the specification of who is allowed to read it—its readers-set. We will refer to a single, fact (self-contained piece of data) that has a writers-set and a readers-set as an axiom.

By defining the writers-set as a set, rather than fixing it to the identity of a single user, we allow users to state facts in the name of groups. For example, academics can state facts in their own names, or in the names of their departments or universities. If they state something in their own names, no one else can update or remove their statement. However, if they use a larger group, other members of that group can modify or remove that fact in case they do not agree with it.

2.3 Managed Information

We can now already formulate what we mean by MI in the context of Saas:

**Definition 3 (MI).** Managed Information is a software architecture and programming model for SaaS applications, in which the server-side consists of a MIP, which by itself forms a Platform-as-a-Service (PaaS).
3.1 Objectivity of Data

SaaS applications that use multiple instances of ACID databases, or a single instance of a non-ACID database, do not have a well defined global state. One approach that gains traction in recent years to overcome the lack of well-defined state is event sourcing [Fowler 2005; Hohpe 2006]. Event sourcing is an approach to the management of state in applications, where the application’s single source of truth is the collection of change events, and partial state is generated on demand from these events.

The core philosophical principle behind event sourcing can be abbreviated as: while state is subjective (depends on the observer), change events are objective. To demonstrate this benefit of event sourcing, let us consider a simple example. The state of an application contains variable $A$, which can be assigned different values at different times. Now assume one user sets variable $A$ to 1 at about the same time another user sets variable $A$ to 2. In the traditional notion of state, variable $A$ can hold either 1 or 2, depending on factors such as the exact timing, the way state is updated, and the identity of the observer. However, the two change events, $A ← 1$ and $A ← 2$, are well defined. When someone wishes to know the value of $A$, they can play the two events and decide, based on their own perspective, what the value should be.

$\text{MIP}$ makes state even more subjective, by annotating data with confidentiality requirements (readers-sets, recall Req. 6 in Def. 2). This means that when viewed at the same time from the eyes of different users, the same application can seem to have multiple different states, since different users are allowed to see different facts. For example, consider the two change events $A ← 1$ and $A ← 2$ from before, but this time, the former’s readers-set is the set $\{u_0\}$ for some user $u_0$, and for the latter, the readers-set is the set $U \setminus \{u_0\}$, where $U$ represents the universal set of users. The state that arises from the accumulation of both events is subjective, and depends on the observer. User $u_0$ will observe $A$ to have the value 1, while any other user will observe $A$ as 2.

To cope with the subjective nature of state, a $\text{MIP}$ should only store events and not accumulate them to state. This means that all the processing done inside a $\text{MIP}$ should be based on events. Unlike the $\text{MIP}$ itself, clients can receive events readable by the user they represent, and accumulate them to form state, as seen by that user.

3.2 Objectivity of Logic

In $\text{MIP}$, not only data is subjective, but also the logic that gives it meaning. For example, social networks often provide their users with timelines or feeds, containing information coming from their social environment. The logic for creating this timeline or feed is specific to each social network, and often changes with time. Therefore, even if all facts contributing to a user’s timeline are known, the contents of a user’s timeline is not objective, but rather dependent upon the exact version of the logic that generates it.

This notion becomes extremely important when dealing with data denormalization. To shorten the time it takes a social network to present a timeline to a user, many social networks prepare their timelines ahead of time [Evans 2010], populating them with social data such as tweets and statuses as they come in. To do so, they need to apply logic.

However, applications evolve with time. The developers of a social network may change the logic for constructing a timeline as time goes by. Therefore, the version of the software that was in place when some tweet $T_1$ was written (and placed into the denormalized timeline) may not be the same as the software
version at the time when some tweet $T_2$ was written, and placed into the same timeline, and that may not
be the same version as the one at the time in which the user has queried his or her timeline.

To overcome this problem, application developers often develop data migration routines that are applied
to pre-existing data during a migration from one version to another, modifying the form of the derived data
(e.g., the pre-calculated timeline) according to the new logic. This makes sure a query will always reflect the
version at the time it was made.

Unfortunately, this kind of migration process comes at a high price. The migration routine is a computer
program intended to run only once, but still it needs to be written and tested thoroughly to make sure its
output is consistent with what the new logic would have produced.

Another challenge is to perform this migration without stopping the application, with new data coming
in and queries being made while the migration process is running.

By storing logic alongside data, MI makes both denormalization and migration, managed aspects. However,
to do so properly, it has to have an objective notion of logic.

Our approach for making logic objective involves two steps: (1) using content-addressable code, and
(2) restricting logic to being purely-declarative.

3.2.1 Content-Addressable Code. Content-addressable storage [Merkle 1988] is a practice by which data
objects are stored using keys derived from applying a cryptographic hash function on their content. If a
data object references another, it does so by mentioning its hash, and therefore this hash is considered when
calculating the hash of the referencing object.

Content addressing can be used with code as well as data. Consider a module system, in which the name
of a module is derived from a cryptographic hash of the code it contains. When such a module references
another module, the hash of the referenced module is written explicitly in the referencing module, making it
part of its content, affecting its hash.

Content-addressable code helps make logic objective. While the term timeline may be subjective, depending
on a specific version of a specific social network, the timeline associated with a specific hash $h_1$ is objective,
since $h_1$ defines a specific module that defines a specific version of the logic building the timeline, along
with all its dependencies.

When a new version comes along, it does not change the logic associated with $h_1$, but rather creates new
logic, associated with a new hash $h_2$. If we name the derived data artifacts (e.g., the pre-calculated timeline)
after the logic that created it, the two versions of the logic would create two distinct artifacts, one prefixed
with $h_1$, and the other, with $h_2$. Being distinct, they can coexist.

This simplifies the migration process. First, migration to the second version is as simple as applying the
new logic to all existing data. Second, the old derived data can be used while migration is taking place.

3.2.2 Purely-Declarative Logic. Another important aspect of keeping logic objective is restricting it to
being purely-declarative. Logic can be applied multiple times to a single piece of data. For example, the
logic of placing a tweet in a timeline can be applied when the tweet is being written, then (with some
modification) during migration to a new version, and finally, when the tweet is removed. To make sure all
applications of the logic yield consistent results, we need to make sure the logic itself is not affected by the
outside world in any way.
If, for example, the logic for calculating the timeline considered the time of processing to populate the timeline, the time the migration process considered a certain tweet would affect the way it is presented in timelines.

3.3 Application Architecture

Similar to a traditional client/server application architecture (Figure 1a), the MI application architecture (Figure 1b) has an application-specific (depicted in gray) client-side, running on an application-agnostic (depicted in white) client. This could be JavaScript [Flanagan 2011] code running on a browser or a mobile client app running on a mobile OS. Having the application’s client-side as payload over a client platform has advantages in protecting user privacy, as it allows executing it from within a sandbox (depicted as a dashed frame)—a controlled environment which limits its access.

However, MI differs from the traditional client/server architecture in the role the application logic plays on the server side. In a traditional applications, the server-side is at the complete control of the application developers, and under their complete responsibility. They may use off-the-shelf software, such as web frameworks or databases to simplify some aspects of the application, but these are used, misused, or bypassed at their discretion. While web frameworks can play an important role in keeping the application code focused on application-specific concerns (e.g., by handling many common concerns within the framework), they do not limit the application code in any way. Once invoked, the application logic is in control, typically having the same level of access as the framework itself. This level of access makes application logic subject to security vulnerabilities and data leaks.

In contrast, the MI architecture stores the application’s server-side logic as payload on a MIP, similarly to the way the client-side logic is stored on the client. Just like the client, it gives the MIP the opportunity to run it from within a sandbox. The sandboxed server-side logic does not have direct access to the data, nor to the client. All communications are brokered by the MIP’s logic, labeled Information Manager in Figure 1b. The Information Manager allows clients to manipulate user data (subject to the restrictions posed in Req. 4), and answer client queries (subject to the restrictions posed in Req. 6). To be able to answer these queries, the Information Manager consults the application logic, providing it all the information it needs. The answers provided by the logic are used by the Information Manager to either answer a query directly, or store answers for a later date.
Much of the stake regarding the feasibility of MI lies on the question of what kind of restrictions we would like to pose on an application’s server-side logic. As in the case of JavaScript on a browser, we need these restrictions to be, on the one hand, restrictive enough to prevent the logic from being a security concern, and on the other hand, permissive enough to allow the logic of any application to be expressed.

The integrity of the application is its own responsibility (according to Req. 5). However, confidentiality, i.e., the prevention of data leakage, needs to be handled by the sandbox. We distinguish between two kinds of leaks: direct and indirect. Direct leakage means that when processing the data it wishes to leak, the code transmits it on some channel to a party ready to receive it. Indirect leakage is done in two steps. At the first step, when processing one user’s data the code stores the data it wishes to leak in some temporary storage, and then, when processing another user’s data (say, the attacker’s), it fetches the stored data and returns it as the answer.

MI prevents both kinds of leakage by disallowing side effects. Side effects are needed to either transmit data or to store it aside. Specifically, MI restricts the application’s server-side logic to a purely-declarative programming language thereby preventing data leakage, while still allowing applications to process user data.

4 DESIGN

As a proof-of-concept for MI we have implemented Axiom, a MIP intended to be provided as a service (Paas). In this section, we describe key characteristics of the design of Axiom intended to make our approach to MI practical and scalable.

4.1 A DSL for Defining Logic

To allow applications to define their logic, Axiom provides a purely-declarative, logic programming DSL, implemented as an internal DSL over Clojure [Hickey 2008]. With this DSL, application logic is defined as a set of rules. A rule is a declarative definition of the relationship between facts it takes as input, and the derived facts it produces as output.

For example, consider a simple social network in which users can post “tweets,” and can follow other users, such that the tweets made by the users they follow would appear in their timelines. The logic of such a network can be defined using a rule that matches facts corresponding to the phrase “u₁ follows u₂”, and facts corresponding to “u₂ tweeted T”, and generate a timeline entry corresponding to “T should appear in u₁’s timeline”. This timeline entry is a derived fact named after the rule.

The DSL rules also permit the use of guards, which allow filtering of facts based on their values, the derivation of new values, and extraction of multiple values from a single value (e.g., indexing tweets according to hash-tags mentioned in them).

One specific guard provided in our DSL (the by guard) is responsible for integrity. It asserts that a fact the rule relates to is attributed to a certain user. For example, it can be used to assert that the fact “Alice follows Bob” is indeed attributed to Alice. Facts that do not meet the criterion posed by the by guard are ignored by such a rule.
4.2 Permacode

To allow logic to be objective, we introduce a novel module system named *Permacode*.\(^1\) In Axiom Permacode (short for “permanent code”) module definitions are guaranteed to always behave the same way. Permacode derives its name for the term “permalink”, which refers to a URL that is guaranteed to always link to the same content. With Permacode, expressions consisting of nothing but constants and definitions coming from Permacode modules will always evaluate to the same values.

This is achieved using a combination of the two elements described in Sect. 3.2. To achieve purity, Permacode provides a DSL that is a purely-functional subset of Clojure. It presents one macro (`pure`), which examines the underlying code at compile time and validates it against a white-list of pure special forms and standard-library functions. If valid, the underlying code is returned unchanged.

To achieve content addressing, Permacode uses a cryptographic hash function (SHA-256) on the contents of a module to determine its name. One Permacode module can reference another, in which case the hash code of the referenced module becomes part of content of the referencing module, and thus affects its own hash code. This makes Permacode modules form a Merkle Tree [Merkle 1988].

Axiom takes application logic in the form of Permacode modules. By doing so, it guarantees the logic to lack any side effects, and to never change. By restricting the definition of the DSL to the declarative subset defined by Permacode, Axiom is able to accept rules and can guarantee that logic that runs from within its guards will not harm confidentiality.

Because Axiom names the derived facts after the rules that created them, their names change as their code is updated. As result, derived facts from different versions of the application can coexist, and updates to one kind of derived facts are always made according to the same logic.

This also has integrity benefits. In case multiple applications are hosted on the same instance of Axiom, it is possible one will try to create fake results, and masquerade them as legitimate results provided by another application. However, by using Permacode this becomes practically impossible, since forging a derived fact becomes as hard as performing a second pre-image attack on SHA256 [Gilbert and Handschuh 2003; Rogaway and Shrimpton 2004].

4.3 Event Sourcing

For the sake of keeping data stored in Axiom objective (as discussed in Sect. 3.1), we designed Axiom as an event sourcing system. An Axiom event corresponds to the concept of an axiom, as described in Sect. 2.2.

We define an event as a tuple \( (d, w, r, c, t) \in E \), where \( d \) is a data tuple representing either a fact or a rule, \( w \subseteq U \) is a writers-set, \( r \subseteq U \) is a readers-set, \( c \in \mathbb{Z} \) represents the quantitative change this event represents \((c = 1 \text{ for addition, } c = -1 \text{ for removal})\), and \( t \) is a unique identifier.

Axiom takes the collection \( E \) of these events as its source of truth. Partial state, as seen by user \( u \), can be built in two steps. First, we define the subset \( V_u \subseteq E \) of the events visible by user \( u \) as: \( V_u = \{ (d, w, r, c, t) | (d, w, r, c, t) \in E \land u \in r \} \). Then we translate these events to partial state by grouping \( V_u \) according to \( d \), \( w \), and \( r \), summing \( c \).

\(^1\)http://axiom-clj.org/permacode.html
Axiom itself never accumulates state. It receives events from the client, and sends events back. Axiom provides a client-side library\(^2\) which provides abstractions for accumulating events into state, as seen from the eyes of a single user, on the client side.

### 4.4 Gateway Tier

For sending and receiving events, the clients communicate with Axiom’s gateway tier.\(^3\) The gateway tier can be seen as the boundary between Axiom and the outside world. As such, it handles the connection to the clients (through WebSockets [Qveflander 2010]), authentication, which is abstracted out through a plug-in architecture, and access control.

Axiom’s access control is decoupled from any application, and follows Reqs. 4 and 6 of Def. 2. This means that when a client which authenticated as user \(u\) sends event \((d, w, r, c, t) \in E\) to Axiom, the gateway tier will accept it if and only if \(u \in w\). If a client authenticated as user \(u\) registers to receive a subset \(E' \subseteq E\) of the events stored by Axiom, the gateway tier will send the client only those \(u\) is allowed to see, i.e., \(E' \cap V_u\).

To implement access control, Axiom takes a two-step approach. First it defines named groups. These are conceptual groups of users which are named after a common property. For example, all “friends” of user \(u\) can be placed in a named group.

Named groups are populated using rules, and are named accordingly, prefixed with the hash of their version. This makes their content objective, e.g., defines the exact criteria for user \(u_1\) to be “friends” with user \(u\) in a specific version of the application.

The second step is constructing a representation of set \(U\) associated with a certain user. This is an intersection of the singleton set consisting of the user (represented by his or her user ID), and all the named-groups this user is a member of. This set represents the smallest set the user is a member of, in the sense that for every set \(U'\), \(u \in U' \iff U \subseteq U'\).

Axiom uses intersets\(^4\) to represent sets. In this representation, named groups are represented symbolically (i.e., mention named groups, and do not list the actual users included in them). Intersection of two intersets, and testing if one interset is a subset of another are implemented efficiently on intersets.

### 4.5 Information Tier

When an event coming from the client passes through the gateway-tier, it reaches Axiom’s information-tier. This tier takes its name from the fact that it holds both data and logic. At the center of the information-tier, Axiom uses an event broker (RabbitMQ)\(^5\) that spreads events through its different components. Events are stored in a NoSQL database (Amazon’s DynamoDB),\(^6\) but are also processed to produce new events.

#### 4.5.1 Migration

New versions of application logic are provided by events pointing Axiom to a git repository containing the new version. This starts a migration process, in which Axiom fetches the sources from the git repository, publishes each source file as a Permacode module, and applies the logic on all existing fact events.\(^7\)

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\(^2\)http://axiom-clj.org/axiom-cljs.html
\(^3\)http://axiom-clj.org/gateway.html
\(^4\)http://axiom-clj.org/cloudlog.interset.html
\(^5\)https://www.rabbitmq.com/
\(^6\)https://aws.amazon.com/dynamodb/
\(^7\)http://axiom-clj.org/migrator.html
4.5.2 Topologies. Once the migration is complete, Axiom deploys a topology to handle further events coming in real time. Axiom uses Apache Storm [Iqbal and Soomro 2015], a platform designed for executing real-time analytics on big data. Although not intended for this use, Axiom uses it to apply application logic at real time. Storm is known to perform computation with low latency and high throughput, be fault tolerant and highly available. By using it, Axiom inherits these guarantees.

4.6 Event Processing

Regardless of when events are being processed, be it during a migration of new logic, or when an existing topology processes a new event, Axiom uses the same mechanism for processing events.\footnote{http://axiom-clj.org/cloudlog-events.html}

Given rule \( R \) we define its initial event as \( e_R = (R, nsR, U, 1, t) \), where \( nsR \) is the namespace \( R \) is defined in (recall that \( R \) is defined in a Permacode module for which the name is based on a hash of the module’s content), \( U \) is the universal user set, and \( t \) is an arbitrary unique ID.

**4.6.1 Product.** Given a fact event \( e_F = (F, w_F, r_F, c_F, t_F) \) and a rule event \( e_R = (R, w_R, r_R, c_R, t_R) \) we define the product of these events \( e = (d, w, r, c, t) = e_R \otimes e_F \) as follows: \( d \) is the result of applying \( R \) to \( F \). This can be either a representation of a residual rule (in case of a join), or a derived fact. Because the rule is responsible for its own integrity, the resulting event’s writers set \( w = w_R \) is taken directly from the rule, and the fact’s writers set is ignored.

For the readers set, we take an intersection: \( r = r_R \cap r_F \). A user \( u \) may read \( d \) if and only if that user is eligible to read both \( R \) and \( F \). With access to \( R \) and \( F \), user \( u \) could compute \( d \). By setting \( r \) this way we make sure the product operation does not change the confidentiality properties of \( R \) and \( F \).

The quantitative change \( c = c_R \cdot c_F \) is the numeric product of the changes \( c_R \) and \( c_F \). If the same fact \( F \) has been added \( m \) times, and the same matching rule \( R \) has been added \( n \) times, we get the result \( d \) as if we applied every rule to every fact, \( m \cdot n \) times.

The unique ID \( t \) is calculated as a hash of both IDs: \( t = hash (t_R, t_F) \). This is to make sure that the new event has a unique ID, but if the same product is calculated twice, we will receive an event with the same ID. This is important for fault tolerance, since Apache Storm provides an at-least-once guarantee, meaning they may re-emit events to cope with failures. Having a consistent event ID helps in making sure we do not count duplicate events.

Note that we simplified the definition of the product for readability. In reality, applying a rule to a fact results in a set of results, and not (necessarily) a single result \( d \). This means that the product operation results in a set of events, and not necessarily a single event \( e \).

**4.6.2 Event Matching.** An Axiom event processor is an object that receives a sequence of fact and rule events, and emits a sequence of their products. An event processor stores all events it received, and accesses this storage as needed. When receiving a fact event, it fetches all rule events that share the same key, and computes their mutual products. Similarly, when receiving a rule event, it fetches all fact events with a matching key, and emits all their products.

Axiom uses DynamoDB for storage. This database is eventually consistent, meaning an event that has been stored at time \( t_1 \) may not necessarily be visible when queried at time \( t_2 > t_1 \), in cases when \( t_2 - t_1 < \Delta t \),
where $\Delta t$ is the time it takes data to spread across all replicas inside DynamoDB. To overcome this problem, Axiom’s event processors use a cache that stores events in memory for a given period of time. Axiom configures its Storm topologies in such a way that guarantees that events with a certain key will always be processed by the same event processor, making sure that even events that are emitted within $\Delta t$ of one another will take each other into consideration.

5 EVALUATION AND DISCUSSION

For a concrete demonstration of MI we have implemented a simple micro-blogging application inspired by Twitter as our test application. TweetMI, pronounced Tweet-Me, is a web application that allows its users to post tweets, follow other users, and view their timeline. A user’s timeline consists of: (1) tweets made by the user, (2) tweets made by the user’s followees (user whom that user follows), and (3) tweets in which the user’s handle (@user-id) appears.

In this section we reflect on the concerns described in Sect. 1 and discuss how they are met by MI on the implementation of TweetMI (App. A).

5.1 Responsibility Over User Data

TweetMI, the example application we chose for this paper, is a social network. As such, its business logic focuses on spreading information among users. Keeping information private, however, may seem as going against the very nature of social media. For this reason, MI makes this the concern of the MIP and not the application.

This can be demonstrated in TweetMI, by adding a requirement for supporting restricted tweets – tweets visible only by users whom the tweet’s author follows. For example, if user ‘alice’ posts a restricted tweet, only the users ‘alice’ follow can see this tweet. This way, by following or un-following other users, she can decide who is allowed to read her restricted tweets.

Traditionally, adding such a feature would include changes in the client (to introduce the ability to mark a tweet as restricted), the data model (addition of a Boolean field to indicate whether the tweet is restricted or not) and the access control logic (avoid displaying restricted tweets to users whom the tweet’s author does not follow.

With MI, this change is made on the client-side only. When creating facts, the client determines their associated readers-sets. To allow restricted tweets to be created, the client code must be updated to allow its users the choice between setting the tweet’s readers-set to $U$ for unrestricted tweets, and a named group of users whom the user operating the client is following, for restricted tweets.

By setting the readers-set according to the user’s wishes the application concluded it job in protecting this tweet. Any further processing done with this fact is guaranteed to respect this choice, by following the logic described in Sect. 4.6. This decoupling makes the application responsible for authorization, but not for access control.

5.2 Protecting Against Vulnerabilities

Not trusting the application with user data is key in making MI secure. As an example, consider the following vulnerability in TweetMI. Suppose that in one of the rules we accidentally try to call `eval` (the Clojure function that executes an s-expression) on data taken from a fact to which the rule is applied. Traditionally,
this may leave the application vulnerable to code injection attacks, allowing attackers to execute their own code from within the rule. This would enable an attacker to compromise confidentiality (leak information out), integrity (make unauthorized updates), and availability (cause a server failure).

Fortunately, Axiom, uses Permacode as a sandbox around application logic. Clojure’s eval function, being imperative, is not allowed there. A replacement function provided by Permacode for evaluating Permacode functions can be used from within rules, but only allows purely-declarative code to run. Such code, even if injected by an attacker, can only change the output of this rule, thus impairing the integrity of the application, in a way that is consistent with it having a bug. Confidentiality and availability are not harmed.

As result, out of the OWASP Top 10 [van der Stock et al. 2017], the only vulnerability that needs to concern an MI application is A7:2017–Cross-Site Scripting, which is the only client-side vulnerability on that list. The rest need to concern the MIP developers, but not the application developers.

5.3 Denormalization

MI holds the key to freeing application developers from having to worry about denormalization in that the MIP encapsulates both the data and the logic the application applies to the data. With access to both logic and data, the MIP can be responsible for applying the logic, whenever it needs to be applied, to the data.

In TweetMI, three rules perform denormalization for three different reasons. One rule takes facts representing the phrase “$u_1$ follows $u_2$”, and generates a derived fact representing the phrase “$u_2$ is followed by $u_1$”. The rationale behind such a rule is that while the raw fact is keyed by the follower ($u_1$), the derived fact created by the rule is keyed by the followee ($u_2$). This facilitates answering the question “who follows user u?” efficiently.

Another rule takes facts that correspond to the phrases: “$u_1$ follows $u_2$”, and “$u_2$ tweeted $T$”, and creates derived facts corresponding to the phrase “$T$ should appear in $u_1$’s timeline”.

This rule performs a join operation between the two kinds of raw facts it takes. By performing it at update-time, the application’s query latency is improved significantly.

The third rule takes facts that correspond to the phrase “$u$ tweeted $T$”, and creates derived facts corresponding to the phrase “$u$ was mentioned in tweet $T$”. The rule extracts the identity of zero or more users from the text itself, by tokenizing it and identifying tokens of the form @user-id. This allows adding tweets to the timelines of users who were mentioned in them, without having to scan all the tweets for such mentions.

In all three examples, the rules specified the format of the denormalized data and the logic of how it is to be derived from raw data.

Under the hood, these rules are interpreted as many small procedures that operate at different times. For example, when a tweet is being updated (e.g., the text is being edited), Axiom fetches all followers of the tweet’s author and updates the corresponding derived facts. The rule tracking users mentioned in tweets will create facts for new user handles, remove facts for handles that were removed, and not touch ones that remain in the updated text.

All these imperative procedures are derived automatically by Axiom, without the rule having (or being able) to specify them.
5.4 Supporting Software Evolution

Consider we wish to make two changes to TweetMI: (1) refine the tokenization we perform on tweets when searching for mentioned user handles, and (2) remove support for restricted tweets (a feature we have added in Sect. 5.1). These changes raise two challenges, namely performing zero-downtime data migration, and respecting authorization rules set by older versions, while not complicating the logic in newer versions.

Performing these two changes to an application based on Axiom is as simple as performing the changes in the source code and re-deploying the application. The first change is done in a rule. Since the code is located in Permacode modules, by updating the rule, its namespace, which is derived from a hash of its content, changes. This means that we did not update a rule, but rather created a new one. After deploying the code, Axiom’s migrator (Sect. 4.5) starts applying the rule to all relevant facts, creating derived facts in the new rule’s namespace. These facts do not replace the old ones, created by the old version of the rule. Both versions co-exist until the old version is explicitly pruned. This allows the old version to be in effect for the duration of the migration process, and even afterwards, to facilitate A/B testing, gradual feature rollout and fast roll-back in case a bug is found in the new version.

The second change is a client-side change, because restricted tweets were implemented as a client-side only feature. Canceling the feature is as simple as rolling back the code to its original version, before the change was originally introduced.

While rolling back the change could have been done in a system not supporting MI as well, doing so would have had undesired consequences. In traditional applications, where access control is coupled with authorization, the two happen in distinct times. Authorization happens when a user decides to designate a tweet as restricted. This restriction is enforced by the application’s access control, when another user is attempting to read that tweet.

When removing both the authorization and access-control portions of this feature, old tweets that were already marked restricted by their authors would be visible to all users. This is obviously not desired. To protect against this, a traditional application would have to retain the access-control logic handling restricted tweets for as long as restricted tweets still exist as part of the application’s state.

With MI, access-control logic is constant, as defined by Def. 2. The MIP respects the readers-sets assigned to facts. As long as restricted tweets are retained, the MIP will respect their readers-sets and only present them to authorized users. The application completed its part when it created these facts with the correct readers-sets.

5.5 Regulatory Compliance

In TweetMI, only two kinds of facts comprise its user data. In both kinds, the key happens to be the ID of the user who creates (and thus “owns”) them. If TweetMI were subject to regulatory requirements, such as GDPR’s right to erasure, its developers would have no problem providing a feature that allows a user to erase all his or her data.

Unfortunately, in real-life applications there may be tens to hundreds of different kinds of facts,\(^9\) where it is not guaranteed that the user owning the fact can be directly inferred from its data. This makes it significantly harder to comply with such regulation.

\(^9\)One can draw intuition from the number of tables an application requires in traditional applications based on relational database.
However, every fact is annotated with a writers-set. This set defines who owns the fact. Having this annotation on every fact allows Axiom itself to comply with the regulation, without involving the application.

For example, to comply with the right to erasure, we can add a feature to Axiom that will allow a user to erase all facts that are owned solely by them. This can be done by, e.g., adding a secondary index, indexing events by the user ID in their writers-set. Adding this index is a one-time effort, both in terms of programming and in terms of applying it to existing data. Then, all applications loaded on Axiom can enjoy the feature of finding and removing all facts belonging to a single user.

6 VALIDITY AND THREATS TO VALIDITY

MI can be characterized as disruptive innovation [Christensen 1997]. As such it starts with a conceptual idea (“Eureka!”) and faces feasibility concerns (“it will never work!”), performance-related concerns (“it might work but it cannot be made to work efficiently!”), and concerns that are social in nature (“No one would want or be able to use it!”).

This paper presents the concept of MI and concentrates on the feasibility phase (is it possible to support MI?). As evidence we submit a substantial software artifact, Axiom, that validates the feasibility claim [Shaw 2002]. We make no claims regarding performance (e.g., runtime or memory usage) due to a lack of a baseline to compare against, although our design choices (e.g., the use of Apache Storm) enable scalability in principle. Nor do we make any claims about the usability of our system (e.g., will SaaS programmers be willing to use Clojure?), although our experience implementing TweetMI over MI was positive. Of course, future work can build upon our work to propose ways to improve performance and usability, comparing future implementations to ours.

Axiom is written in Clojure. We selected Clojure thanks to its combination of expressiveness on the one hand, and the richness of its ecosystem on the other hand. The choice of Clojure was also driven by the ease of creating DSLs, along with access to the vast Java ecosystem, available through Clojure’s Java interoperability. Axiom’s code consists of 3442 lines of Clojure code, and 258 lines of ClojureScript [McGranaghan 2011] code (Axiom’s client-side library). Its documentation is bundled with its tests, and the examples in the documents run as Axiom’s unit tests, assuring these examples are always up to date.

The development of Axiom was driven by the five concerns related to information that we introduced as criteria for MI. Obviously, there are other concerns that could have been raised. However, this threat to validity is mitigated by the fact that abstracting any of these concerns is a challenge in and by itself and collectively these concerns provide a nontrivial benchmark.

Part of our observations about the behavior of MI is based on our own experience developing TweetMI. Naturally, a real-life application such as the equivalent of Twitter or Facebook would be more demanding, and these observations should be substantiated in other applications too. However, TweetMI merely serves here as a part of the demonstration of the feasibility of MI, for which even one example is meaningful.

Table 1 shows latency measurements we took with TweetMI. We measured the latency in milliseconds it takes a tweet to arrive to the same user’s timeline (first row), and to a follower’s timeline (second row). In the former case, fact events describing the tweet are processed by a single link to create the result event, which is sent to the client. In the latter case, fact events arrive at a rule which produces derived facts. These facts then arrive at another rule, which creates the result events.
Table 1. Latency measurement results measured in milliseconds, averaged over 20 runs

| Number of Links | Min  | Max  | Average |
|-----------------|------|------|---------|
| 1               | 84   | 154  | 117.2   |
| 2               | 108  | 186  | 144.3   |

The ~30 milliseconds difference between the two measurements provides an indication of the latency of a single link, including processing time, and the latencies of the event broker and the database. Assuming links are comparable (data passes through the same event broker and is stored on the same database), about 85 milliseconds in each case are attributed to the global overhead, including time spent on the client (measurements were made end-to-end on the client side), communication latency and time spent at the gateway tier.

7 RELATED WORK

While there is a multitude of approaches to application development with significant trade-offs between one another, the closest work to ours in terms of the problem addressed is Solid [Mansour et al. 2016]. Solid is a set of conventions that allow building social applications in a decentralized manner. But even Solid, which seems to address a similar need, actually adopts a different approach. Specifically, Solid allows each user to choose his or her own information solution, but this comes at the cost of not being able to run any update-time logic on the server-side, which is a crucial factor in large-scale applications.

In Solid, the application is implemented on clients. Users of Solid applications can choose a personal data store, which implements the Linked Data Platform (LDP) web standard to store their personal data. The application sends this server requests to update the user’s data, and queries, which are answered by following links on the data, which may cross over to data stored on other servers.

Solid provides a data ownership model similar to our own, in which the user is the sole owner of his or her data, capable of restricting access and removing the data at all times. In Solid this is achieved by decoupling the data storage concern from the application completely, in the sense that users are free to choose their own personal data stores, regardless of the applications they use.

However, this freedom comes at a cost. With data for different users residing on different servers, it is unclear how efficient would a query in Solid be, if it spans different servers. Even if LDPs employ clever heuristics to pre-fetch data from other LDPs if it seems relevant to queries they are asked, it is still unclear how data ownership is handled in such cases.

Furthermore, it is unclear how features that require applying logic on data are implemented in applications based on Solid. For example, how can a Solid Twitter-like application index tweets according to users mentioned in them. A Solid application can perform this denormalization in a similar way to traditional applications, as tweets are created, with similar limitations. However, it is unclear how this can be done on existing data, when such a feature is added as an evolutionary step when tweets already exist.

Similar to Solid, an Axiom application is implemented primarily on the client side. However, Axiom does allow limited server-side logic to be specified by an application. This logic allows data denormalization that is missing in Solid. This comes at the price that all users using one application must trust the same MIP.

https://github.com/linkeddata/cimba
provider. However, this is still a big improvement relative to the state of the art, in which users need to trust the application provider for every application they use, with their data.

7.1 Triggers, Stored Procedures, and Row-Level Security
Relational databases have the ability to store data-aware functions and update procedures, and to invoke them automatically upon changes to the data. Some databases go beyond this and support row-level security, where user-provided functions are used to determine if a certain user should or should not be allowed to access a certain record. These database features allow for developers to make access control and denormalization part of the database schema, thus freeing the logic tier from having to worry about these aspects. In fact, such databases can be accessed directly from the client-side, as they apply access control by themselves.

However, compared to the traditional three-tier architecture, in which access control and denormalization are applied at the logic-tier, this is merely a change of venue. The same logic, written in a different language, runs in the data-tier instead of the logic-tier.

In comparison, M1 provides a separation between an application-agnostic MIP and application-specific logic that does not have access to the data. Using stored procedures and triggers may raise a database to the level of an AP (Def. 1, Sect. 2.1), but it needs more than that to become a MIP. Specifically, stored procedures have unrestricted access to the database. Code injection into a stored procedure (e.g., through the use of Dynamic SQL) can provide an attacker the ability to steal and corrupt user data.

7.2 Access Control Lists
With M1, every piece of data is annotated with a readers-set and a writers-set to specify user permissions over it. This may seem similar to Access Control Lists (ACL) [Karjoth et al. 2008], an access-control approach which attaches a list of allowed users for each operation (e.g., read, write, manage permissions, etc) to each resource (e.g., file, directory, record, etc).

While both approaches are similar in that permissions are provided as annotations on objects, making access control generic, these two approaches feature some fundamental differences.

First, they are different in how they treat integrity. M1 allows any user to create any piece of data, given that the user attributes this piece of data to herself. In contrast, ACL typically uses hierarchy to authorize the creation of new objects. For example, the ACL on a directory determines who is allowed to create new files in it.

Second, ACL, does not have a notion of user groups. its group-aware variant – ACLg, does have a notion of user groups, but requires groups to be managed explicitly. M1, in contrast, allows for user group membership to be derived automatically from the application logic.

Third, ACL does not have a sense of derived data, and does not propagate permissions to computational products. In Sect. 4.6 we describe how the MIP propagates permissions to derived facts, so that the application’s implementation does not get a chance to get it wrong.

7.3 Access Control for SaaS
Like ACL, some access control models have been developed specifically for SaaS. S-RBAC is one, which extends RBAC [Ferraiolo et al. 1995] with a hierarchical model to address applications in which multiple customers share the same instance [Li et al. 2010].
Unfortunately, this model assumes that SaaS applications maintain some of the properties of enterprise applications, in that they serve organizations that have little interaction with one another. Social networks are a counter-example, since in a social network every single user can be associated (follow, be friends with, etc.) with any other user. As result, roles should be applied at the granularity of a single user. At this level of granularity, RBAC-base approaches lose their advantage relative to ACL.

8 CONCLUSION

In this paper we present a novel way to abstract away what is currently a core part of every application: the management of information. By doing so, we move many of the concerns every application needs to deal with today, to a single piece of software – namely, the MIP, similar to how managed memory moved memory safety concerns previously dealt with by individual programs to a single piece of software – namely, the virtual machine.

Trust is a key concept in MI. By not trusting applications, the MIP relieves the application of its traditional responsibility as the gate keeper of user data. A client representing a user is expected to do so truthfully (i.e., create facts with readers and writers-sets that correspond to the user’s expectations), but once the fact has been created, it is no longer the application’s concern. This means that the application has almost no consequence for any of the various aspects of information security. Indeed, out of the nine application-level vulnerabilities listed in the 2017’s OWASP Top 10 [van der Stock et al. 2017] (Sect. 5.2), only one remains a concern for Axiom applications, being a client-side vulnerability.

Obviously, trust has to go somewhere, and in MI both users and application developers need to trust the MIP. However, the MIP has more potential in becoming trustworthy than any given application, since it has a small attack surface relative to typical SaaS applications.

From the application developer’s perspective, MI provides a way to enjoy the benefits of SaaS while deferring much of its challenges to the MIP. In many ways, MI brings software developers back to being just that. They are entrusted to provide good software, and are exempt from the need to host it, secure it, and comply with data protection regulations.

From the end user’s perspective, MI brings an ownership model in which users are once again in control over their own data.

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A TWEETMI EXAMPLE

To give the reader a concrete sense of what it means to develop an application under MI, we describe here the implementation of TweetMI. App. A.1 provides the complete requirements for this application. App. A.2
describes how the client manages state. App. A.3 describes TweetMI’s the update-time rules, and App. A.4 describes TweetMI’s timeline query, and the clauses that implement it.

A.1 TweetMI Specification

TweetMI’s user interface has three panes: (I) a tweet pane, in which users can create, update or delete their own tweets, (II) a following pane, in which a user can control who they follow and see who follows them, and (III) a timeline pane, in which users can see their timelines.

The timeline of user $A$ consists of tweets made by either (I) user $B$, whom user $A$ follows, or (II) user $A$ him/herself. The timeline is sorted according to the time of the tweet in descending order, so that the most recent tweets will be presented first. Since the complete timeline can be very big and contain many old tweets, TweetMI only shows the most recent tweets (initially, tweets from the last 7 days). If a user wishes to see older tweets, clicking a button at the bottom of the list fetches older tweets.

The pane for user $A$ displays two lists: (I) a list of followers (any user $B$ who follows user $A$), and a list of followees (any user $C$ who user $A$ follows). Next to each user name there is a “follow” or an “unfollow” button, depending on whether or not user $A$ follows them already. Clicking a “follow” button attached to user $B$ will cause user $A$ to follow user $B$, causing user $B$’s tweets to appear in user $A$’s timeline, user $B$ to appear in user $A$’s followees list, and the button to change its caption to “unfollow”. Pressing an “unfollow” button attached to user $B$ causes user $A$ to no longer follow user $B$ and user $B$’s tweets to be removed from $A$’s timeline.

Tweets can be either public, i.e., visible to all users, or restricted, in which case they are only visible to followees. For example, if user $A$ follows user $B$, and user $B$ follows user $C$, if user $B$ tweets a public tweet, user $A$ will see it. However, if user $B$ tweets a restricted tweet, user $A$ will not be able to see it. Only if user $C$ starts following user $B$ can user $C$ see user $B$’s restricted tweets.\footnote{Twitter uses a similar criterion for authorizing private messages: https://help.twitter.com/en/using-twitter/direct-messages}

A.2 Managing State

In an MI application, the client is responsible for managing data for the user it represents. In TweetMI, the client is written in ClojureScript. To synchronize the state with the user interface, TweetMI uses Reagent\footnote{https://github.com/reagent-project/reagent} a ClojureScript adapter for React.\footnote{https://reactjs.org} React and Reagent allow the user interface to be defined as declarative functions, mapping the state into its presentation, in the form of HTML elements. Behind the scenes, these libraries are responsible for tracking changes in the data, mapping them to changes in the presentation.

A.2.1 Managing Tweets.

View Definition. Listing 1 shows the view definition used by the TweetMI client to bind tweets made by a certain user. Line 1 defines the view’s name and arguments (the argument $me$ in this case, representing the user ID).

Line 2 provides the pattern of the fact this view corresponds to. In this case, the fact’s name is tweetmi:tweeted, its key (the user who wrote the tweet) is bound to the view’s parameter, $me$. This
Listing 1. The tweets view definition

(defview tweet-view [me]
  [:tweetmi/tweeted me text ts attrs]
  :store-in (reagent/atom nil)
  :order-by (- ts)
  :writers #{$user}
  :readers (if (:restricted attrs)
      #{{[:tweetmi.core/follower me]}
        #{}})
)

means that the view represents, at one time, only tweets by a single user – the user logged in to the client. The view’s data arguments, text, ts, and attrs are given as well.

Lines 3 to 8 define the view’s optional properties. Line 3 assigns a Reagent atom as the mutable container for the view. This allows Reagent to track updates to the state, and reflect them to the presentation.

Line 4 defines the sorting order. By sorting according to (~ ts) (the negated timestamp value) we actually sort the facts in descending time order.

Lines 5 to 8 define the readers and writers set for the tweet. On line 5 we attribute the tweet to the logged-in user (represented by $user), by setting the writer set to be a user group that consists of only that user. This value is the default, and is given here for introductory purposes only.

Lines 6 to 8 define the reader set conditionally, depending on the optional attribute :restricted. If this attribute is present and true, the reader set is set to a parametric group [:tweetmi.core/follower me] consisting of users who the current user (me) follows. If the attribute :restricted is false or is not defined, we define the readers set to be the universal set #{}. An interset is a set represented as an intersection of groups. If no groups are intersected, the set is universal.

Using the View Function. The view is represented as a ClojureScript function. This function, which derives its name from the view, takes n 1 arguments, where n is the number of parameters the view takes. As first argument, the function takes a host map, which represents the connection to Axiom. The rest of the arguments correspond to the view parameters. The view function returns a sequence of records (Clojure maps) representing the different facts in the view.

Listing 2 shows the function that renders the user interface that allows users to view and edit their own tweets. The function takes as parameter the host map, and returns a nested structure of Clojure vectors representing an HTML fragment. Reagent, along with the underlying React, is responsible to call this function for every state change that affects it, and to translate the vectors into DOM updates.

Line 10 calls the view function tweet-view, giving it the host map and the current user (user host) as parameters. The sequence of records is stored in variable tweets. Line 11 extracts the function add from the returned sequence’s metadata. This function adds a new record to the view. It is used in lines 14 and 17 in the :on-click callback functions associated with the "tweet!" and "tweet_restricted!" buttons. When either button is clicked, a new record with an empty text field and a current time (returned by the :time function provided by the host map) is created. The "tweet_restricted!" button also sets the :restricted attribute to true.

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[14] Document Object Model (DOM): A tree of visual objects that correspond to elements in an HTML document, facilitating programmatic manipulation.
Listing 2. Component function for editing tweets

(defn tweets-pane [host]
  (let [tweets (tweet-view host (user host))
        {keys [add]} (meta tweets)]
    [:div
      [:h2 "Tweets"]
      [:button {:on-click #(add {:text "", :ts ((:time host)) :attrs {}})}] "tweet!"
      [:button {:on-click #(add {:text "", :ts ((:time host)) :attrs {restricted true}})}] "tweet restricted!"
      [:ul
        (for [{:keys [me text ts attrs swap! del!]} tweets]
          [:li {:key ts}
            [:input {:value text :on-change #(swap! assoc :text (.target.value %)) :style {:color (if (restricted attrs) "red" "black")}}]
            [:button {:on-click del!} "X"])]))]

Lines 21 to 28 display the list of existing tweets, allowing the user to update and delete each of them. Line 22 uses Clojure’s for macro, binding the text, ts and attrs fields from each record to variables of the same names. In addition, two functions: swap! and del! which are provided by the view are also extracted.

On line 23 a list item (li) is rendered. Reagent requires that each item in a list (as the one returned by the for macro) have a unique key, so we use ts for this purpose. Lines 24 to 27 define an input box for editing the tweet. Its :value attribute is set to the text field, to show the content of the tweet. Its :on-change event handler uses the record’s swap! function to update this record, updating its :text field to the .value attribute of the input box at the time the event fired. Calling the swap! function causes the associated fact to be updated both locally on the client, and in Axiom, by generating a change event and sending it to the host. The :style attribute defined on lines 26 and 27 sets the tweet’s text color to red or black, depending on whether the tweet is restricted or not. Line 28 creates a button associated with the del! function, which when invoked deletes the associated fact.

A.2.2 Follow Button. Listing 3 shows the function rendering the follow button, and its associated view. The follow-view view defined in lines 29 to 31 defines a view for :tweetmi/follows facts, that indicate that user u1 follows user u2. Unlike the tweet-view view defined in Listing 1, here the view arguments appear in both the key (u1) and the data elements (u2) of the fact pattern. This means that the view is Boolean. It indicates whether or not u1 follows u2. If yes, the sequence returned by the view function will contain one element, and if not, the sequence will be empty.

Lines 33 to 41 show the component function that renders the follow/unfollow button. It takes as arguments both the current user (u1) and the user to follow or unfollow (u2), and renders, based on whether the sequence is empty or not a “follow” button, which when clicked will add an element to the collection, effectively making u1 follow u2, or an “unfollow” button, which when clicked will delete the single element that exists in the sequence, making u1 stop following u2.
A.3 Update-Time Logic

Update-time logic is required to perform computation for which waiting to query-time will be too late. In the case of TweetMI, this includes pre-calculating user timelines, based on users they follow and their tweets, and indexing tweets according to text that appears in them.

The complete logic needs to take care of one additional concern: pagination.

Pagination. Pagination is the practice of limiting the amount of data received from a server, to save resources on both the client and the server. A practical application needs to make sure that any given client request is answered with a bound amount of data. This can be addressed as a generic server-side rule, limiting all responses to a pre-determined size, but by doing so we may be leaving out important information.

To fix this problem for TweetMI, we index tweets according to the day in which they were created. Each tweet has a ts field, which contains the UNIX time (in milliseconds) of its creation. By dividing this number by the number of milliseconds in a day (integer division) we can get a number that can act as an effective key for tweets. Users are often interested in recent tweets and are less interested in older ones. A timeline is therefore organized in time-descending order. To only get tweets we need we can only fetch tweets that were created on a certain day-range. We can extend that range as users look deeper and deeper into their timelines.

A.3.1 Followee Tweets. Listing 4 shows the definition of the followee-tweets rule. Lines 42 and 43 define the helper function ts-to-day, which converts a timestamp into a day number, as needed for pagination. This is an ordinary Clojure function. The rule itself is given on lines 45 to 48. Line 45 defines the format of the derived facts to be generated by this rule. The key to these facts is compound, consisting of both the user ID for the user whose timeline this is, and the day number in which the tweet has been written. The data elements are the author of the tweet, its text, and its timestamp (ts).

On line 45 we use a let guard to calculate the tweet’s day based on its timestamp, by calling ts-to-day.

A.4 Queries and Clauses

Now that we have defined our rules for creating derived facts, we can define the timeline query to aggregate them.
Listing 4. The followee-tweet rule

(defn ts-to-day [ts]
  (quot ts msec-in-day))

(defrule followee-tweets [[user day] author text ts]
  [:tweetmi/follows user author] (clg/by user)
  [:tweetmi/tweeted author text ts attrs] (clg/by author)
  (let [day (ts-to-day ts)]))

Listing 5. Timeline query

(defquery timeline-query [me day-from day-to]
  [:tweetmi/timeline me day-from day-to -> author tweet ts]
  :store-in (reagent/atom nil)
  :order-by (- ts))

Listing 6. Timeline clause

(defn days-in-range [from-day to-day]
  (let [day-range (range from-day to-day)]
    (if (> (count day-range) 20)
      []
      day-range)))

(defclause tl-1
  [:tweetmi/timeline user from-day to-day -> author text ts]
  (for [day (days-in-range from-day to-day)]
    [followee-tweets [user day] author text ts]))

(defclause tl-2
  [:tweetmi/timeline user from-day to-day -> user text ts]
  [:tweetmi/tweeted user text ts attrs] (clg/by user)
  (for [day (days-in-range from-day to-day)]
    (when (= (ts-to-day ts) day))))

Listing 5 shows the query definition for the user timeline in TweetMI. Line 29 defines the query’s name and parameters, including the user ID (me) and two parameters to identify the time-range we are interested in. These parameters (day-from and day-to) are used for pagination, to limit the query results to only those of the last few days. A user can request older tweets by clicking a button at the bottom of the list.

Line 30 provides the query’s pattern, taking the user and the day range as input, and the tweet details as output. Similar to the view definition in Listing 1, lines 31 and 32 define the storage to use a Reagent atom, and the order to be descending by time.

Like a view, a query defines a function which can be called by the functions rendering the user interface. Unlike a view, the records returned by a query do not contain mutation functions (swap! and del!), since the results cannot be updated by the client.

A.4.1 Clauses. In the server-side logic, clauses contribute answers to queries. Listing 6 shows two clauses that contribute results to the :tweetmi/timeline query. lines 53 to 57 define a function days-in-range, which converts the boundaries from-day and to-day to a Clojure sequence of days in that range. It checks that the range does not span over 20 days to protect against abuse.
The clause defined on lines 59 to 62 contributes results based on the followee-tweets rule defined in Listing 4. Line 59 provides the clause’s name, which is not referenced anywhere. Line 60 provides the signature of the query this clause is intended to answer. This signature matches the one defined in the query definition in Listing 5. Line 61 uses a for guard to iterate over the different days in the range, which is calculated by calling days-in-range. Line 62 references the followee-tweets rule, providing the user ID and a concrete day as key.

The clause defined on lines 64 to 68 contributes to the timeline tweets made by the user whose timeline we are querying. It makes direct access to :tweetmi/tweeted facts, guarded by a by guard to make sure the tweets were indeed made by the user in question. Then the for guard and the when guard are used together to make sure the day that corresponds to the tweet’s timestamp (ts) is within the requested day range.