A Data Capsule Framework For Web Services: Providing Flexible Data Access Control To Users

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Abstract

This paper introduces the notion of a secure data capsule, which refers to an encapsulation of sensitive user information (such as a credit card number) along with code that implements an interface suitable for the use of such information (such as charging for purchases) by a service (such as an online merchant). In our capsule framework, users provide their data in the form of such capsules to web services rather than raw data. Capsules can be deployed in a variety of ways, either on a trusted third party or the user’s own computer or at the service itself, through the use of a variety of hardware or software modules, such as a virtual machine monitor or trusted platform module: the only requirement is that the deployment mechanism must ensure that the user’s data is only accessed via the interface sanctioned by the user. The framework further allows an user to specify policies regarding which services or machines may host her capsule, what parties are allowed to access the interface, and with what parameters. The combination of interface restrictions and policy control lets us bound the impact of an attacker who compromises the service to gain access to the user’s capsule or a malicious insider at the service itself.

1 Introduction

Internet users today typically entrust web services with diverse data, ranging in complexity from simple credit card numbers, email addresses, and authentication credentials, to datasets as complex as stock trading strategies, web queries, movie ratings, and purchasing histories. They do so with certain expectations of “what” their data will be used for, “who” it will be shared with, and “what” part of it will be shared. These expectations are often violated in practice; there are 400 reported incidents of data loss from web services in 2009 per the Dataloss database [1], each of which exposed an average of half a million customer records outside the service hosting those records.

Such data exposure incidents can be broadly categorized into two classes: external and internal. External violations occur when an Internet attacker exploits software vulnerabilities at a web service to steal sensitive user data, e.g., credit card numbers. Software and configuration complexity are often to blame here; the web service does not benefit from these and, indeed, loses reputation as a result. Internal violations occur when a malicious insider within a web service, or even the service operator itself, abuses the possession of sensitive user data beyond what the user signed up for, e.g., by selling customer marketing data to other companies. Both external and internal violations are frequent: 65% of the afore-mentioned data exposure incidents fall in the external category, while about 30% fall in the internal category (the other 5% do not have a specified cause).

One option for a security-conscious user who wishes to limit the impact of these threats is to avoid housing her sensitive data (say, credit card number) at the service’s site altogether. She can instead host it close to herself: on her own machine. She then insists that the service access this data over the network using a purpose-specific interface. For instance, a credit card number need never be seen by a merchant; the merchant site simply needs to request for a certain charge to be made to the user’s credit card number and receive an authorization code to verify the transfer. This interface-based approach assumes that the service refactors their existing applications (e.g., shopping service) to work with such an interface. However, this client-side deployment option requires the user to have her machine online whenever the service needs to access it (a problem with recurring credit card charges, for instance) and incur bandwidth costs (which may be significant in some cases, such as data analytics).

Alternatively, the user can choose to host her data a bit further away from herself; she can enlist a “data service”, an entity administratively decoupled from the “application service” which requires access to her data. We refer to such a remote data service as a trusted third party (TTP). For instance, Amazon Payment is such a TTP that encapsulates a user’s credit card number with support for restrictions such as limit on maximum charge. This option does delegate the bandwidth consumption and reliability issues to the TTP; however, for high-bandwidth interactions, the TTP would require non-trivial provisioning cost on the user. Further, the flexibility afforded to the user in terms of policy is limited by what the data service provider offers.
Given the trade-offs of provisioning cost, performance, and level of protection against threats provided by the options of service-side data hosting, TTP-based hosting, and client-side hosting, the motivation for a flexible framework that lets a user pick a suitable deployment based on her needs is clear. In this work, we generalize the concept of interface-based access approach to re-architecting web services that supports such flexible deployment. We built a capsule framework around this notion of interface-based access allowing the freedom to enforce the interface by any number of means; administrative isolation (as in a trusted third party solution) or by software (such as a virtual machinemonitor) or hardware module (such as a trusted platform module).

Before elucidating the four main design principles that ground our capsule framework, we present an instantiation of our framework in Figure 1. In the first option shown, the user (a daytrader) reveals her trading strategy to AmeriTrade (an online brokerage service) so that AmeriTrade can execute fast trades on his behalf; however, the service is free to access the strategy as it sees fit and may exploit it to its own advantages. In the second option, AmeriTrade’s view of the data is contrained by the interface; this interface only allows AmeriTrade to report the current price of a tradable instrument, and the only information revealed is the trade the user wishes to make.

Our first design principle is that user’s data should be accessed only via a simple, narrow interface that conforms to the principle of least privilege. For instance, the only use a service has for a credit card number is to charge it; access to the number itself is not required. This let a user impose her own expectation of “what” is done with her data, rather than rely on the service to enforce it. Our main notion is that of a secure data capsule (SDaC), an encapsulation of a specific kind of data (say, a credit card number) with code that implements a well-defined and open interface suitable for the data (say, charging by a merchant). This open interface model allows other parties to provider suitable implementations, which can then be used by users in depositing their data with web services. We demonstrate broad applicability of such an interface-based model with examples from four significant application classes: (1) a daytrading service in which large data volumes of stock ticker data are parsed by complex private user queries to determine automated trading actions. (2) a targeted advertising service in which large volumes of per-user browsing history are mined. (3) a purchasing application in which the capsule proxies requests for a credit card number to a bank. (4) a provenance capsule that tracks changes to a document with those who made them.

Our second principle is allow flexible interposition of the boundary between the capsule encapsulating a user’s data and the web service; such flexibility is crucial so that users can choose suitable options to match their criticality, performance, cost, and threat model requirements. Our framework supports, in addition to a trusted third party model and client-side model, the use of trusted modules (such as a virtual machine monitor) at application services to allow secure co-location of the user’s data at the application service itself, whilst still guaranteeing interaction only via the interface. Such a co-location based hosting model addresses some of the limitations of the TTP Model: it is applicable for high-bandwidth interactions, requires no additional provisioning cost for the user, and can operate even under disconnection. As an example, a trusted virtual machine monitor can be used to logically isolate the capsule from the service. At a higher per-invocation overhead, but for stronger isolation guarantees against insider attacks, the capsule can be physically isolated from the application service on distinct hardware collocated at the provider’s site. For even stronger isolation, while avoiding provisioning costs, the capsule can be collocated with the user’s client on a separate virtual machine, but with high network overheads and reliability only as high as that of the client machine.

The third design principle is allow for fine-grained and flexible user control over how the interface to her data to her exercised and where her capsule is hosted. This lets the user impose her own requirements on “what” is done to

Figure 1: Trading Strategy Execution At AmeriTrade: (a) Current Model (b) The SDaC Framework
Table 1: Comparison of various deployment models

| Scenario               | Flexibility of Policy | Performance | Provisioning Cost Borne By | TCB                      | External Threat | Internal Threat |
|------------------------|-----------------------|-------------|----------------------------|--------------------------|----------------|----------------|
| Raw Data at app service| Limited by app service| No network required | None | Unknown TCB (OS, apps) | No | No |
| TTP Capsule            | Limited by data service | Limited by network | User | Trusted data service | Yes | Yes |
| Client Capsule         | User can run own code | Limited by network | User | Open-source compact TCB | Yes | Yes |
| Co-located Capsule     | User can pick own code | No network required | Service | Open-source compact TCB | Yes | Yes |

Our framework includes a policy layer based on an existing authorization language and mediates: (1) the parameters used by the service in accessing her capsule’s interface (2) transfers of the user’s capsule from one service to another. We note that this policy layer is not part of the interface implementation since this layer is meant to be controlled by users whereas the interface is picked based on what functionality the service requires from the service.

Our final design guideline is to allow a user direct control over what part of her data is shared; in particular, to allow transformations of her data before any sharing. We support two transformations currently; filtering and aggregation. Capsule filtering enables a capsule at one service to spawn a derivative version of itself at another service containing only a subset of the user’s original data. For example, a purchase history capsule at a shopping site may spawn a version of itself with only music purchases for the use of a music recommendation service. Although the same semantics could be implemented via a policy extension (i.e., only allowing the music service to read history entries pertaining to music purchases), explicit filtering narrows the attack surface offered to the music service, in the case where the isolation it offers were to be violated. Capsule aggregation allows the merging of the data from multiple capsules into an aggregate capsule that can be treated monolithically by an application service. This is useful when services simply require access to raw user data rather than interface-restricted access; in such cases, one option is for users to aggregate their data with others to gain privacy. For example, a user and her friends may instruct their purchasing history capsules to merge before interfacing with a recommendation service, to provide a degree of anonymity for individual purchases across all friends included.

Table 1 summarizes the various options of hosting the data in our capsule framework: the first is the current case where data is stored at the application service, whereas the other options are all supported by the capsule framework with the consequent trade-offs. We note that the co-located capsule can help defend against both internal and external threats with the support of a secure co-processor, and only against external threats if a virtual machine monitor or trusted platform module is available. The security guarantee provided by our framework against these threats is that the combination of interface restrictions and policy control is an upper-bound on the impact of an attacker.

We have implemented a prototype SDaC framework that supports three deployment models: TTP, client-side, and co-location using the Xen hypervisor [2] to isolate the data capsule from the service. Our prototype implementation can only defend against internal attacks in the client-side or the TTP model. Our co-location implementation can only defend against external attacks, and not internal attacks, since our implementation does not support a secure co-processor. However, we believe it would be simple to extend our implementation to support co-location based on TPMs and secure co-processors, based on standard techniques (e.g., Flicker [3]).

We evaluate the SDaC approach along four axes: broad application applicability, flexibility increase, performance, and TCB reduction. We demonstrate broad applicability by refactoring exemplars from four significant application classes. We demonstrate flexibility and performance gains by evaluating the performance of each application in a different deployment scenario, further showing that the optimal deployment for each application differs, and significantly outperforms other possible deployments. For instance, the co-location option consumes no network bandwidth, as opposed to the TTP and client-side capsules, which requires over 1 Gbps network bandwidth per user in the stock trading example. The Xen-based co-located capsule does incur non-negligible access overhead (around 1 ms) and storage costs (around 120 KB; though this can be amortized across users). However, given the value of high-stake data, such as financial and health information, and the fact that the cost of data exposure was estimated by a recent study [4] to be over 200 dollars per customer record, this overhead may be an acceptable price to pay for controls over data exposure. The trustworthiness of our framework is dependent on the SDaC implementation’s correctness. As compared to a complex and proprietary application service, the SDaC is typically simple and can be divulged openly allowing for early discovery of vulnerabilities. Our SDaCs do not require any complex OS services; our design offloads the device drivers, network stack, etc to an untrusted entity.

While we acknowledge that the concept of encapsulation is a well-known one, we view as our main contribution
a general architectural solution to the problem of data access control in web services based on the encapsulation
principle, as opposed to custom solutions suited for credit cards or targeted advertising. Our work is also related to
service composition approaches, but is specialized to providing improved security, rather than improved functionality.

Our capsule framework’s applicability to a particular service is limited by three main factors. First, capsules are not
useful where the interface required by the service involves complex function calls (which precludes a simple
capsule implementation) or when it reveals the data directly (once the data is revealed directly to an untrusted service,
information flow control mechanisms [5][11] are required; data access control only controls release not propagation).
Second, our work also presupposes that a particular interface is chosen by the service and vetted by the broader
community. It is a non-goal of our work to identify such interfaces automatically for a service, or to prove that a given
interface provides a given level of privacy or other guarantees. For the various web services we consider in this work,
we suggest and implement possible interfaces. Third, we assume that the service provider will be willing to undergo a
moderate amount of application refactoring, possibly executing SDaC code they did not implement. We believe this is
realistic given that web services like Facebook already run third-party applications as part of their business model.

The rest of the paper is structured as follows. Section 2 defines our problem statement, while Sections 3 and 4
present an architectural and design overview respectively of our capsule framework. We discuss our implementation
in Section 5 and evaluate its performance in Section 6 and its security in Section 7. We then present related work 8
and then conclude in Section 9.

2 Problem Statement

The object of our capsule framework is to allow users secure and flexible control over who does what to their data,
when they do it, and where their data is stored. Thus, our goal is to enable flexible data access control. The what
is specified by the interface used to access the data, and is based on least privilege; user data is exposed to the service
only to the extent required to accomplish the desired functionality. A user-specified policy allows fine-grained control
over the what, who, when, and where aspects of operations performed on what part of her data.

Two broad requirements for our capsule framework are: (1) Generality: The framework must be broadly applica-
tible across several kinds of web services. (2) Flexible Hosting: The design should allow a variety of hosting options
depending on the trust assumption; co-location or TTP or client-based. The requirements of data-specific interfaces
and flexible hosting in our framework distinguish us from the two closely related papers in literatures (Wilhelm’s the-
thesis [12] and Iliev et al. [13]); we discuss related work in more detail in Section 8. We now flesh out our security goals
and assumptions in more detail.

Security Goal: Our security goal is to ensure that the policies specified by the user over her data are never violated.
In particular, any access to her data must be a sequence of legal invocations of the interface sanctioned by the user
that conforms with her policy, and the only data exposed to the service is the output of such a legal sequence of legitimate
interface invocations. Note that we only aim to circumscribe the influence of an adversary by the limits set by the
policy; the adversary will be able to exercise her influence to the maximum allowed by the policy. For instance, if
the budget in a CCN capsule is specified as 100 dollars, an adversary will be able to exhaust this quota. However, the
adversary will neither be able to extract the CCN from the capsule, nor can she go over 100 dollars. There are two
kinds of adversaries that we wish to achieve this goal against.

Adversaries with software-only access: This models an Internet attacker external to the service who can exploit
vulnerabilities in the service software stack (above and including the OS; we will assume the VMM, if any, is secure).
Such adversaries are responsible for the external category of attacks.

Adversaries with physical access: This models a malicious agent at the service site who has physical access to the
machine hosting sensitive data; for instance, she may be able to monitor the memory bus (say). This agent may be an
admin or the organization itself, who can launch internal attacks.

We present statistics from the DataLoss database [1] to quantify the impact of these adversaries. Over the last
decade, adversaries with software-only access have been responsible for 65% of data exposure incidents; there have
been 394 such incidents caused due to hackers with an average of over 1 million sensitive user records exposed per
incident. During the same period, adversaries with physical access have caused 10% of the incidents; there have been
170 such incidents with an average of over 340,000 records exposed per incident. We note that these two classes of
adversaries directly account for 75% of the incidents in the database; of the remaining 25% incidents, the 21% for
which the cause is known are due to accidental exposure due to inside elements. This category includes incidents such
as stolen/lost/disposed computer/laptop/disk/drive/tapes and accidental mis-configuration of software due to human
error. For our purpose, the former kind of incidents falls in the second class as the adversary has physical access, while
the second kind of incidents falls in the software-only access case.

**Security Assumptions:** Our framework can leverage any of the following trust assumptions to ensure isolation between the SDaC and the application service:

- **Trusted Third Party (TTP):** A TTP is an administratively different entity from the service that the user wishes to protect her data from. This trust can be based on a service-level agreement and the TTP would be paid for by the user. The option of hosting the capsule at the client’s own computer is similar to the TTP option, since from the service’s perspective, it interacts with the user’s data over the network in both cases.
- **Trusted Hardware:** A user can place her trust in a hardware module at the service site. Two kinds of hardware modules are currently available: Trusted Platform Module (TPM [14]) and Secure Coprocessor (e.g., IBM 4758 [15]). TPMs are now widely available in server machines, while secure co-processors, though preceding TPMs, are suitable for high-value data since they are considerably more expensive.
- **Trusted Software:** A user can trust a virtual machine monitor (VMM, e.g., Terra [16]) at the server site in order to achieve her goal. VMMs are now widely used in server environments, making this very viable. We envision two options here: attested VMs (where a TPM attests the execution of the VMM remotely to the client) and an un-attested VM (where the user trusts the service to invoke the VMM).

Of these four trust assumptions, the TTP and the secure co-processor models enable the capsule framework to defend against both threats (internal and external), while TPMs and VMMs suffice to protect against the threat of a software compromise. Once again, we note that our prototype implementation cannot defend against internal attacks in the co-location model.

**Scope:** Our work currently make two assumptions. First, we assume that a satisfactory interface has been arrived at for a service of interest that provides the desired privacy to the user; we do not attempt to verify that such an interface guarantees the desired level of privacy, or to automate the process of re-factoring existing service code. For the specific interfaces we present in this work, we argue for their privacy based on informal arguments; we leave formal verification for future work. Second, we assume that a given capsule implementation carries out this interface correctly, and that there are no side channels or bugs. For the capsules we discuss, we strive to keep the interface simple and argue for the correctness of the implementation based on the simplicity of the interface; proving the correctness formally is a non-trivial research problem that we do not aim to address in this paper.

### 3 Architecture

The main elements of our capsule architecture are presented in Figure 2 that shows a user who capsulizes his trading strategy at AmeriTrade’s site; the capsule relies on a VMM for security. The figure also shows the capsule lifecycle; the user generates the capsule on her machine (say) and then transfers the capsule to Amazon. This capsule then interacts with the data via a prescribed interface. From hereon, we will refer to the user of a web service as a **user** and to the web service as a **service**. In the rest of this section, we will first examine the implications of our framework in terms of how users and services interact with it. We will then show that such an architecture is general and has several applications; thus, our design principle of interface-based data access is widely applicable.
3.1 Implications to Users and Services

A user, who wishes to use the capsule framework to protect her sensitive data when stored at a service, picks a capsule implementation from third party software companies (say a security company such as Symantec) which exports an interface suitable for the kind of data. Or, she may pick one from an open-source repository of capsule implementations, or purchase from an online app-store. It is even possible that the service itself offers a third-party audited capsule implementation which the user may trust. For such a healthy ecosystem of capsule implementations to exist, we envision that APIs suitable for specific kinds of data will eventually be well-defined for commonly used sensitive information such as trading strategies, credit card numbers, email addresses, and web histories. Services that require use of a specific kind of data can support such an API, which would then be implemented by open-source reference implementations and security companies. The development of such interfaces would have another beneficial collateral effect; it would enable data portability for users across services. Once the user picks a suitable implementation, she then customizes it with policies that limit where her data may be stored and who may invoke it. Our current implementation requires users to use a declarative language for this purpose; we envision that simpler user interfaces will be used for this purpose. Once customization is done, the user initiates an installation process by which the capsule is hosted (at a TTP or at the service as desired) and the association between the service and the capsule established.

From the perspective of the web service, the following changes need to be made. First, they need to be willing to run third-party code in the form of capsules. We believe this is reasonable since the functionality of capsules is very limited; they can be executed within a sandbox with simple policies (e.g., allow network access to only the payment gateway, allow no disk access). Further, a service can insist that the capsule be signed from a set of well-known security companies, similar to how applications are signed today. This gives the service confidence in protecting its own code and data from the capsule code. Given the success of Facebook applications, we believe this model is reasonable. Second, a service may have to modify its code to interact with the capsule via a programmatic interface, instead of accessing raw data as they do today. This appears feasible given the short life cycle of web service code (which are re-written much more frequently than applications) and the fact that most web services are architectured so as to retrieve data from a remote machine or via an application server. Modifying the Zen shopping cart application [17] to interact with the credit card capsule took us only a single day. Third, the overhead of capsule storage and invocation may be a hindering factor for adoption. The storage overhead of the capsule seems reasonable especially if the capsules of various users consists of code written by a small set of security companies; thus, there would be considerable overlap in the code, and the only additional storage required is for the user’s data. We deal with the invocation overhead in more detail in our evaluation section (Section 5), but for now, we note that the overhead of invocation depends on the particular trust module in use. VMMs may offer acceptable overhead since servers typically use highly optimized virtualization already; several ways are known to optimize intra-VM communication (e.g., shared-memory based [18]) and to run in-line code securely without incurring inter-VM context switch overhead (e.g., using hardware paging features [19]). TPMs and secure co-processors incur significantly more overhead, and may be feasible only for high-value data such as stock quotes and health records. Late launch invocation in TPMs is still slow since this feature is meant only for VM launches; however, in the future, the trend is towards improving the performance of these devices especially if they are used widely by web services.

3.2 Notation

We denote a capsule $C$ owned by user $U$ and resident on a machine $M$ owned by principal $S$ as $C_U[\mathcal{M}, S]$. We denote the machine $M$ in the notation since whether or not a capsule $C$ can be hosted at $M$ may depend on whether $M$ has a trusted hardware/software module. Every capsule $C$ (we omit the service and the machine when the exact capsule referred to is clear from the context) has a policy database $D[T]$ specified by the user during creation. A capsule $C_U[\mathcal{M}, U]$ is created by the user $U$, for instance, on her own machine $MU$. The user can then choose to host this capsule elsewhere, say to a trusted third party $T$, by requesting a transfer operation. The capsule $C_U[\mathcal{M}, U]$ then initiates a transfer operation to the TTP $T$, at the end of which a capsule $C_U[\mathcal{M}, T]$ is now hosted on the TTP $T$ ($M$ belongs to $T$). Alternatively, the user can choose to host this capsule on the service’s site itself by relying on a VMM for security. In this case, the user’s data is stored at the capsule $C_U[\mathcal{M}, S]$ where $S$ denotes the service that owns $M$. Once resident at $S$, the capsule $C_U[\mathcal{M}, S]$ can be accessed by $S$; any invocations conforming with the user’s policies (specified in $D[T]$) are allowed by the capsule.

In order to model scenarios where one web service can share (with the user’s consent) the user’s data with another service, we allow a service $S$ to share the user’s data with a second service $S’$. Alternatively, $S$ can proxy invocation requests from $S’$; however, this makes $S$ liable for accesses that $S’$ initiates and further, requires $S$ to incur overhead on behalf of $S’$. $S$ may not desire such responsibilities and may prefer to transfer the capsule to $S’$. To do

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so, S requests the capsule \( C_U[M,S] \) to transfer to \( S' \). If the user’s policy allows such a hosting, then the capsule \( C_U[M,S] \) transfers itself to be hosted on \( S' \) as \( C_U[0][M',S'] \). We note that, in order to support replication within the same service, the service \( S \) can ask that the capsule be hosted at another machine \( M' \) owned by the service \( S \); this is treated as equivalent to an across-service transfer. After the capsule has been installed, the user also has the option of updating her data in various ways; we support simple addition/redaction as well as allowing derivate capsules that may have lesser data (by filtering) or may have aggregate data from several users. Our subsequent sections deal with these three issues in more detail: hosting protocol for transfers, policies on invocation, and data transformations.

### 3.3 Choice of Interface

We now explain how the interface for a service is chosen, and will illustrate the wide applicability of interface-based data access. Denote by \( F \) the service functionality that operates on the data; in general, it is a function of \( D_U \) (user’s data) and \( D_S \) (data provided by the service). In the credit card scenario, \( D_U \) is the CCN number, \( D_S \) is the merchant’s account number, and \( F \) contacts a payment gateway and requests a transfer from CCN number \( D_U \) to merchant account number \( D_S \).

When such functionality \( F \) is provided by a capsule, it is refactored as \( F_C \) (implemented by the capsule), and \( F_S \) (implemented by the service) that operates on the output of \( F_C \). We will allow \( F_C \) to operate on \( D_U \) and \( D_{SU} \) (which denotes part of the service data \( D_S \) which is revealed to the capsule). The requirement is that the functionality remains the same as before; thus, \( F(D_U,D_S) \) is semantically equivalent to \( F_S(D_S,F_C(D_U,D_{SU})) \). The service reveals \( F_C \) and \( D_{SU} \) (a subset of \( D_S \)) to the capsule, while the user reveals \( F_C(D_U,D_{SU}) \) to the service. The final output of the function \( F(D_U,D_S) \) is typically exposed to the user, and in some cases, the service as well. The order of invocation of \( F_C \) and \( F_D \) is immaterial; we choose the formulation where \( F_C \) acts first since we are concerned with protecting the user. Using this notation, we present some example classes of capsules; these classes are distinguished based on a particular kind of application scenario. So, it is useful to think of them as a starting set of usage idioms for capsules.

#### Query Idiom:
In this usage idiom, the server provides a stream of incoming data, and the user would like to obtain part of this stream or initiate actions based on this stream using a filter without revealing either her filter or the matching items. In this case, \( D_S \) is this stream of incoming of data and \( D_U \) is a filter representing \( U \)’s interest in the data. The user’s data is thus like a continuous query in databases. For a capsule following the query idiom, the following additional conditions hold: (a) \( F(D_{S,new},D_U) \) is the functionality that infers if the filter \( D_U \) matches a new data item \( D_{S,new} \in D_S \). (b) \( F \) is well-known (c) \( S \) reveals \( D_S \) to the user since the user has paid for this data already (e.g., stock quotes) or because the stream \( D_S \) is public. Condition (b) implies that the specs for \( F \) can be revealed publicly, enabling capsule implementers to support \( F \). Condition (c) implies that the service can share \( D_S \) with the user’s capsule. These conditions ensure the capsule architecture is suitable here.

Examples where this idiom applies include: (a) Stock Trading: Filter is list of stock quotes that the user is interested and trading algorithms that operate on ticker data. Stream of incoming data at the server is high-rate financial ticker updates. The capsule functionality makes trades based on ticker data. (b) Google Health: Filter is list of medicines taken by user and list of diseases that user has. Incoming stream at server consists of newly discovered conflicts between certain diseases and certain medicines. A match occurs if a new conflict involves user’s medicines and diseases. (c) Google News: Filter is user’s list of interested keywords, while the incoming stream is list of news articles. (d) Auction websites (e.g., Swoopo): Filter represents the bidding strategy of a user, while incoming stream is the current auction price and stream of bids from other users.

A query capsule supports two interface calls: \( \text{Match} \) (used by the service to update the capsule with a new data item in the stream) and \( \text{RetrieveMatches} \) (invoked by the user to retrieve matching items). Both are extremely simple to implement: \( \text{Match} \) adds the new datum to a match buffer if a filter criterion matches, while \( \text{RetrieveMatches} \) authenticates the user and delivers matches. Care is required in implementing these functions to avoid side channels that expose the user’s filter; we will address these in Section [5]. For now, we assume that the capsule buffers up all matches within itself; whenever the user wishes to receive updates, he pulls matching data items from the capsule. This is to simplify the implementation; the \( \text{push} \) option is also possible. Alternatively, the capsule may initiate some actions automatically (such as make trades automatically) without any user involvement.

#### Analytics Idiom:
This idiom captures scenarios such as targeted advertising, recommendation systems, where the service \( S \) performs statistical analysis on the user’s data, such as, web visit logs, query logs, location trajectories, previous purchases. In this idiom, the following hold: (a) \( F(D_S,D_U) \) performs statistical analysis on the user’s data \( D_U \) along with service data \( D_S \). (b) \( F \) can either be proprietary or public (c) \( D_S \) can either be proprietary or public. This
scenario is more complicated than our other scenarios since both parties have private data: the user does not wish to reveal \( D_U \) while the server may not wish to reveal either \( F \) of \( D_S \).

We will discuss the targeted ads scenario in detail. Here, \( D_S \) is the list of possible ads to display to the user which is not proprietary. \( F(D_U, D_S) \) selects one ad out of the list \( D_S \) to display and may be proprietary. We discuss the capsule interface under two cases: when \( F \) is well-known and when \( F \) is proprietary. There is one further choice to be made: whether \( F(D_S, D_U) \) the ad to be selected, is known to \( S \). For simplicity, we assume that the user only wishes to hide \( D_U \) and not \( F(D_S, D_U) \) since \( D_U \) is typically much more detailed than \( F(D_S, D_U) \); it is possible to extend this interface to hide the selected ad as well.

**Well-known F:** This case is similar to the query capsule case since both \( F \) and \( D_S \) are public. Thus, the re-factorization is: \( F_C = F, F_S = \phi \), and \( D_{SU} = D_S \). \( F_C \) is shown in Algorithm 1 (we rely on Adnostic [20] for the description of \( F \)). In this description, \( C \) denotes a category space representing various kinds of user’s interests such as “Entertainment → Comics and Animation → Cartoons”, “VideoGames → PS3”. Interest categories are hierarchical; \( → \) represents a sub-hierarchy. Google uses a 3-level hierarchy with around 600 categories overall. For simplicity of presentation, we ignore the hierarchical structure within \( C \) and consider it as a pre-specified list of possible interest categories. \( K \) denotes a keyword space consisting of meta keywords that occur in webpages which convey semantics; this keyword space is private to the capsule and is used in the computation of \( F \). The simplicity of this capsule is evident from the conciseness of our pseudo-code.

**Proprietary F:** Google may choose to develop an algorithm \( F \) that depends on the user’s browsing history, the ad’s category, the contents of the webpage that the ad is displayed on, and the user’s click through rates on ads previously shown to him. It is difficult to anticipate what information may be used by Google, so in such cases, we envision a capsule interface \( F_C = F_C(D_U) \) (meaning \( D_{SU} = \phi \); that is, the service reveals nothing to the user), and thus \( F = F_S(D_S, F_C(D_U)) \). One such interface \( F_C \) is to return a *perturbed* histogram of keywords that occurred in web pages visited by \( U \); this perturbation is carried out using differential privacy techniques [21] which offers provable privacy guarantees to the user. This interface gives different privacy guarantees compared to the interface for public \( F \); in this case, the user gives up part of his privacy for the sake of the complete privacy of Google’s code.

**Proxy Idiom:** A capsule belongs to the proxy idiom if the user has delegated some rights she has on a second service \( S' \) to the capsule; the service \( S \) uses the capsule to access \( S' \) using the user’s right. We use the term proxy capsule since the capsule which acts as a proxy between \( S \) and \( S' \). For such capsules, \( D_U \) is typically a credential that is required to authenticate \( U \) to \( S' \). For example, \( D_U \) may be a credit card number, \( S' \) is the user’s credit card company, and the capsule allows a merchant to charge the user.

A proxy capsule offers two kinds of guarantees to the user. First, it ensures that \( D_U \) is not exposed to \( S \). Second, it also constrains the kind of operations that can be invoked under \( U \)’s authority on \( S' \). For a capsule following a proxy idiom, the following conditions hold: (a) \( F \) is a well-known function. (b) \( D_S \) is not confidential information, so it can be exposed to the capsule. (c) \( F \) requires interaction with a second service provider \( S' \). Conditions (a) and (b) imply that following factoring is acceptable to \( S \): \( F_C = F, F_D = \phi \), and \( D_{SU} = D_S \). Condition (c) implies that the capsule functionality can be offloaded to the service provider \( S' \) in some cases, but this is not always possible if \( S' \) does not support the kind of policies that \( U \) would like. Condition (c) also implies that the capsule requires network access, typically over SSL. We now discuss payment capsules, one particular instantiation of a proxy capsule, and then discuss
Algorithm 2 Charge user’s credit card number and transfer requested amount to merchant’s account

1: Function $F_C =$ Charge($Amt$, $MercAcct$)

Require: Params: $D_{SU} = (Amt$, $MercAcct$), $Amt > 0$,
$D_U = CCN$(set by user),
CapsuleState: PaymentGateway (set to dns name of payment gateway such as “gateway.authorize.net”),
PaymentGatewaySSLName(set to VeriSign-signed name of gateway such as “Authorize.Net”),
RequestTemplate (set to template HTTP POST request for charging)

Ensure: $RetVal = ConfCode$ if successful, $= -1$ otherwise

2: Request = RequestTemplate
3: Request = Replace(Request, “Amount”, $Amt$)
4: Request = Replace(Request, “MerchantAccount”, $MercAcct$)
5: Response = SubmitOverSSL(PaymentGateway,PaymentGatewaySSLName, Request)
6: ConfCode = RegexpExtractBody(Response,/conf\code=/\)
7: return ConfCode

The capsules allow a service $S$ to charge user $U$ on a recurring basis while allowing the user to impose policies on such charging (e.g., do not charge more than once a month) and protecting the user’s charging token (such as a CCN or a gift certificate or e-cash) from the service. The interface $F_C$ for such a capsule and its implementation is shown in Algorithm 2. $D_{SU}$ is passed into the function $F_C$ during invocation, and $D_U$ is stored within the capsule permanently. We use the notation Capsule State to indicate scratch state retained across invocation. The notation Require and Ensure indicate the pre-condition and the post-condition for the function respectively. Lines 1–4 construct the POST request to be sent. The two functions in this capsule dispatch the request and parse the reply: SubmitOverSSL and RegexpExtractBody. RegexpExtractBody is a simple regular expression matching function used to extract the confirmation code from the server’s response. SubmitOverSSL is responsible for contacting the gateway over SSL and obtaining the server response to the constructed POST request. We will explain in Section 5 how this function can be implemented by leveraging an untrusted network stack; for now, we will note that it can be implemented with the aid of a trusted cryptographic library and an untrusted network stack.

Two other instantiations of a proxy capsule are access capsules and notification capsules; due to space constraints, our discussion below is limited. An access capsule allows a service $S$ to have limited access to the user’s data stored at a second service $S'$, while keeping the user’s authentication token for $S'$ (e.g., password) secret from $S$ and imposing restrictions on accesses made from $S$ to $S'$. For instance, an access capsule is used by a user $U$ to allow FaceBook restricted access to her contacts list on Gmail, and hide the rest of her Gmail data (emails etc) from Facebook. Other examples include services like Mint that require access to the user’s up-to-date bank financial transactions at say, Bank of America. A notification capsule allows a service $S$ to send messages to a user $U$, while the user $U$ need not reveal anything about how and where she can be reached, and can specify policies on message sending (such as rate limiting). An example is a email capsule where $F$ implements sending the message via email to $U$, $D_U$ is $U$’s email address, $D_S = ∅$, $S$ is an online merchant, $S'$ is $U$’s mail server, and $F(D_S,D_U)$ returns a success code if the delivery was successful.

**Provenance Idiom:** In this idiom, the user’s data $D_U$ is modified by various parties that have access to it; the goal is to ensure that each modification is tied to the party which modified it. Thus, for this case, $F(D_U,D_S)$ updates the data $D_U$ and $D_S$ is the modifications made by the party to which the capsule is forwarded. The security guarantee is thus an integrity requirement rather than a privacy requirement. The various parties are willing to reveal $F,D_U,D_S$ to each other; the security guarantee is that a data modification $D_S$ is tied to the party $S$ that made the modification.

We envision such a capsule being useful in a enterprise scenario for collaborative editing. A provenance capsule containing a text file (say, a legal memo or a business plan) is forwarded by a user to a group of people who will collaboratively edit the data; the data owner wants to ensure that any changes to the data is tied to the person who made the change. This usage is reminiscent of a distributed version control system with additional security requirements.

A provenance capsule supports two calls: ReadData and WriteData. Upon invocation, the capsule authenticates the caller and returns the data (for ReadData) or updates it along with a signature of the modification by the caller (for WriteData). The implementation is simple: WriteData() appends the modification to a write log along with the signature of the invoking principal as a proof of provenance; ReadData() returns the current version of the data.

other instantiations.

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Summary: The four idioms above capture a wide set of scenarios; of these, the proxy capsule is the most complicated since it requires network access. For these scenarios, the capsule interface is simple and provides the required privacy guarantees to the user; we believe that this simplicity bodes well for a correct implementation. Capsules are not useful where the interface involves complex function calls or when it is leaky. As an example of the first, consider the interaction between Google Docs and a user’s document. While one can theoretically envision an interface (e.g., display the first page on the screen, delete character at line 20 and position 30), the interface would be so rich as to make it difficult to characterize leaks and to give any confidence as to the correctness of the capsule implementation. The interaction between Facebook and a user’s profile data is an illustration of the second case. Facebook requires direct access to the user’s data (e.g., name, address), and such an interface affords no privacy to the user; once the capsule releases the data to a Facebook process, it is not possible to ensure any policy constraints. These two scenarios are better handled by information flow control (e.g., XBook [8]) or end-to-end encryption (e.g., NOYB [22]).

4 Design

In this section, we discuss the design of the capsule architecture in more detail. The previous section mainly focused on our design principle of interface-based access; the components of the base layer we discuss in this section are based on the principles of (a) flexible deployment with policy control, (b) policy control over invocation, (c) policy control over data on which the invocation operates.

Figure 3 shows a capsule co-located at the service site that uses a VMM as a trusted module to isolate itself from service code. It shows a host hub that resides within the service partition and a base layer in the capsule partition (we use the term partition to imply the isolation between these components). We assume the base layer is installed by the service within the VM allocated for a user’s capsule; during the installation protocol, the user can verify that this is the case using attestation. The host hub acts as the proxy for communication between the external world and the capsule. The base layer includes generic functionality (such as hosting protocol, policy checking) common to all capsules, while the data layer implements interface calls specific to the data item.

The figure also shows the three main components of the base layer: the policy engine, the data transformation module, and the service front end. The policy engine is used by the base layer to check whether an invocation request or an hosting request should be allowed or not. Regarding invocation requests, we are guided by the principle of providing fine-grained flexible control, and regarding hosting requirements, our goal is to allow a range of flexible deployment options. The data transformation module is responsible for implementing a secure aggregation protocol (filtering is data specific, and are implemented in the data layer). The service front end is responsible for carrying out complex functions (such as network access, disk access) which are outsourced to the service back end in the host hub which uses device drivers to provide this functionality to the capsule (the concept of front end and back end is similar to how Xen supports devices inside a guest VM). Such service requests are made by the data layer and are proxied to the service back end by the service front end. This split architecture significantly reduces the complexity of the capsule and our TCB; the capsule only relies on the host hub for availability, not for confidentiality or integrity guarantees on the data. The only code inside the capsule correspond to the base layer functionality and data layer functionality; typical OS components such as device drivers, network stack, are not required.
The rest of the section presents the detailed design. We first discuss the interaction between the host hub and the base layer (Section 4.1). We then discuss the policy engine in two parts: the hosting policy engine (Section 4.2) and the invocation policy engine (Section 4.3). We then finally discuss the data transformation module (Section 4.4).

4.1 Interaction between Host Hub and Base Layer

The interaction between the host hub and the base layer is secured by the base layer by leveraging the trust module. If the capsule is hosted at a TTP or at the client, then the trust is guaranteed by the physical isolation between the capsule and the service. If the capsule is co-located at the service, then the base layer requires the following functionality from the trust module: (a) isolation (b) non-volatile storage, (c) random number generation (d) remote attestation (optional). Isolation is needed to ensure that the service code cannot interfere with the capsule and steal its data during execution. Non-volatile storage is required to defend against replay attacks. Otherwise, it is possible for an adversary to rollback the capsule state to an earlier point in time in an undetectable fashion; this would allow them to violate the security guarantee desired by the user. Randomness is required in order for secure key and nonce generation in the various protocols that the base layer implements. Remote attestation is optional; it lets the trust module can prove to the user that her data is indeed processed by the capsule. We will later argue in Section 7 that these properties suffice for the security of our framework; for now, we note they are provided by all the three trust modules we consider (VMM, TPM, secure co-processor). We now introduce the host hub and the base layer.

The host hub has two main roles. The first is to serve as a proxy for all communication to and from the capsule; such communication may be to/from the user (during capsule installation) or to/from the service code (during invocation). This design decision lets us decouple the application on the service side from the details of capsule invocation and is a modularity-based decision. The second role is to provide services to the DC such as network access and persistent storage; this allows the capsule to leverage functionality without having to implement it, considerably simplifies the implementation. The host hub runs within a un-trusted OS, but this does not violate our trust, since the capsule only relies on the host hub for availability, not safety: data is encrypted before any network communication or disk storage via the host hub. Based on the various data layer capsules we have implemented, we have identified a set of common services they require:

- **Raw Network Access via the BSD Socket API:** When a data layer (such as a CCN capsule) requires network access, in order to avoid placing a complex TCP/IP network stack within the capsule, the base layer offloads the implementation to the host hub. For instance, when the data layer invokes the `connect` BSD socket call, the base layer marshals the parameters and conveys them to the host hub. The host hub invokes the `connect` call using its network stack (which need not be trusted) and returns a file descriptor (or error) to the base layer which conveys it to the base layer. The data layer can thus avail of the standard socket API. We have also included the PolarSSL SSL/TLS library in the base layer and modified the socket calls to use the base layer’s rather than using the standard system calls. We chose the PolarSSL library since it is a significant smaller code base (12K) compared to OpenSSL (over 200K lines of code); this design decision can be revisited if required. Thus, data layers can use the SSL library as well; this is necessary to access any remote web service securely.
- **Time:** The base layer can also request the host hub to retrieve the current time from a remote trusted NTP server using SSL; this is useful for supporting certain policies (for instance, expire the data after a certain date).
- **Persistent Data:** The host hub also offers a simple block-based storage interface for reading and writing data persistently. None of our capsules use this feature so far (since they live within a VM, and are re-incarnated along with the VM image), but this functionality may be required when large data sets are involved.

The base layer handles all requests from the host hub and implements the hosting protocol and the invocation policy. It also interacts with the trusted module to ensure that the security properties hold. Thus, the data layer that implements the data-specific interface is decoupled from the security mechanisms, and is much easier to write. We now describe the components of the base layer.

4.2 Capsule Hosting

In order to meet our requirement of allowing flexible data hosting policies, our capsule framework allows user to specify a hosting policy which is then enforced by a hosting protocol. We first discuss our hosting policy language and then discuss the hosting protocol.

**Hosting Policy:** The requirement for our hosting policy language is that it be expressive enough to accommodate typical user requirements and be simple enough to be interpreted easily by the framework. We arrived at a design that is a simplified version of SecPAL [24], an authorization policy language for distributed systems. The simplifications were
At the end of this three-message exchange, the base layer at
\[ M \] is owned by the same user
\[ U \]
as to enable easy interpretation. Our language is flexible enough to allow a user to grant a service \( S \) the right
to host her data based on: (a) white-list of services (b) trusted hardware/software modules available on that service. (c)
if a service \( S' \) trusted by the user vouches for the service \( S \). This space of options is inspired from the typical privacy
options supported by websites. The flexibility to trust based on the availability of a trusted modules is key; a user
may chose to trust any service that houses her data in a physically secure co-processor, while it may only trust a select
set of services to host her data on a VMM or a TPM. We show an example below to illustrate the flavor of our language.

We use a typewriter font to indicate principals like Alice (the user; a principal’s identity is established by a certificate
binding its name to a public key), an underlined font to indicate language keywords, and italics for indicating predicates
(such as \( \text{CanHost} \) and \( \text{HasTPM} \)). The first rule says that Alice allows any machine \( M \) to host her capsule provided
Amazon acknowledges a machine as its own, and the machine has a TPM. The second rule says that Alice trusts \( CA \)
to certify the public keys of a machine’s TPM. The third rule allows any service to certify a machine as its own. The
fourth rule allows Amazon to recommend any service \( S \) as a trusted service. The fourth rule indicates Amazon allows any
machine \( M \) to host her capsule if (a) Amazon vouches for such a service \( S \) (b) \( S \) asserts that \( M \) is its machine (c) the
machine \( M \) has a secure co-processor (since Alice is delegating the decision to Amazon, she would like a more secure
option than a TPM, so her policy asks for a secure co-processor). The last rule indicates Alice delegates her decision
of which machines have secure co-processors to the certification authority \( CA \). This example illustrates all features of
our policy language; the simplification from SecPAL is that we do not support recursive delegation.

A hosting request received at \( C_U \circ [M, S] \) has three parameters: the machine \( M' \) to which the hosting transfer
is requested, the service \( S' \) which owns machine \( M' \), and a set of assertions \( P_{HR} \). The set of assertions \( P_{HR} \) are presented by the
requesting principal in support of its request; it may include delegation assertions (such as “\( S \) says \( \text{CanHost} (X) \)”) as well as capability assertions (such as “\( CA \) says \( \text{HasTPM} (M') \)”). When such a request is received
by \( C_U \circ [M, S] \), it is checked against the policy \( P (C_U \circ [M, S]) \). This involves checking whether the fact “\( U \) says
\( \text{CanHost} (M') \)” is derivable from \( P (C) \cup P_{HR} \). If it is, then the hosting protocol is initiated.

**Hosting Protocol:** The hosting protocol is responsible for the forwarding of a capsule from one party to another.

We treat the initial transfer of a capsule from the user’s machine to a TTP or service as a hosting transfer as well. Thus,
capsule \( C_U \circ [M_U, U] \) denotes the capsule initially created and resident on the user’s machine. The hosting protocol is
based on the Diffie-Hellman key-exchange protocol, and has three steps:

- **Step 1:** \( M \rightarrow M': K_{C}, N \)
- **Step 2:** \( M' \rightarrow M: K_{C'}, \text{Attestation}(M', BL, N, K_{C}, K_{C'}) \)
- **Step 3:** \( M \rightarrow M': \{ C_U \circ [M, S] \}_{DHK} \)

The only differences from the Diffie-Hellman protocol (involving the keys \( K_{C}, K_{C'} \) and the Diffie-Hellman secret
\( DHK \)) are the use of the nonce \( N \) and the optional attestation that proves that the key \( K_{C'} \) was generated by the DC
base layer code which, on input \( N, K_{C'} \), produced output \( K_{C'} \). This attestation is made along with an attestation key
\( M' \) which is vouched off for by a certification authority, guarantees freshness (since it is bound to \( N \)), and rules out
man-in-the-middle substitution on both the input and output (since the attestation is bound to both \( K_{C} \) and \( K_{C'} \)). At
the end of this three-message exchange, the base layer at \( M' \) then de-serializes the freshly transferred capsule
\( C_U \circ [M', S'] \) identified by the key \( K_{C'} \). At this point, the capsule \( C' \) is operational; it shares the same data as \( C \)
and is owned by the same user \( U \).

**Consistency:** We note that when a user’s data is spread across several services in the form of several capsules, we do not
attempt to enforce any notion of consistency across them after they have forked off; each of them is an independent
entity (much like the case today; if Amazon hands out a user’s credit card number to a third party, it does not necessarily
update it automatically on any changes by the user). Our architecture allows a user or service to notify any descendant
capsules and update them if so desired, but this is not automatically done since it is not possible to maintain both
consistency and availability in the face of partitions, and further, the overhead of synchronizing the multiple copies
would be high. However, during the process when one capsule is forked off from another, we appropriately transfer
policies during the transfer so that the policies continue to hold.
4.3 Capsule Invocation Policy

An invocation policy allows the user to specify constraints on the parameters to the capsule interface during invocations by various principals. We support two kinds of constraints: stateless and stateful.

Stateless constraints specify conditions that the argument to a single invocation of a capsule interface must satisfy. For example, such a constraint could be “never charge more than 100 dollars in a single invocation”. We support predicates based on comparison of numerical quantities, along with any conjunction or disjunction operations. Stateless constraints apply across several invocations; for example, “no more than 100 dollars during the lifetime of the capsule”. We found such stateful constraints to be useful for specifying cumulative constraints. It is very likely that users would desire to specify a budget on their credit card number over a period of time. An even more important use of a stateful constraints is in specifying a query budget for differential privacy based interfaces. Thus, it is crucial for users to be able to specify a query budget that limits the number of times their data is accessed; this requires maintaining state of the number of queries served so far. Once again, we aim for the policy language supporting both these kinds of invocation constraints to be simple; this language is very similar to the hosting policy language and we present an example for a CCN capsule below.

Alice says CanInvoke(Charge, Amazon, A) if LessThan(A, 100)

Alice says CanInvoke(Charge, DoubleClick, A) if LessThan(A, Limit), Between(CurrentTime, ‘Jan 1st, 2010′, ‘Jan 31st, 2010’) state (Limit = 50, Update(A))

Alice says Amazon can say CanInvoke(Charge, S,A) if LessThan(A, Limit) state (Limit = 150, Update(A))

The first rule gives the capability “can invoke up to amount A” to Amazon. This allows Amazon to call the charging interface with parameter A and the constraint A < 100 checks that the amount is less than 100. The second rule shows a stateful example; the semantics of this rule is that DoubleClick is allowed to charge up to a cumulative limit of 50 during Jan 2010. To implement this policy, we introduce a state variable called Limit which is set to 50 initially by the user. The predicate Update(Limit, A) is a stateful predicate that indicates if this rule is matched, then the Limit should be updated with the amount A; thus, when a rule is matched with a state keyword, it is removed from the policy database (the database of assertions), the state variable (e.g., Limit) is updated in the rule, and the new rule inserted into the database. This usage idiom is similar to SecPAL’s support for RBAC dynamic sessions; we have added the state keyword to allow retention of state between authorization requests. The alternative is to move this state outside the SecPAL policy, and house it within the capsule functionality; we make the design choice of making it explicit in the policy itself to ensure that the policy implementation is not split across SecPAL and the capsule implementation of the interface. Though this choice implies that the policy database is updated over time, there are no undesirable consequences with allowing such dynamic changes. The third rule is very similar to the second rule; the interesting thing to note here is that this rule is matched for any principal to which Amazon has bestowed invocation rights. This means that the limit is enforced across all those invocations; this is exactly the kind of behavior a user would expect.

Transfer of Invocation Policies: We now discuss how this invocation protocol interacts with the hosting protocol discussed earlier. During a hosting protocol initiated from \( C_U \otimes [M, S] \) to \( C_U' \otimes [M', S'] \), \( C \) should ensure that \( C' \) has suitable policy assertions \( P(C') \) so that the user’s policy specified in \( P(C) \) is not violated. First, any policy statements \( PHR \) specified by \( S' \) during the hosting request need to be added to \( P(C') \) to record the fact that this newly derived capsule operates under that context. Second, any stateful policies need to be specially handled. For example, consider the third rule in the invocation policy in Section 4, which requires that the total budget across all third parties that are vouched for by Amazon is 100 dollars. If this constraint is to hold across both \( C' \) and any future \( C'' \) that might be derived from \( C \), then one option is to use \( C \) as a common point which ensures that this constraint is violated. However, this requires any transferred capsule \( C'' \) to communicate over the network with \( C \) upon invocations. Instead, in order to allow disconnected operation, we use the concept of exo-leasing [25].

In the exo-leasing concept, the constraint (e.g., budget) is broken up into sub-constraints (e.g., sub-budgets) so that if the sub-constraints are enforced, the parent constraint is automatically enforced. In the capsule context, decomposable constraints (such as budgets, number of queries answered so far) from \( AC(C) \) are split into two sub-constraints: the original constraint in \( AC(C) \) is updated with one sub-constraint, and the second sub-constraint is added to \( AC(C') \).

In our example, the assertion “Alice says X can invoke Charge A State Limit 100 if Amazon says I vouch for X, \( (A < Limit), Update (Limit,A) \)” would be transformed into “Alice says X can invoke Charge A State Limit 75 if Amazon says I vouch for X, \( (A < Limit), Update (Limit,A) \)” and “Alice says X can invoke Charge A State Limit 25 if Amazon says I vouch for X, \( (A < Limit), Update (Limit,A) \)”.
4.4 Capsule Data Transformation

In exploring the use of capsules in various application scenarios, we found it useful to allow users to perform transformations on their data post-installation, especially when the data is of an aggregate nature (e.g., web history). Providing users control over the transformations on their data is distinctly different from providing control over invocation; the latter controls operations invoked over the data, and the former controls the data itself. We refer to a capsule whose data is derived from a set of existing capsules by some transformation as a derivative capsule. We support two data transformations: filtering and aggregation.

Filtering: A derivative capsule obtained by filtering has a subset of the data of the originating capsule; for instance, only the web history in the last six months, instead of the entire year. A capsule that supports such transformations on its data exports an interface call for this purpose; this is invoked alongside a hosting protocol request so that the forwarded capsule contains a subset of the originating capsule.

Aggregation: This allows the merging of raw data from mutually trusting users of a service, so that the service can use the aggregated raw data, while the users still obtain some privacy guarantees due to aggregation. We refer to this scenario as “data crowds” (inspired by the Crowds anonymity system [26]). Examples of usage include ads clicking behavior of users or online product purchase history. In the first, Google (say) may use the aggregate ad click behavioral history to fine-tune their targeted advertising algorithms. In the second, the latter could be used by Amazon to build statistical models for recommendation systems.

To enable this, a user \( U \) instructs her capsule \( C_U \) to aggregate her data with a set of capsules \( C_U \) \( M, S \) where \( U \) is a set of users that she trusts (this trust is necessary; otherwise, if her data was merged with data belonging to fake users, the privacy guarantees would be much poorer). These set of users \( U \) form a data crowd. We envision that a user \( U \) can discover such a large enough set of such users \( U \) by mining her social networks (for instance).

During capsule installation, each member \( U \) of the crowd \( C \) confides a key \( K_C \) shared among all members in the crowd to their capsule. During installation, a user \( U \in C \) also notifies the service of her willingness to be aggregated in a data crowd identified by \( H(K_A) \). \( S \) can then identify the set of capsules \( C_A \) belonging to that particular data crowd using \( H(K_A) \) as an identifier. The service can, at this point, then determine any kind of aggregation strategy. For instance, in order to reduce network overhead, it could request all the capsules stored on a rack in its data center to aggregate with each other first, and then ask the resultant capsule to aggregate with the resultant capsules from other racks. Note that the aggregation protocol does reveal the size of individual user data; such side-channels can be avoided by padding data if desired.

From the capsule’s perspective, aggregation is a pair-wise operation; a capsule \( C_U \) is requested to merge with \( C_U \), and these mergings are appropriately staged by the service. During the aggregation operation of \( C_U \) with \( C_U \), capsule \( C_U \) simply encrypts its sensitive data using the shared data \( K_A \) and hands it off to \( U \) along with its owner’s key. During this aggregation, the resultant capsule also maintains a list of all capsules merged into the aggregate so far; capsules are identified by the public key of the owner sent during installation. This list is required so as to prevent duplicate aggregation; such duplicate aggregation can reduce the privacy guarantees. Once the count of source capsules in an aggregated capsule exceeds the user-specified constraint \( C_{min} \), the aggregate capsule can then reveal its data to the service \( S \). This scheme places the bulk of the aggregation functionality upon the service; this is ideal since it gives the service freedom to optimize the aggregation, while at the same time requiring the capsule to only implement a simple pair-wise aggregation function.

5 Implementation

Our implementation supports three deployment models: TTP, client-side, and Xen-based co-location. In the future, we plan to support TPMs and secure co-processors using standard implementation techniques using as late launch (e.g., Flicker [3]). We implement four capsule instances atop this framework, one per usage idiom: a stock trading capsule, a credit card capsule, a targeted ads capsule, and a provenance capsule. We describe some of the details of our framework followed by a description by each capsule.

5.1 Capsule Framework

For TTP deployment, the network serves as the isolation barrier between the capsule and the service. For co-location deployment, we used the Xen virtual machine [2] as the isolation mechanism; the web service code and the data capsule are run inside different virtual machines thus providing protection against software compromise. We ported and
Table 2: Capsule Implementation: LOC Estimates of Modules

| Software Module | LOC  | Functionality                                      |
|------------------|------|----------------------------------------------------|
| Base Layer       | 6K   | Implements installation, invocation, and policy checking. |
| Data Layer       | Stock (340), Ads (341) CCN (353), Provenance (156) | Implements functionality specific to data |
| PolarSSL         | 12K  | Light-weight cryptographic and SSL library used for embedded systems. |
| XenSocket        | 1K   | Fast inter-VM communication using shared memory and event notification hyper-calls. |
| Trousers (optional) | 10K | Library for TPM functions. Can be removed from TCB by accessing TPM directly. |

extended XenSocket [18] to our setup (Linux 2.6.29-2 / Xen 3.4-1) in order to provide fast two-way communication between the web service VM and the capsule VM using shared memory and event channels.

The base layer implements the Diffie-Hellman based installation protocol and invocation protocols. It implements policy checking by converting policies to DataLog clauses, and answers query by a simple top-down clause resolution algorithm (described in SecPAL [24]; we could not use their implementation as such since it required .NET libraries). We use the PolarSSL library for embedded systems for light-weight cryptographic functionality. We use a TPM, if available, to verify that a remote machine is running Xen using the Trousers library; this TCB can be reduced by invoking the TPM directly rather than via the library. Note that we only use a TPM to verify the execution of Xen; we still use Xen as the isolation mechanism. The host hub uses the libevent event library (the host hub is not part of the TCB). We use 2048-bit RSA public keys (for identifying capsule instances, data owners, services), 256-bit AES/DES keys (used internally when encrypting data using public keys), and HMAC/SHA-2 hash functions (for signatures).

We now estimate the TCB of our Xen based capsule. This consists of the Xen VMM, Dom0 kernel, and our capsule implementation. Table 2 shows the LOC estimates of the various modules in our capsule implementation. Our capsule implementation currently has two dependencies which we plan to remove in the future. First, our capsule VM boots up the capsule on top of Linux 2.6.29-2; however, the capsule code does not utilize any Linux functionality, and can be ported to run directly atop Xen or MiniOS (a bare-bones OS distributed with Xen). Second, the capsule uses the memory allocation functionality by glibc and some functionality from the STL library; we plan to include a custom memory allocation module to substitute glibc and to hand-implement custom data structures to avoid this dependence.

We also plan to incorporate mechanisms focussed on improving VMM-based security (such as removing Dom0 functionality from the TCB by using disaggregation techniques [27]); such mechanisms are orthogonal to our framework. We have yet to incorporate several performance optimizations discussed in literature for improving performance while providing isolation. One technique that is pertinent is from Sharif et al. [19]. [19] allows us to run the capsule within the same VM as the service, while still guaranteeing code and data isolation; this is achieved by having the VMM use hardware paging functionality. [19] demonstrates an order-of-magnitude gain in performance using this technique, which we hope to implement in our framework. We now discuss the implementation of the base layer’s internals followed by the sample capsules we implemented.

5.2 Capsule Hosting

We currently use a policy language which supports three base types: principal names, strings, and integers. An argument in a predicate can either be a constant or a variable, and is annotated with its type, e.g., VPRINCIPAL(XP) denotes a variable XP which stands for a principal. A policy in our language is represent as a 5-tuple \((P; F; CF; C; S)\) where \(P\) is name of the principal issuing this statement (such as \(CPRINCIPAL(ALICE)\) which denotes a constant ALICE of type PRINCIPAL), \(F\) is the statement made by \(P\) (e.g., \(FACT\{ PRED \{ INVOCATION, VPRINCIPAL(XP), VNUM(AMT), VSTR(ACCOUNT) \} \}\)), \(CF\) and \(C\) is a set of conditional facts and constraints which are required to be satisfied if \(F\) is to be true, and \(S\) records any state variables. In order to verify whether a particular statement is derivable from a set of policy statement, we translate all statements to DataLog clauses, and then use a simple top-down resolution algorithm (described in SecPAL [24]). We defer a detailed description of our policy language and resolution algorithm to the technical report due to space constraints.
5.3 Invocation Policies

An invocation request has four parameters: \( S' \), the service making the request (not necessarily the service \( S \) hosting the capsule), the request type \( R \) (e.g., “Charge”), the arguments to the request \( A \) (e.g., “10” dollars), and a set of supporting assertions \( P_{IR} \). To service such a query, the base layer of \( C \) checks to see if the fact “\( U \) says \( S' \) can invoke \( R \) \( A \)” or the fact “\( U \) says \( S' \) can invoke \( R \) State \( S'' \)” is derivable from \( P(C) \cup P_{IR} \). If there is no proof for such a query, the request is denied. If there is a proof, the base layer retrieves any policy specification \( ac_{S} \) in the proof with a State keyword. For all such assertions \( ac_{S} \), the corresponding state \( S \) is also extracted. The invocation is then dispatched by the base layer to the data layer; after the successful completion of the request, the state \( S \) is updated to \( S' \) as per the Update rules. At this point, the old specification \( ac_{S} \) is removed from \( P(C) \), and a new specification \( ac_{S}' \), is inserted into \( C_U \oplus S[M] \). This ensures that the state is updated as required. To avoid race condition issues, for now, the base layer waits for the invocation to complete before serving any other requests. Since the database of policies may change from one invocation to the next, we do not cache any intermediate facts that are derived during one invocation for subsequent ones; thus, we avoid any inconsistency issues.

5.4 Data Transformations

Filtering is easy to implement; a capsule \( C \) supports an interface call Filter which takes a filtering criterion as an argument, and produces a capsule \( C' \) per the filter. Filtering can be invoked in conjunction with a hosting transfer; alternatively, the policy can insist that it should only be invoked by the owner of the capsule. For the latter case, every capsule maintains the public key of its owner \( K_{C} \) (which is sent during the installation and hosting protocols), and authenticates requests for data transformation using this key.

Aggregation is a more expensive operation since it involves coordination of \( U \)’s capsule with multiple other capsules. To enable secure aggregation, our aggregation protocol operates in two stages; the first stage is performed off-line by a set of users \( U_{A} \) who have decided to cooperatively perform aggregation of their data stored on a common service \( S \), the second is the aggregation itself performed at the service site.

During the setup phase, a set of users \( U_{A} \) establish a shared key \( K_{A} \) amongst themselves; a user \( U \) can securely discover such a set of willing users \( U_{A} \) and establish a key \( K_{A} \) using her social network. All the user’s implementations support an aggregation call in their interface. At the end of this phase, every user \( U \in U_{A} \) notifies her own capsule \( C_U \oplus [M,S] \) of \( K_{A}, A_{min} \). Here \( A_{min} \) represents the minimum number of capsules that should be aggregated before the data is released; we return to this later. Note that this notification step can be performed during the installation itself. Further, this set of users \( U_{A} \) can be the same across multiple services. Thus, a user need only establish this \( U_{A}, K_{A} \) once; this set can be re-used across multiple services.

The second phase performs the actual aggregation itself, and is performed with the coordination of the service. During installation, a user \( U \in U_{A} \) notifies the service of her willingness to be aggregated in a data crowd identified by \( H(K_{A}) \). \( S \) can then identify the set of capsules \( C_{A} \) belonging to that particular data crowd using \( H(K_{A}) \) as an identifier. The service can, at this point, then determine any kind of aggregation strategy. For instance, in order to reduce network overhead, it could request all the capsules stored on a rack in its data center to aggregate with each other first, and then ask the resultant capsule to aggregate with the resultant capsules from other racks.

From the capsule’s perspective, aggregation is a pair-wise operation; a capsule \( C_U \) is requested to merge with \( C_U \), and these mergings are appropriately staged by the service. During the aggregation operation of \( C_U \) with \( C_U' \), capsule \( U \) simply encrypts its sensitive data using the shared data \( K_{A} \) and hands it off to \( U' \) along with its owner’s key. Thus, the shared key \( K_{A} \) serves as a security token; only another capsule belonging to the same crowd will be able to decrypt the data. During this aggregation, the resultant capsule also maintains a list of all capsules merged into the aggregate so far; capsules are identified by the public key of the owner sent during installation. This list is required so as to prevent duplicate aggregation; such duplicate aggregation can reduce the privacy guarantees. Once the count of source capsules in an aggregated capsule exceeds the user-specified constraint \( A_{min} \), the aggregate capsule can then reveal its data to the service \( S \). This scheme places the bulk of the aggregation functionality upon the service; this is ideal since it gives the service freedom to optimize the aggregation, while at the same time requiring the capsule to only implement a simple pair-wise aggregation function.

5.5 Sample Capsules

The broad guideline behind our sample capsule implementations is to model the essence of the application scenario in realistic enough fashion so that experimental comparative analysis of different deployment options is feasible.
Stock Trading Capsule: We model our stock capsule functionality after the automatic trading functionality in a popular day trading software, Sierra Chart \(^{[28]}\), which is representative of the complex mechanisms used by financial traders. We chose one specific feature of Sierra Chart for illustration: make trades automatically when an incoming stream of ticker data matches certain conditions. Our implementation follows the the Sierra Chart technical manual’s description \(^{[28]}\).

This capsule belongs to the query idiom (Section 3.3) and exports a single function call of the form TickerEvent (SYMBOL, PRICE) and returns a ORDER(“NONE” / “BUY” / “SELL”, SYMBLO, QUANTITY) indicating whether the capsule wishes to make a trade and of what quantity. The capsule allows the user to specify two conditions: a BUY (ENTRY) condition and a BUY(EXIT) condition. A condition is an arbitrarily nested boolean predicate with operations like AND, OR, and NOT, and base predicates that consist of numerical variables, comparison operations (> , < , =), and numerical constants. The numerical variables include: LP (the latest price of stock), MA (moving average of price), POS (position: amount of stock purchased by the software), and POSAV (average price of stock purchased already). As an example, a BUY(ENTRY) condition could be LP > MA and a BUY(EXIT) condition could be OR(\(\text{AND} (> 0, \text{LP} <= \text{POSAV} - 1), \text{AND} (\text{POS} > 0, \text{LP} >= \text{POSAV} + 2)\)). This means that the system purchases upto \(Q\) (a user-chosen parameter) everyday the last price exceeds the moving average, and this stock is sold off either when: (a) last price is less than the average price the BUY Entry was filled at minus 1 full point. (b) the last price is greater than the price the Buy Entry was filled at plus 2 full points. Our implementation of boolean predicate matching is straight-forward; we do not apply any query optimization techniques like common sub-expression matching from the database community. Thus, our performance results are only for comparative purposes.

Sierra Chart currently executes at the user’s desktop on a feed of incoming stock symbols (similar to the TTP case). In the Xen case, the user capsulizes her BUY(ENTRY) and BUY(EXIT) conditions at her broker. The only information revealed by the capsule is any trades it makes; the strategy is itself secret. It is not possible to hide the trades from the broker, thus any leaks of the strategy through the trades cannot be avoided; we assume that this leak is tolerable. We expect that the re-factoring of the application service at the broker site would not require significant effort since the interface is very simple; since we do not have access to any broker site code, we can only estimate this effort.

Credit Card Capsule: We implemented a credit card capsule that interacts with the authorize.net gateway to implement charges, and modified an open-source shopping cart application (Zen) to interact with the capsule to implement charging. As discussed in Section 3.3 this capsule supports a single interface call, Charge(Amt, MercAcct), and returns a confirmation code to the service. This capsule illustrates the flexibility of the framework with respect to invocation policies and matches the proxy idiom. This functionality is offered by some banks already; we only implement and evaluate this capsule to measure the cost of our framework in emulating this functionality in a more general fashion. We implemented both stateless policies (allow only invocations for less than X dollars) and stateful policies (maintain a per-month budget of X dollars).

Targeted Advertising Capsule: We implemented two capsules for targeted advertising both of which belong to the analytics idiom (Section 3.3). They both store the user’s web browsing history and are updated periodically (say, on a daily basis). The first capsule is used by a service to serve targeted ads when a user visits a specific web page. The second is used by the service to build long-term models related to the affinity of users with specific profiles to specific advertisements. These models are used, for instance, by Google, to fine-tune their targeted advertising methods. Both capsules support a simple interface call that is used by the data owner to update her web browsing history; we now detail the other interface calls exported by these capsules below.

Serving targeted ads: This capsule supports two possible interfaces: ChooseAd(List of Ads, Ad Categories) and GetInterestVector(). In the first case, the capsule selects the ad to be displayed by using a procedure similar to those used in web services today (per the description in Section 1). In the second, the capsule extracts the keyword vector of the user from her browsing history, and then computes the true normalized interest vector \(U = \{U_c\}\) based on the user’s data \(D_U = \{W_1, W_2, \ldots \}\) where \(W_i\) is the user’s web visit history. Here, \(0 \leq U_c \leq 1\) reflects the interest of the user in category \(c\) and \(\Sigma_c U_c = 1\). The capsule then obfuscates this vector per a generic differential privacy prescription. We obfuscate each element \(U_c\) of this vector \(U\) individually, and then re-normalize the vector \(U\).

The \(L_1\) sensitivity of this function, denoted by \(\Delta(U_c)\), is \(1/V\) where \(V\) is the total number of visits by the user to various websites since if the user visits one particular different website, the count of the number of visits in one specific category \(c\) can at most increase or decrease by 1. We insist that the user visit a minimum number of websites \(V_{\min}\) before the capsule would start serving ads. Thus, the sensitivity \(\Delta(U_c)\) of this function is upper-bounded by \(1/V_{\min}\). The obfuscated value \(U'_c\) of \(U_c\) is chosen per the distribution function \(P_T[U'_c = a] \propto \exp(-\frac{||U'_c - a||}{\sigma})\) where \(\exp\) is the scaled symmetric exponential distribution function and \(\sigma\) is the variance of the distribution. This function guarantees \(\epsilon\)-differential privacy for \(\epsilon = \Delta(U_c)/\sigma \geq 1/(V_{\min}\sigma)\).
This capsule also makes use of a stateful policy in the differential privacy case to record the number of queries made so far. The amount of information leaked by interactive increases linearly with the number of queries made [21]; thus it is necessary for users to specify a private budget \( Q_{\text{max}} \) and the framework ensures that this budget is enforced by using stateful policies (in a manner similar to the credit card budget). As discussed earlier, these two calls provide different privacy guarantees. The first leaks no information; the selected ad is sent to the user’s computer where a client-side component displays the ad. In the second, one implication of the \( \epsilon \)-differential privacy guarantee is that even if the service knows all but one of the websites visited by the user, the ability of the service to deduce the one private website is limited by \( \epsilon \). In particular, the distributions of the output for various possibilities of that one private website are point-wise \( \epsilon \) close. We choose a typical value \( \epsilon = 0.01 \). We

**Building long-term models:** The second capsule allows the service access to the websites visited by the user and the particular advertisements clicked by the user when visiting a website (thus this data is more detailed than the data used for targeted advertising). This information is used to refine the service’s targeting algorithms. For this purpose, it suffices for the service to obtain aggregate data from a large population of users; we can thus leverage our aggregation functionality. Individual user data is represented as \( D_U = \{ W_i \}, \{(P_i, A_i, C_i)\} \) where \( \{ W_i \} \) represents all websites visited by the user, and \( \{(P_i, A_i, C_i)\} \) represents how the user responded to ads displayed on a publishing websites \( P_i \) that participates in the advertising service (such as Google AdSense). \( C_i \) is 0/1 depending on whether the user clicked on ad \( A_i \) shown to her when visiting website \( P_i \). This information is aggregated across all users by our aggregation protocol and delivered to the service. To do so, the users distribute a shared secret key amongst themselves which is then used as an authentication token amongst the capsules to authenticate themselves. Currently, we simply aggregate this information and return it to the service; if desired, differential privacy techniques can be applied here as well.

In the future, we plan to merge these capsules with a client-side browser plugin to build a full-fledged system so that the plugin can automatically update the server-side capsule without any manual intervention from the user. This plugin would also interact with the capsule to obtain and display the selected ad in the case of the ChooseAd interface. If it is necessary for the server to maintain ad impression counts (for charging advertisers), then information about the selected ad can be sent after aggregation or via a broker to preserve anonymity; our system can borrow such functionality from PrivAd [29] and Adnostic [20]. Alternatively, our aggregation functionality may be used for this to obtain aggregate ad impressions as well.

**Provenance Capsule:** The final capsule we implemented belongs to the provenance idiom (Section 3.3) and models a editable document. It supports three calls: Get(), Insert(Position,String), and Delete(Position, NumChars). These calls suffice for any sequence of edits; we assume an editor program propagates any edits made by collaborators as calls to this interface so that the capsule is altered. Get() returns the current version of the document, while Insert() and Delete() can be used by, say, an editor, to convey changes made by a user to the document. The capsule retains a log of all invocations, thus binding each modification to the invoker. This illustrates that the capsule framework can also be used to provide properties such as accountability in addition to privacy.

**Other Possible Capsules:** There are also services where the some private data may be required when the service is disconnected from the Internet during invocation of the capsule so that a trusted third party solution is not feasible. One example is a service like CommonSense [30] where sensors are worn by users that record information about the user. This information may be processed by proprietary algorithms (for example, to monitor blood pressure); such algorithms have to be implemented at the sensor itself because the user may not be connected to the Internet at all times. In the future, we hope to implement this capsule.

### 6 Evaluation

We evaluate our framework based on four capsule instances (one per usage idiom): stock trading capsule, credit card capsule, targeted ads capsule, and provenance capsule. We omit the provenance capsule’s results since they reflect similar trends as for the other capsules. For the three capsules we evaluated, we present three scenarios: (A) the base case where the service interacts with the raw data with no access guarantees. (B) the TTP case, where the service interacts over the network with the user’s capsule hosted at a TTP. Since a TTP deployment is equivalent in terms of performance in most respects to a client-side capsule, we discuss both of them together, and mention any differences specifically. (C) the co-hosting case, where the service interacts with the data capsule housed in a Xen VM.

Our goal in this section is two-fold. Our first goal is to to evaluate the cost of privacy as the performance impact of the client-side / TTP deployment and co-location deployment options, as compared to the base case. Our metric of success here is hard to quantify in terms of absolute numbers; we only wish to show that this cost does not render our framework impractical. The second goal is to compare the various deployment options amongst themselves to determine the ideal deployment for each scenario.
Table 3: Invocation Cost (1 KB sensitive data, 1 KB invocation request, 1 KB invocation response)

| Scenario | Latency (micro-seconds) | Bandwidth (bytes) | In-Memory Storage (KB) | On-Disk Storage (KB) |
|----------|-------------------------|-------------------|------------------------|---------------------|
|          | (Mode, 50%-ile range, 95%-ile range) |                   |                       |                     |
| Base Case | 471.5 [379, 496] [347, 552] | NA | 1 (data) | 1 (data) |
| TTP       | 24796 [24718, 24867] [24525, 25033] | 3336 | 120 (capsule) + 1 (data) | 120 (capsule) + 1 (data) |
| Xen Capsule | 1237 [1097, 4203] [942, 4617] | NA | 120 (capsule) + 1 (data) | 120 (capsule) + 1 (data) |

We evaluate the performance for these scenarios along three dimensions: the setup cost (when the data or data capsule is transferred to the service), the invocation cost (when the service accesses the user’s data or data capsule), data transformation costs (the cost of operations such as aggregation). The term cost includes latency, network bandwidth consumption, and storage cost. Of these, the invocation cost is borne every time the user’s data is accessed, and is thus the primary metric of comparison. The setup cost is incurred during the initial and subsequent transfers of the user’s data, while the transformation cost, thought not as frequent as invocation, may be significant if the transformation involves data belonging to large numbers of users (such as aggregation).

Our test server is a 2.67 GHz quad core Intel Xeon processor with 5 GB memory on which Xen, the service code, and the capsule code run. A desktop (Intel Pentium 4 1.8 GHz processor, 1 GB memory), on the same LAN as the server, served as a TTP (or client). The bandwidth between the server and this desktop was 10 Gbps and the round-trip about 0.2 milli-seconds. To simulate a wide-area network between the client/TTP and the service, we used DummyNet [31] which artificially delays packets by a configurable parameter; by default, the round-trip is 10 ms (typical wide-area latencies from home users to well-provisioned services like Google are about 30 ms; we chose 10 ms under the conservative assumption that a TTP might have faster connectivity than average).

6.1 Framework Benchmarks

We first evaluate our framework independent of any specific kind of data. For these measurements, we used a dummy data layer that does not do any processing; it simply accepts a invocation payload of a specific size and returns a response of specific size to help in benchmarking.

Invocation Cost: The invocation costs for a fixed payload size of 1 KB are shown in Table 3 (the invocation request and response are both 1KB). For the base case, we assume that the service is architected as an server-side application that interfaces with a database process to access the user’s data. We assume that the database process runs on the same machine as the server-side application (ignoring any transfer costs) and that the user’s data is in memory (ignoring any costs of retrieving the data from disk). For the TTP case, the web service interacts with the capsule over the network. For the Xen capsule, the web service process accesses the data via the host hub module which invokes the capsule housed in a different VM instance. We assume that the capsule VM is housed on the same machine as the service VM (similar to the base case). We measured the latency as the time required for the process storing the user’s data to respond to an invocation by the web service; for this benchmark, we fixed the message sizes for the invocation request and response to be the same in all three scenarios. The bandwidth consumed is measured using tcpdump and includes packets in both directions as well as TCP headers. The in-memory storage cost and on-disk storage cost is measured directly. These results are reported in the table; all results are reported over 100 runs. For latency, we report the median, the 50% confidence interval, and the 95% confidence interval, since it is somewhat variable; we report only the median for bandwidth since we found it to be much less variable.

Though the latency via Xen is about 800 micro-seconds worse compared to the base case, it is still significantly lower compared to the TTP case. We found considerable variation ranging from 900 micro-seconds to 4000 micro-seconds with a median of 1237 micro-seconds; we believe this is related to the Xen scheduling algorithm which may delay the execution of the capsule VM. We plan to use techniques based on hardware virtualization [19] that allow for order-of-magnitude reductions in overhead by executing the capsule inside the service VM while still guaranteeing VM-like isolation (since capsules require no access to service VM state except via the interface, the “semantic gap” issue does not arise).

In the TTP case, the latency is primarily due to two round-trips (one for exchange of TCP SYN and SYN ACKs, and another for the invocation). The TTP option consumes 3.3 KB worth of network traffic per invocation, as opposed to the Xen co-location option and the base case where the invocation is local. The invocation request and the response are 1 KB each: a constant overhead of about 1 KB is incurred since our protocol sends invocation requests and responses over RPC/HTTP using libevent. In both the TTP and Xen case, the capsule code has to be stored in memory and disk; in our current un-optimized implementation, this code is about 120 KB. The LOC of the capsule in this case
is only 111 LOC; our current compilation technique bundles the glibc library as well which leads to this additional overhead. In practice, we believe that a single capsule implementation will be shared by several users (for instance, supplied by Symantec); thus a single copy of the capsule code need not be maintained for every user.

We now present a component-wise breakdown of the cost of an invocation request; recall that a request is made by the service to the host hub which then relays it to the Xen capsule. In this experiment, the average invocation latency was 1399 micro-seconds from the service’s perspective. Of this, 101 micro-seconds is due to host-hub processing, and 768 micro-seconds due to processing at the Xen capsule; thus, 530 micro-seconds was due to communication overhead (between the service and host hub, and between the host hub and the capsule). Within the Xen capsule, 165 micro-seconds was spent in verifying the invoker’s signature and 109 micro-seconds for policy verification; the remaining 494 micro-seconds was due to the processing of the 1 KB invocation payload and response. In conclusion, communication overhead is about 35% of the total latency; the rest is primarily due to processing within the Xen capsule (which may be slower since it is run in a guest VM).

**Varying Payload Sizes:** To examine the variation of the invocation cost across different payload sizes, we plotted the latency as a function of payload size (varied in multiples of 2 from 256 bytes to 32 KB) in Figure 4 (A). In the plot, the “cross” represents the median, the square box represents the 50%—ile, and the lines around the cross represent the 95%—ile. The plot only shows the base case and Xen case; since the TTP latencies are much higher, those are listed in the figure’s caption. This plot shows that the overhead added by Xen as a percentage of the base case declines, while the network transfer time increases the latency for the TTP case. Once again, we note that the variance in the Xen latency is substantial, especially at low invocation sizes. The bandwidth consumption for the TTP case varies roughly linear with the size of the payload, and are 1.7 KB (for invocation of 256 bytes size), 10 KB (4 KB), and 72 KB (32 KB); of course, in the Xen case and the base case, no network communication is involved for invocation.

**Setup Cost:** We now discuss the setup costs in the three scenarios (which are similar to the transfer costs from one service to another) for sensitive data of size 4 KB. In the base case, the latency is 13 ms (primarily due to the 10 ms round-trip) and the bandwidth consumed is 6 KB (the data size of 4 KB, plus libevent overhead, plus TCP headers and acknowledgement packets). In both the TTP and Xen case, the capsule code is sent from the client to the TTP / service, and then invoked from the base layer. The respective latency figures are 332 ms and 491 ms respectively; we found that this cost was dominated by about 300 to load the capsule code into memory and invoke it. We currently use dlopen for this purpose; we intend to replace this when removing glibc from our TCB, so the overhead should be significantly improved. The bandwidth cost is roughly the cost of transferring the capsule code along with the sensitive data; in the TTP case, this cost is incurred between the user and the TTP, while in the Xen case, the cost is incurred between the user and the service. Our main observation here is that, in comparison with the TTP case, the Xen capsule setup is not significantly higher; the cost of a two round trip protocol involving key generation for installation is out-weighed by the cost of the data and code transfer.

**Summary:** In terms of invocation costs, our main finding is that, in terms of latency, the capsule case is more expensive than the base case, but this overhead (as a percentage) decreases with payload size. In comparison with the TTP case, the latency gain provided by capsules is significant; even with a low round-trip delay of 10 ms, the capsule
| Scenario  | Stock Capsule | CCN Capsule |
|----------|---------------|-------------|
|          | Latency (micro-seconds) (Mode, 50%-ile, 95%-ile) | Bandwidth (bytes) | Latency (micro-seconds) (Mode, 50%-ile, 95%-ile) | Bandwidth (bytes) |
| Base Case | 413 [359, 466] [353, 478] NA | 336 [330.9, 344.5] [322.2, 436] NA |
| TTP       | 24224 [24143, 24303] [23954, 24432] 1294 | 366.4 [360.2, 380.2] [350.8, 550.8] 1327 |
| Xen Capsule | 1045 [1001, 4179] [936, 4407] NA | 344.6 [336.0, 361] [328.868, 523] NA |

Table 4: Single Invocation Costs for (A) Stock Capsule (B) CCN Capsule

Latencies are significantly better. And of course, bandwidth consumption proportional of the size of the invocation request and response are incurred in the TTP case, and not in the co-location case. In terms of setup costs and storage costs, the main cost is due to the size of the capsule code itself; we plan to reduce this in the future by removing the dependence on glibc and by altering our compilation tool-chain to produce flat code. However, in practice, this setup and storage cost may be amortized across several users who may trust the security company to provide their capsule.

6.2 Stock capsule

Table 4 shows the invocation cost for the stock capsule for the three scenarios. The advantage of the Xen option with respect to the TTP option is clear; co-location offers significant advantages here since the latency is about 15 ms lower and no network bandwidth is consumed. In the financial high-frequency trading market, this improvement is invaluable; firms typically pay substantial money to obtain such an advantage. The single invocation consumes a bandwidth of around 1 KB for the TTP Case.

In order to reflect a typical stock trading scenario where there are hundreds of ticker events per second, we plotted the latency metric versus varying number of back-to-back invocations (corresponding to ticker events in the stock market) in Figure 4 (B). Admittedly, this is an apples-to-oranges comparison since the TTP case requiring network access is substantially slower as compared to the Xen option and the base case. Comparing the Xen case and the base case for a sequence of 100 back-to-back invocations, the latencies are respectively 43.4 ms and 9.05 ms respectively; though the overhead due to Xen is substantial, it is still a significant improvement than the TTP case which requires 12 seconds. Regards the bandwidth, in the TTP case, the bandwidth consumed for a sequence of 5, 10, 50, 100, 500 and 1000 invocations are respectively 2.8, 4.8, 20.2, 39.4, 194, 387 KB respectively. In our experiments, we have only considered one symbol being traded; typically, a user would be interested in trading on tens or hundreds of different symbols, which would lead to a proportional increase in the bandwidth. Thus, the bandwidth required for say, 500 events per second, is about 1.6 MBps per user. Though well within the ability of today’s network, this bandwidth still to be provisioned and paid for, and can be expensive.

These results reflect that the flexibility of the framework with respect to deployment at the service site is a significant benefit in terms of network bandwidth. The capsule option is beneficial to both the stock broker and the user; the stock broker need only invest in a trusted module on its computers and avoid paying for bandwidth, while the user obtains the advantage of housing her trading strategy very close to the data source itself thus avoiding wide-area network round trips.

6.3 CCN capsule

We present the latency and the bandwidth consumption of a single invocation of the capsule in Figure 4. The invocation here involves interacting over the network with the payment gateway over the wide-area over SSL, and thus the additional overhead in the Xen Capsule or the TTP case is minimal as compared with the base case. The Xen capsule, in this case, consumes 10 ms more as compared to the the base case, and is in fact, more expensive than even the TTP case. This is due to the fact that we have offloaded the network stack to the host-hub; the SSL negotiation before the HTTP request is sent requires many packets to be sent, which involves several context switches between the two VMs, which leads to the increase in latency. We plan to reduce this overhead in the future by implementing a front end and back end specific to SSL which would farm out the significant portion of the computation to the host hub; the SSL front end in the capsule would only be responsible for (a) certificate verification (b) session key generation. This would help us both reduce the overhead as well decrease the TCB size. The credit charging request itself is a one-step HTTP request response protocol; thus this latency can be reduced by pre-establishing SSL communications or re-using session keys to avoid SSL negotiation during invocation. The latency numbers also reflect some outliers in the 95%-ile range; this is due to delay outliers at the payment gateway itself, and are not related to our framework itself. A nominal
Figure 5: (A) Invocation Costs for targeted ads capsules that serves ads under three different scenarios (base case, TTP, xen capsule) for the SelectAd interface: Latency (Y-Axis) vs (Number of Ads) (X-Axis). (B) Aggregation Bandwidth Requirement: Column titles denote number of users, Row titles reflect the scenario, and the matrix element denotes the bandwidth consumed (KB). Individual user histories are about 15 KB per user.

bandwidth of about 1.3 KB is consumed in the TTP case. Once again, we emphasize that these results demonstrate the cost of the generality in our framework as compared to custom solutions already deployed today; the main gain in the CCN case is due to the flexibility of policy, not performance.

6.4 Targeted Ads capsule

We present two sets of results for the targeted ads scenario. Figure 5 (A) shows the latency per invocation for the capsule to serve targeted ads using the SelectAd interface (we do not show results for the GetInterestVector interface due to lack of space). This graph shows that the Xen capsule has nearly the same overhead as the Base case capsule once the number of ads out of which the capsule selects one exceeds 5. This is mainly because the payload size dominates the transfer time. In the TTP case, the latency is clearly impacted by the wide-area network delay. The bandwidth consumed in the TTP case was measured to be 2.6, 8.3, 15, 8, 29.2 KB for 10, 50, 100, 200 ads respectively. These reflect the bandwidth savings of the co-located capsule option; since this bandwidth is incurred for every website the user visits, this could be significant.

There are two other operations supported by this capsule which are of interest: allowing a user to update her web history and the data aggregation transformation. For these operations, we present the bandwidth consumed, since latency is not the primary constraint in these cases. Regarding the update operation, the bandwidth required was measured to be 2.1, 4.8, 15.9, 23.3, 52.7 KB for 5, 10, 50, 100, 200 new websites visited per day by the user. The average number of websites visited per user is typically around 50 websites per day [32], so we chose to experiment in the range of 5 – 200 websites per day. This bandwidth is incurred in the server-side capsule, the base case, and the TTP case; it however is not necessary in the client-side capsule. In the case of targeted advertising, we expect that the update traffic per day is much lower than the cost of sending ads (which change much more frequently); thus the server-side co-located capsule is advantageous with respect to bandwidth consumption. In other cases where user data is much more frequently updated, a client-side capsule may be more suitable.

Regarding the aggregation operation, we currently employ an aggregation strategy that optimizes the total bandwidth consumed. In these experiments, we consider \( N \) users who have decided to pool their data together. In the base case and Xen case, we assume that the data of each user is hosted on a physically different machines in the data-center; the optimal way to combine their data in terms of bandwidth is for a simple hub-and-spoke model. This is accomplished by the local host-hub for users 1, \( \cdots \), \((N - 1)\) executing a pull operation on their capsules, and pushing the resultant encrypted histories to the host-hub for user \( N \). At this point, the capsule for user \( N \) would release the aggregate data upon request. In the TTP/client-side case, we assume that the \( N \) users have each entrusted their data to \( N \) different administrative entities; in this case, the bandwidth-optimal strategy is for the service is a similar hub-and-spoke strategy. We experimented with varying numbers of users and present the bandwidth consumed in Figure 5 (B). In this experiment, the data per user is fixed to be 1KB per user. The bandwidth consumed for the Xen case and the base case are the same since the same strategy is involved; the TTP case consumes much more bandwidth since both the push and pull requests require remote access, as does the final pull from capsule \( N \). Thus, the advantage in the Xen case is that the bandwidth is lower, and further the bandwidth consumed is only intra-data-center. Further, the bandwidth consumed can be optimized much more easily for the server-side capsule and the base case since it is
within the confines of a single administrator. This demonstrates the usefulness of the aggregation operation especially when thousands of users are involved.

7 Security Analysis

We now discuss the desirable security properties of our capsule, determine the TCB for these security properties to hold, and argue that our TCB is a significant improvement over the status quo.

7.1 Security Properties

Security Goal: Our over-arching security goal (from our problem statement in Section 2) is that any access to the data or any transfer of the data must only occur in accordance with the interface and policies sanctioned by the user. The adversary is a party that has compromised the software stack at the service or is a party that has physical access to the machine hosting the capsule. Note that this goal offers protection only to the extent to which the data is protected by the interface and user’s policies. For instance, if the user specified a budget of 100 dollars for her credit card, and the machine hosting her capsule was compromised, her card could be charged up to her budget by the compromise. However, such a charge would still be securely tied to the compromised service since it is not possible to spoof the invoking principal, thus offering sufficient data for post-mortem forensics. Further, we note that the service can always launch an availability attack in the co-located case by simply refusing to service requests using its host hub or by denying access to a user in accessing her capsule to, say, retrieve a record of all operations; we only aim to prevent the adversary from violating the policy constraints, not liveness requirements.

Informal Security Argument: We will now present informal arguments as to why our capsule framework achieves this security goal. In the case of a TTP-based deployment, the argument is simple; we rely on the isolation provided by the TTP and the correctness of the capsule implementation to ensure the security goal. The rest of this section is concerned with the co-hosting case. We are currently exploring using the LS$^2$ framework [33] to state and formally verify our security goals in the co-hosting scenario; we defer such any formal argument for future work. In the following informal arguments, we will assume that the trusted module provides the four security properties detailed in Section 4.1: isolation, remote attestation, anti-replay protection, and random number generation.

We make this argument in two steps. First, we argue that any interaction between the service and the user’s data occurs only via the functions exported by the capsule base layer. Second, we will rely on the base layer protocols and its correctness to ensure that all these interactions are in conformance with the user’s policies.

For the first, we will rely on the isolation property of the trusted module. In the case of the VM, this assumes that the VM hosting the service code can interact with the capsule VM only via the XenSocket interface. This requires that the VMM be placed in our TCB. We also assume that the VMM prevents significant leakage of information through side-channels such as memory page caching, CPU usage: this is a subject of ongoing research (e.g., Tromer et al. [34]). For the second, we note that the following lists all the possible interactions between the service and the capsule: installation, invocation, hosting transfer, and data transformation (going through the parts of the framework in Section 3). We will now consider each in turn.

Installation: The installation protocol (Section 4.2) provides three properties in this regard. First, it uses the attestation functionality of the trusted module to ensure that only the base layer code generates the public key in response to the first installation message. Second, the installation protocol (based on the classic Diffie-Hellman protocol with RSA keys exchange alongside the Diffie-Hellman messages) ensures the confidentiality of the information; only the party which generates the public key in response to the first installation message can decrypt the capsule. Due to the attestation guarantee, this party is guaranteed to the base layer, which is trusted. Note we rely on the random number generation ability of the trusted module to ensure that the generated public key is truly random and cannot be biased or guessed by the adversary. Third, since the attestation verifies the purported input and output to the code which generates the public key, man-in-the-middle attacks are ruled out; an adversary cannot alter any part of the message without rendering the attestation invalid. These three properties ensure in conjunction that the capsule can only be decrypted by the base layer. We then rely on the correctness of the base layer to argue that the capsule is correctly decrypted and instantiated at the service.

Invocation: We next need to argue that any invocation occurs in accordance with user’s policies. Every invocation is checked by the base layer to ensure: (a) the identity of the invoking principal (b) the correctness of any supporting policies (c) that the user-specified policies along with the supporting policies allow the invoking principal the privilege to make the particular invocation.
The identity of the invoking principal is verified either against a list of public keys sent during the installation protocol (this data list binds the names of services to their public keys) or, in the case of the owner, it is verified against the public key of the data owner sent during the installation protocol. In either case, the correctness of the installation protocol ensures that the identity cannot be spoofed since the list of public keys used to validate the identity is correct. The correctness of the supporting policies is ensured by verifying that each statement of the form $X$ says $\cdots$ is verified against the signature of $X$. The policy resolver takes two sets of policies as input: the database of policies sent by the user and the set of supporting policies sent by the invoker. The correctness of the latter we have already argued for; for the former, we rely on the anti-replay property provided by the trusted module to ensure that the database of policies in the capsule (which can be updated over time) is up-to-date and reflects the outcome of all the invocations made so far. We assume the correctness of the policy resolver to ensure that it answers invocation queries correctly in accordance with these policies. For stateful constraints, the implementation also updates the state before returning the result of the invocation to the service.

Once the invocation is granted by the base layer, it is passed on to the data layer which carries out the required functionality. In cases such as a query capsule or an analytics capsule, this functionality is carried out entirely within the data layer, which we assume to be correct. In cases such as the proxy capsule, which requires access to the network, we note that though the network stack is itself offloaded to the host hub, we rely on the host hub only for availability, not for safety. The SSL library and cryptographic library are enclosed within the capsule, and thus, it does not matter that the host hub is effectively a man-in-the-middle. In this respect, we also note that the other services provided by the host hub, namely, persistent storage and obtaining the current time, are similarly relied only for availability, not safety, since the base layer validates persistent storage using its own integrity and confidentiality checks (once again, relying on the anti-replay functionality provided by the trusted module), and verifies the current time by validating the source (such as a trusted NTP server).

We next consider the hosting protocol. Since it consists of the invocation protocol (used by the service to make the transfer request) and the installation protocol (used to effect the transfer), we rely on our arguments regarding invocation and installation to argue that hosting is in accordance with our security goal as well.

**Data Transformation:** We now turn our attention to the data transformation protocol. The filtering and update protocol happen only within the confines of a single capsule, and their correctness arguments is similar to those for invocation. The aggregation protocol though more complicated decomposes into a number of simple pair-wise aggregation operation. Since during the pair-wise operation, a capsule verifies the identity of its peer as belonging to a user who is part of the data crowd, the data is merged only between capsules that are part of the same data crowd. Since the merged information is only revealed to the service after a minimum number of capsules belonging to the data crowd are merged, this aggregation is in accordance with the user’s policies.

### 7.2 TCB

We now evaluate the TCB of our capsule framework. From the previous section, it is clear that our TCB consists of: (A) the trusted module (B) the data layer interface and implementation (C) the base layer protocols and implementation.

The trust assumption in (A) appears reasonable for VMMs, TPMs, and a secure co-processor. A carefully managed VMM which presents a minimal attack surface to applications inside a guest VM may be judged to be adequate enough to defend against software threats. Similarly, TPMs and secure co-processor have both been designed across several iterations; it seems reasonable to expect that their designs and implementation in today’s chipsets will be difficult to exploit. Regarding (B) and (C), the LOC metrics are discussed in Section 5.1. We base our trust in the data layer interface and implementation in the simplicity of the interface; the data specific portion of the interface is less than 500 lines even for our most complicated capsule (the CCN capsule). For other capsules following the query idiom, analytics idiom, and provenance idiom, the implementation is even simpler since no network access is required.

Currently, the base layer protocols and implementation are much more complex than the data layer itself, as reflected in the LOC metric (the base layer has roughly 6K LOC). While we have aimed to keep our design simple right from a minimal policy language to offloading network access to the untrusted host hub, the base layer is still complex, and currently includes a cryptographic library (PolarSSL) as well. In the future, we hope to formally verify the correctness of this implementation. For now, our only argument is that even granting that the base layer is complex, it offers a significant improvement in security to users of web services today who have no choice but to rely on an unaudited closed source service code for their privacy guarantee. More importantly, it restores control to the user over her data, allowing a security conscious user to invest in a secure capsule implementation for her data from a trusted security company. Another comparison point in this respect is an information flow control system (such as JIF or Asbestos). The TCB in such a case includes the run-time (in Jif’s case, this is the Java run-time along with Jif’s typing rules; in Asbestos’s case, it would be the operating system) along with any trusted de-classifiers (a declassifiers is a
code block or a process that is allowed to break the typing rules or propagation rules; such declassifiers are essential to prevent over-conservative information flow propagation. We believe this compares favorably with our TCB; building a general enforcement mechanism seems a more complex undertaking than implementing a simple interface which makes our approach easier to verify.

8 Related Work

We first discuss two closely related papers in literature, before examining broader related work. The closest related work to our own is in Wilhelm’s thesis [12] (Chapter 5). This work leverages mobile agents (a well-investigated research paradigm; an agent is code passed around automatically from one system to another in order to accomplish some functionality) to address the issue of privacy. The suggestion is to encapsulate data with a generic policy enforcement layer that provides a fixed set of functionality (such as, enforce time for retention, audit operations). The main differences from our approach are: (a) our work is tailored towards web services; in particular, operations like hosting transfer and data transformation were chosen to model how web services handle data today (b) our approach is extensible to various kinds of sensitive data; the enforcement layer is configurable by the user and is specific to the particular kind of sensitive data (c) we aim to design the capsule interface itself so as to reduce data exposure. The second closely related paper to ours is by Iliev et al. [13]. They propose the use of trusted hardware to offer client privacy when operating on server data for two applications: private information retrieval (without traditional cryptographic mechanisms) and an armored network traffic vault. This proposal is similar to our co-location option. Two characteristics of our framework that are pertinent to web services, and do not apply to [13] are: (a) support for scenarios where a user’s data is spread across multiple services. (b) policy-based control over invocation, hosting, and data transformation. Apart from these specific papers, our work is related to the following broad areas:

Information Flow Control (IFC): The principle of IFC has been implemented in OSs (e.g., Asbestos [9]) and programming languages (e.g., JIF [5]), and allows the control of flow of information between multiple processes or security compartments. IFC has also been used to build secure frameworks for web services in W5 [35], xBook [8].

The main difference from the capsule framework is that we provide data access control, not data propagation control. Privacy is guaranteed by the interface chosen by the user, and not by run-time policy enforcement. Capsules apply only to cases where an interface can be arrived at that offers sufficient privacy to the user as well as is usable to the service; if no such interfaces exist, we can leverage IFC frameworks to control the propagation of sensitive information. The advantage in restricting to interface-based access control is that we can rely on a variety of isolation mechanisms (such as TPMs) without requiring a particular OS or programming language. Further, the simplicity of the interface makes it feasible to envision the possibility of proving the correctness of capsule code; doing so in the IFC case requires one to prove the correctness of the enforcement mechanism (OS or compiler) which can be significantly more complex.

Decentralized Frameworks For Web Services: Privacy frameworks that require only participation from users have been proposed as an alternative to web services. VIS [36] maintains a social network is maintained in a completely decentralized fashion by users hosting their data on trusted parties of their own choice; there is no centralized web service. Capsules are more compatible with the current ecosystem of a web service storing user’s data and rely on the use of interfaces to guarantee privacy. NOYB [22] and LockR [37] are two recent proposals that rely on end-to-end encryption to hide data from social networks; both these approaches are specific to social networks, and their mechanisms can be incorporated in the capsule framework as well, if so desired.

Enterprise Privacy Architectures: Several privacy architectures that deal with the propagation of information within an enterprise or across closely-related enterprises have been proposed. These include Ashley et al. [38], Backes et al. [39], GeoDac [40]. Broadly, these papers propose specification languages and enforcement mechanisms that help enforce enterprise-wide policies on data retention, access logging, and other accountability guarantees. The main difference from the capsule framework is that (a) our framework involves two mutually distrusting parties, the user and the service, and thus we only base enforcement on hardware or system software, rather than application software. (b) our framework is designed for web services. (c) our goal is to enforce interface constraints and policy control that control data leaks, rather than to enforce generic data control policies. In future, we hope to incorporate guarantees provided by these architectures in our framework as well. Our provenance capsule is also related to VFIT [41] and GARM [42] which follow the modification of data across multiple machines.

Privacy in Cloud Computing: The area of cloud computing has seen a lot of work in the context of privacy as well. These include Trusted Cloud [43], Accountable Cloud [44], Cloud Provenance [45]. These works deal with the more complex problem of guaranteeing correctness of code execution on an untrusted third party. Capsules are only concerned to protecting the privacy of the user’s data; we assume the application service carries out the service (such as sending correct ticker data) as expected. Airavat [46] proposes a privacy-preserving version of MapReduce.
based on information flow control and differential privacy; capsules support general kinds of computation, but have to rely on manual re-factoring whereas Airavat can automatically ensure privacy by restricting itself to specific types of MapReduce computations. We also note that attacks based on leakage across VMs are known [47] and defense mechanisms against such attacks are also being developed [34]. Our capsule framework can avail of such defense mechanisms as they are developed further; we view such work as orthogonal to our central goal.

Targeted Advertising Systems: PrivAD [29] and Adnostic [20] are recent proposals that are client-side systems for targeted advertising; this is somewhat similar to a client-side targeted ads capsule in our framework. The difference is that our framework generalizes to other deployment scenarios as well. In the future, we hope to borrow their techniques for anonymized ad impression collection in our targeted ads capsule as well; currently, we do this using aggregation, PrivAD and Adnostic offer dealer-based and encryption-based mechanisms respectively for this purpose.

Mechanisms: The capsule framework builds on existing isolation mechanisms, such as the virtual machine security architecture (e.g., Terra [16]), proposals that use TPMs (e.g., Flicker [3]), and systems based on a secure co-processor [48]. These proposals offer the foundation upon which our capsule framework can build on to provide useful guarantees for data owners. Our implementation also borrows existing mechanisms (XenSocket [18], vTPM [49], disaggregation [27], use of hardware virtualization features [19]) that help us improve the performance and security of a virtual machine based architecture. Currently, we do not provide any automatic re-factoring mechanisms; in the future, we hope to explore using existing program partitioning approaches (e.g., Swift [50], PrivTrans [51]) for this purpose.

9 Conclusion and Future Work

Our capsule framework applies the well-known principle of encapsulation to provide data access control guarantees to users who wish to avail of web services that operate on their data whilst still retaining control over the use of said data. Our design goals are to allow flexible deployment of such capsules and to provide flexible policy control to their users. The capsule approach works when a satisfactory interface can be arrived at that gives privacy to the user while still sufficing to carry out the service: we show this to be the case for a broad variety of currently operating web services. For others, one can rely on information flow control techniques or end-to-end encryption to obtain privacy guarantees. Our prototype implementation includes four kinds of capsules as examples; although the performance of the co-located Xen-based capsule is not quite suitable for deployment in a production service, they do offer substantial advantages over the TTP and client-side capsules in the dimensions of network bandwidth consumption and/or provisioning cost.

We identify three fruitful avenues for future work. First, our implementation can be improved by incorporating known virtualization techniques to reduce overhead and by removing the need for including system libraries and kernels in our TCB by a more careful implementation. Second, formal verification of the control layer implementation and its security protocols would allow for much greater confidence in its correctness as compared to today. We have done some preliminary work in this area towards expressing our implementation in a formal language and proving that it conforms to our security expectations. Similar correctness guarantees would be useful for the data layer interface and implementation as well. The flavor of correctness proofs here is different from those in the control layer protocol; the goal is to prove that there is no leakage of information via the implementation. One can envision static information flow checking (such as JIF [5]) to provide such a guarantee, or a proof from scratch based on computational non-inference. Third, given the complementary nature of information flow control systems, it would be useful to integrate such elements into the capsule framework; interface calls which do not leak any information would be part of the capsule framework, leaky interface calls can leverage use of the information flow policies. Of course, the former would involve a smaller TCB, since information flow requires placing the information flow enforcement kernel in the TCB.

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