Secure Serverless Computing Using Dynamic Information Flow Control

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The rise of serverless computing provides an opportunity to rethink cloud security. We present an approach for securing serverless systems using a novel form of dynamic information flow control (IFC).

We show that in serverless applications, the termination channel found in most existing IFC systems can be arbitrarily amplified via multiple concurrent requests, necessitating a stronger termination-sensitive non-interference guarantee, which we achieve using a combination of static labeling of serverless processes and dynamic faceted labeling of persistent data.

We describe our implementation of this approach on top of JavaScript for AWS Lambda and OpenWhisk serverless platforms, and present three realistic case studies showing that it can enforce important IFC security properties with low overhead.

1 INTRODUCTION

In May 2017, the Equifax credit reporting agency suffered a security breach, leaking social security numbers and other personal information of 145.5 million consumers [34]. The breach, which exploited a code injection vulnerability in Apache Struts [49], became the latest in a series of high-profile attacks on public and private clouds compromising sensitive personal information of hundreds of million users [22, 23, 28, 33, 62, 65–68, 72, 73].

Most of these attacks can be traced down to two types of faults: misconfigurations and software vulnerabilities. The former include issues like incorrect database security attributes [28, 53, 61], the choice of weak authentication schemes [23], or the use of unpatched software [34]. The latter include code and SQL injections, file inclusions, directory traversals, etc. [21, 22, 72, 73].

Simply put, the enormous Trusted Computing Base (TCB) of modern cloud applications makes it intractable to enforce information security in these environments.

A promising avenue to a smaller TCB lies in the use of information flow control (IFC)-based security [25, 54]. In the IFC world, information is protected by a global security policy that cannot be overridden by a misconfigured application. The policy explicitly and concisely captures constraints on end-to-end information flow through the system, e.g., “credit card numbers can only be exposed to appropriate card associations (e.g., Visa or MasterCard)”.

The IFC system enforces the policy even for buggy or malicious applications, thus removing application code and configuration from the TCB of the cloud. In particular, an application that has been hijacked by a code injection attack should not be able to bypass the enforcement mechanism. This is in contrast to security models based on access control lists or capabilities, where, for instance, a compromised program running with database administrator privileges can easily leak the entire database to a remote attacker.

Despite significant progress on IFC, it remains difficult to apply in real software. Dynamic IFC systems [8, 24, 29, 60] incur high runtime overhead. Static IFC [47, 48, 54, 71] systems shift the costs to development time,

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usually via the use of type systems; however, they restrict the style of programming, which complicates their adoption.

We demonstrate that *IFC for cloud computing is not only feasible, but can be implemented with low overhead and for essentially unmodified applications*. We achieve these properties by leveraging recent developments in cloud computing, namely, the rise of *serverless computing* [56]. Initially popularized by Amazon’s AWS Lambda [2], serverless computing is rapidly gaining adoption by cloud providers [6, 32, 38, 41, 46] and tenants [1, 14, 19, 20, 30, 31, 36, 43, 51] due to its key benefits: elastic scalability, ease of deployment, and flexible pay-per-use pricing.

It achieves these benefits by decoupling application logic from resource management. In the serverless model, users express their applications as collections of functions triggered in response to user requests or calls by other functions. A function can be written in any language and may request a certain runtime environment, including, e.g., specific versions of the Python interpreter and libraries. However, the function is agnostic of where this environment is instantiated: a physical machine, a virtual machine or a container. The cloud platform manages function placement and scheduling, automatically spawning new function instances on demand. This requires application state to be decoupled from functions and placed in a shared data store (e.g., a database or a key-value store), allowing all function instances to access the state regardless of their physical placement in the cloud.

We argue that serverless computing has fundamental implications for cloud security. In particular, it enables practical IFC for the cloud. Our key observation is that *a serverless function constitutes a natural unit of information flow tracking*. First, a serverless function activation handles a single request on behalf of a specific user and only accesses secrets related to this request. Second, each invocation starts from a clean state and does not get contaminated with sensitive data from previous invocations. Under a conservative assumption that all secrets obtained during function execution propagate to all its outputs, we *can track the global flow of information in the system by monitoring inputs and outputs of functions comprising it*.

Based on this observation, we develop the first IFC system for serverless applications, called Trapeze. Trapeze encapsulates each unmodified serverless function in a *sandbox*, which intercepts all interactions between the function and the rest of the world, including other functions, shared data stores, and external communication channels, and redirects them to the *security shim* (Figure 1). The shim tracks information flow and enforces the global security policy.

The class of supported policies, along with policy enforcement rules, is defined by Trapeze’s *dynamic IFC model*. The model addresses a weakness in most existing static and dynamic IFC systems, which leak information through the *termination channel*, whereby an adversary can infer secrets by observing termination or non-termination of the program. The massively parallel nature of the serverless environment amplifies this weakness, allowing the attacker to construct a high-bandwidth information channel, effectively defeating the purpose of IFC (Section 2).

Our IFC model eliminates this channel by enforcing a strong security property known as *termination-sensitive non-interference* (TSNI) [55]. Only a handful of previous IFC models achieve this level of security; however these models are either too restrictive for most practical applications [15, 55, 58], or introduce significant overhead [27] (see Section 7).

Trapeze achieves TSNI through a novel combination of static program labeling with dynamic labeling of the data store based on a faceted store semantics. Static program labeling restricts the sensitivity of data a serverless function can observe ahead of time and is key to eliminating the termination channel. Dynamic data

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![Fig. 1. Trapeze architecture. Serverless function F is encapsulated in a sandbox. All inputs and outputs of F, including (a) invocations of F from within and from outside of the cloud, (b) calls to other serverless functions, (c) reads and writes to shared data stores, and (d) external communication channels, are monitored by the security shim.](image-url)
labeling is crucial to securing unmodified applications that do not statically partition the data store into security compartments, while the faceted store semantics eliminates implicit storage channels. We present a formal proof, validated using the Coq proof assistant, that our model enforces TSNI.

We evaluate Trapeze on three real-world serverless applications: an online retail store [51], a parallel build system [35], and an image feature extraction service [57]. We use Trapeze to secure these applications with minimal changes to application code and with low runtime overhead.

Thus, our key contributions in this work are (1) a light-weight IFC shim architecture for serverless computing, (2) a new IFC model that enforces TSNI, along with its formal semantics and proof of correctness, and (3) an experimental evaluation of the architecture and the model on three serverless applications.

Finally, we point out that our IFC model is not limited to the serverless domain. Generally speaking, it applies to any reactive system that decouples computation from state. Algorithmically, we show that TSNI can be enforced in such systems efficiently. Examples of such systems include, e.g., Hadoop [5], Apache Spark [70] and Stateless Network Functions [44].

2 WHY A NEW IFC MODEL FOR SERVERLESS?

As discussed above, a serverless function offers a convenient unit of information tracking, enabling practical IFC for serverless applications. It seems natural that our next step should be adapting one of many existing IFC models to the serverless environment. However, we do not take this path, as existing models do not provide adequate security for serverless applications. Specifically, most previous IFC models, both dynamic and static, enforce a security property known as termination-insensitive non-interference (TINI) [55]. Intuitively, TINI guarantees that an attacker cannot deduce secrets stored in the system from its non-secret outputs. However, they may be able to deduce part of a secret from the fact that the system stopped producing outputs.

This information channel, known as the termination channel, is often disregarded because it has low bandwidth, typically leaking just a single bit. This is not true in serverless systems. Below, we construct an attack on a serverless application, that amplifies the termination channel by spawning many parallel computations, each leaking one bit.

Example 2.1. Consider a serverless system with two users: a benign user Bob and a malicious user Eve. We introduce security labels $b$ and $e$ to tag Bob’s and Eve’s data respectively. Labels form a lattice, with labels higher up in the lattice representing more secret data. Bob and Eve are mutually distrusting, therefore their labels are incomparable (Figure 2a).

Eve launches a code injection attack against serverless function $F$, forcing the function to execute malicious code in Figure 2b. This code is designed to leak Bob’s 64-bit secret stored under key 100 in the key-value store to Eve.

We assume that the system is secured using a classical dynamic IFC model, where, upon reading a value from the store, the function’s label gets bumped to the least upper bound of the function’s previous label and the value’s label (note that, since the security shim cannot observe the data flow inside the function, it must conservatively taint the entire function with this label). The function initially runs with Eve’s label $e$ (every line in the listing is annotated with the current label of the function). Before reading Bob’s secret, the function forks 64 instances of helper function $H$ (lines 2–3). Each instance of $H$ will leak one bit of the secret. Next, we read the secret, bumping the function’s dynamic label to $b \sqcup e = \top$ and encode it using the first 64 keys in the store: we store an arbitrary value under key $i$ iff the $i$th bit of the secret is 1 (lines 5–7).

The helper function $H$ also starts with initial label $e$. After a short delay (line 10), it reads the key equal to the function’s argument $i$ from the store (line 11). At this point the function’s label either bumps to $\top$ if the corresponding bit of the secret is 1 or stays at $e$ otherwise. Line 12 attempts to send a message to Eve (here, $eve$ is a handle to Eve’s HTTP session), which succeeds if the label of the channel ($e$) is higher than or equal to the
function’s current label and diverges otherwise. Eventually, the attacker at the other end of the channel receives the list of bits of the secret equal to 0.

We implemented the above attack in AWS Lambda and were able to leak 170 bits per second by scaling the number of threads. Thus, by elastically scaling the computation, the serverless architecture also scales the termination channel. This is inline with theoretical results, which suggest that in a concurrent system, the termination channel can leak a secret in time linear in the size of the secret \[7\].

We therefore aim for a stronger security guarantee, known as termination-sensitive non-interference (TSNI) \[55\], which eliminates the termination channel. Note that the termination channel in the above example arises as the function’s label, and hence its ability to send to an external channel, depends on the labels of values the function reads from the store. In contrast, our proposed model assigns a static security label to each function activation. To do so, we take advantage of the fact that a serverless function always runs on behalf of a specific user and can be assigned a corresponding security label. The complete model, presented in Sections 3 and 4, also offers a secure way to dynamically increase the function’s label without introducing a side channel.

The function’s label determines its view of the data store: the function can only observe the existence of data whose label does not exceed the function’s label. For example, when reading a key that contains a secret above function’s current label, the store returns the same result as if the key was not present in the store. This information hiding semantics is somewhat tricky to maintain when multiple functions with incomparable labels write to the same store location. We avoid information leaks in this situation by employing faceted store semantics, where each record can contain several values (facets) with different security labels \[10, 69\].

To the best of our knowledge, Trapeze is the first IFC system to combine static program labeling with dynamic labeling of data (using faceting). This combination eliminates termination and storage channels and enforces a strong security property, TSNI.

3 INFORMAL DESIGN

3.1 Threat model and assumptions

We assume that the following entities are trusted, i.e., not malicious or compromised: (1) the cloud operator, (2) physical hosts and network, (3) system software (OS, hypervisor, container manager, scheduler), (4) serverless

```plaintext
1 function F/*compromised*/():
2 e for i = 0 to 63:
3 e fork H(i)
4 e secret = store.read(100)
5 T for i = 0 to 63:
6 T if secret[i]:
7 T store.write(i,1)
8
9 function H(i):
10 e delay(1s)
11 e store.read(i)
12 e/T eve.send(i) /*diverges if label is T*/

(b) High-bandwidth termination channel in the classical dynamic IFC model.
```

(a) Example security lattice. \( \top \) is the most secret label at the top of the lattice; \( \bot \) is the bottom (least secret) label.

Fig. 2. A security lattice and a termination channel.
runtime, (5) shared data stores, (6) the sandboxing technology. Assumptions (1) through (5) can in the future be relaxed with the help of a secure enclave technology such as Intel SGX [40, 42], data encryption, and software verification [26, 39].

We further trust the serverless application administrator to enforce the following invariants on application configuration: (1) all data stores used by the application are configured to only be accessible from serverless functions, (2) all serverless functions in the system are sandboxed.

Finally, we trust the application developer to correctly define the application’s information flow policy and declassifier functions (Section 3.4).

The rest of the application is untrusted. In particular, we assume that the attacker can compromise application code running inside serverless functions, including any of the frameworks and libraries it uses.

In this paper we focus on data confidentiality, i.e., protecting sensitive data from being exposed to unauthorized users. The complementary problem of enforcing data integrity, i.e., protecting data from unauthorized modification is outside the scope of Trapeze, although it can also be enforced with the help of IFC techniques [54]. Finally, we are not concerned with timing and other covert channels [17]. An example of such a channel is a function running with a high label communicating with a function running with a low label by modulating its CPU or memory usage.

3.2 Security lattice

We start the construction of our IFC model with the lattice of security labels. Labels represent security classes of information flowing through the system. Trapeze does not assign any specific semantics to labels; however in practice they typically represent users or roles of the system.

Trapeze relies on a trusted authentication gateway to tag all external input and output channels with correct security labels. For example, when Eve establishes an HTTP session with the system, the session gets tagged with Eve’s label $e$.

Given the labeling of inputs and outputs, Trapeze applies information flow rules presented below to enforce that information received through an input channel labeled $l_i$ can only be exposed through an output channel labeled $l_o$ if $l_i \sqsubseteq l_o$.

3.3 Information flow rules

The choice of information flow rules determines two critical properties of an IFC system: security and transparency. The former characterizes the class of insecure behaviors the system prevents. The latter characterizes the class of secure programs that the system executes with unmodified semantics and that therefore do not need to be modified to work with Trapeze. Trapeze’s enforces the strong security property of TSNI at the cost of some loss of transparency that, we argue, is acceptable in serverless systems.

Trapeze assigns a runtime security label to every serverless function activation. This label is derived from the event that triggered the function. In particular, if the function was invoked via an HTTP request from a user, it obtains the user’s security label. Alternatively, when invoked by another function, it inherits the caller’s label. The function’s label controls its ability to send to an output channel: a send is only allowed if the function’s label is smaller than or equal to the channel label.

Trapeze also dynamically labels records in the data store. To this end, the security shim intercepts data store operations issued by the function and modifies them to insert and check security labels. When a function creates or updates a record in the store, the record inherits the function’s label (see detailed write semantics below). When reading from the store, the function only observes values whose labels are below or equal to its own label. From the function’s perspective, the store behaves as if it did not contain any data that the function may not observe.
A function can upgrade its label to an arbitrary higher label using the `raiseLabel` operation. This operation does not introduce an unauthorized information channel, as the decision to upgrade cannot depend on secrets above function’s previous label (such secrets are simply invisible to the function). The upgrade mechanism is useful, for example, when a function running on behalf of a regular user needs to update global statistics on behalf of a superuser. Upgrade is a one-way operation: a function’s label can never be downgraded below its current value.

```
function Fb():
    b secret = store.read(100)
    for i = 0 to 63:
        if secret[i] == 1:
            store.write(i,1)
    function Fe():
        e x = 0
        for i = 0 to 63:
            store.write(i,1234)
        if store.read(i) == 1:
            x[i] = 1
        eve.send(x)
```

Fig. 3. Implicit storage channel via conflicting writes.

**Store semantics** Trapeze’s security shim conceals the existence of data whose security label is not less than or equal to the function’s label. Maintaining this semantics is straightforward when all writes to a data store location carry the same label. In the presence of conflicting writes, a resolution mechanism is required to avoid implicit storage channels [9]. When the conflicting labels are comparable, conflict resolution can be performed, e.g., using the no-sensitive-upgrade rule [9]. However, no such mechanism that avoids storage channels exists for writes with incomparable labels. The following example illustrates the problem:

**Example 3.1 (Implicit storage channel).** Suppose we resolve conflicts by ignoring writes when an incomparable label exists in the store (alternative strategies, e.g., silently overriding the existing value or failing the conflicting write are similarly vulnerable). Figure 3 shows two functions running with labels $b$ and $e$ respectively that collude to leak Bob’s 64-bit secret to Eve. $Fb$ reads the secret in line 2; however it does not have the authority to send it to Eve directly. Instead it encodes each bit of the secret using a record in the key-value store, as in Example 2.1 (lines 3–5). $Fe$ reconstructs the secret by attempting to write to locations 0 to 63 and then reading the value back in. Writes to locations that correspond to 1s are ignored, indicating that the corresponding bit of the secret is 1.

We eliminate such unauthorized flows using *faceted store semantics*, where each record can contain several values (facets) with different labels [10, 69]. Facets are created dynamically: when a value with a new label is stored in the record, a facet is created for it (see Section 4 for precise semantics). A read returns the most recent write that is visible to the function. Thus, facets conceal writes with label $b$ from a function running with label $e$, unless $b \sqsubseteq e$.

**Example 3.2.** We replay the example in Figure 3 with faceted store semantics. Since function labels $b$ and $e$ are incomparable, their respective writes will go into different facets. The functions do not observe each other’s writes either explicitly or indirectly, as in Example 3.1.

Faceted stores were previously introduced in IFC research in work on faceted execution [10, 12, 69]. The fundamental difference from our approach is in the read semantics. Under faceted execution, a read conceptually forks the program, creating a separate branch for each facet read from the store. If the program sends to an external channel, only the branch whose label is compatible with that of the channel is allowed to send. Similar to our design, faceted execution eliminates storage channels; however it does so at a potentially high runtime cost and may become impractical in a system with a large security lattice. In contrast, Trapeze avoids faceted-execution using the apriori knowledge of the function’s label by pruning all incompatible facets at read time. Existing faceted execution systems expose the termination channel and therefore enforce TINI, whereas Trapeze enforces the stronger TSNI property.
In the practical use of Trapeze, faceting is an exceptional situation. Trapeze is designed to run unmodified applications that assume conventional store semantics. The moment multiple facets are created in some store location, this semantics is violated, as different functions can now observe different values at the same location. Trapeze treats such situations as attempted exploits and notifies the administrator, who can then take recovery actions, e.g., remove the offending function from the system and rollback the store to the previous consistent state. In the meanwhile Trapeze guarantees that the system continues running without exposing any sensitive information to the attacker.

Faceted store semantics is emulated by the security shim on top of a conventional non-faceted store. In Section 6, we implement facets on top of a key-value store. Yang et al. [69] present the design of a faceted SQL database. The flip side of Trapeze’s strong TSNI security guarantees and light-weight protection is the theoretical loss of transparency, i.e., the ability to run existing unmodified applications. By assigning a static security label to a function, we restrict data that is visible to it. In particular, the function cannot access values above its security level even if it does not send these values (or anything derived from them) through unauthorized channels. On the other hand, all writes to the data store performed by the function are conservatively labeled with the function’s label even if they do not carry any secrets.

Both problems can be addressed by refactoring the application. In particular, the function can gain access to secret data via the raiseLabel operation. Conversely, one can avoid tainting data with excessively high labels by splitting the offending function into several functions that run with lower labels. However, if many such changes are required in order to adapt existing applications to work with Trapeze, this will create a barrier to Trapeze’s practical adoption.

Our evaluation in Section 6 indicates that in practice the loss of transparency is not an issue in serverless applications due to the common serverless design practice where every function only accesses values that are related to a specific small task and are therefore likely to have compatible security labels.

3.4 Declassifiers

Many real-world applications allow limited flow of information down the security lattice. For example, a credit reporting agency may make the distribution of consumers across credit score bands publicly available. This statistics is computed based on the credit history of all consumers and must therefore be labeled with the least upper bound of all their labels. However, since the aggregate statistics exposes negligible amount of information about individual consumers, it can be safely declassified.

Similar to previous IFC models, Trapeze introduces declassifiers to support such scenarios. A declassifier is a triple \( \langle h, l, D \rangle \), where \( h \) and \( l \) are security labels, such that \( l \subseteq h \), and \( D \) is a serverless function. A declassifier is invoked just like any other serverless function; however its security label is computed using special rules. Let \( x \) be the label of the calling function. Then the declassifier is assigned label \( x' \), such that:

\[
x' = \begin{cases} 
  l, & \text{if } l \subseteq x \subseteq h \\
  x, & \text{otherwise}
\end{cases}
\]

By design, declassifiers violate the non-interference property; therefore the formal model and proofs in Section 4 are given for the pure IFC model without declassifiers.

4 FORMAL SEMANTICS

In this section, we formalize our IFC semantics for serverless systems with an underlying persistent key-value store. Since computations at different security labels might write to the same key, the key-value store maps each key to a set of values (facets), each with a different label, and we order this set into a sequence according to the temporal order of the writes. The initial store \( \sigma_0 \) maps each key to the empty sequence: \( \sigma_0 = \lambda k. \epsilon \).
A state $\Sigma \in \text{State}$ of the system consists of a key-value store $\sigma \in \text{Store}$, plus a multiset of currently executing serverless function activations called processes (see Figure 4(a)). Each process $p = (t, l)$ consists of a thread $t$ plus its associated security label $l \in \text{Label}$.

Observable events $e \in \text{Event}$ of the system include the input event start $p$, which starts a new process $p$, and the output event output $ch \ v$, which sends the value $v$ on output channel $ch$ (see Figure 4(b)).

The state transition relation $\Sigma \xrightarrow{\epsilon} \Sigma'$ shown in Figure 4(c) describes how the system executes. The first rule $[\text{s-start}]$ handles an incoming event start $p$ simply by adding $p$ to the multiset of processes. The next five transition rules all involve executing a particular process $(t, l)$ until its next I/O operation $op \in \text{Operation}$. For maximal generality, we do not formalize the computation language, but instead assume that the function $\text{run} : \text{Thread} \rightarrow \text{Operation}$ executes the thread $t$ and returns $op$, which includes a continuation for the rest of the thread (analogous to the coinductive definitions used by Bohannon et al. [18]).

We describe each operation and its corresponding transition rule in turn:

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1. Serverless systems spawn a new function/process $p$ to handle each incoming event. Here, we assume that each incoming event contains that new process, to simplify the formal development.
\[
S'_l = S \setminus \{(v', l') \in S \mid l' \not\subseteq l\} \\
ps'_l = \text{multiset}\{(t, l') \in ps \mid l' \subseteq l\} \\
\sigma'_l = \lambda k. \sigma(k)'_l \\
e'_l = \begin{cases} 
  e & \exists t, l'. e = \text{start}(t, l') \text{ and } l' \not\subseteq l \\
  \text{nop} & \text{otherwise.}
\end{cases} \\
(e_1 \ldots e_n)'_l = e_1'_l \ldots e_n'_l \\
(\sigma, ps)'_l = (\sigma'_l, ps'_l)
\]

Fig. 5. Definition of projection function.

- [s-send] for send \( ch \nu t' \): This rule checks that the process is permitted to output on channel \( ch \) (here, \( \text{label} : \text{OutputChannel} \rightarrow \text{Label} \) returns the security label of each channel). The process becomes stuck if this check fails. Otherwise, it generates the output event \( e = \text{output} \ ch \nu \) and the new process state \( (t', l) \) using the continuation \( t' \) returned from \( \text{run} \).
- [s-read] for read \( k \ nu \ f \): This rule reads the labeled value sequence \( \sigma(k) \) from the store; uses the projection operation \( \bullet'_l \) defined in Figure 5 to remove all values not visible to the current label, and passes the last entry in this list (i.e. the most recent visible write) to the read continuation \( f \).
  
Note that \( \sigma(k)'_l \) may be the empty sequence \( \epsilon \), either because key \( k \) was never written, or because no such writes are visible to the current process; in this case, \( \text{last}(\epsilon) \) returns \( \bot \), which is passed to \( f \).
  
This rule (and the following four below) generates a dummy event \( \text{nop} \), since it does not have any externally visible behavior.
- [s-write] for write \( k \nu t' \): In a conventional data store, a new write would overwrite the previous value at that key. In contrast, our faceted store semantics must ensure that a low-label process unable to see the new write will still read an older write. Hence we represent \( \sigma(k) \) as a sequence of labeled values. At a new write \( (v, l) \) of value \( v \) at label \( l \), we can garbage-collect or remove all older writes \( (v', l') \) in this sequence \( \sigma(k) \) that are no longer visible, namely those where \( l \not\subseteq l' \), since any process that could read \( (v', l') \) can also read the more recent write \( (v, l) \). The following function performs this garbage collection, and then appends the new labeled value:

\[
\text{write} : \text{LabeledValueSeq} \times \text{Value} \times \text{Label} \rightarrow \\
\text{LabeledValueSeq} \\
\text{write}(S, v, l) = (S \setminus \{(v', l') \in S \mid l \not\subseteq l'\}) \uplus (v, l)
\]

The symbol \( \uplus \) denotes sequence concatenation.
- [p-fork] for fork \( t' t'' \): This rule forks a new thread \( t'' \), where \( t' \) is the continuation of the original thread. Both threads inherit the security label of the original process.
- [s-raise-label] for raiseLabel \( l' t' \): This rule simply raises the label of the current process to a higher label \( l' \), which, for example, permits the process to read more secret data.
- Finally, [s-skip] allows a state to perform stuttering \( \text{nop} \) steps at any time, as a technical device to facilitate the non-interference proof below.

Note that no rule is needed for the stop operation. Instead we just leave the stopped processes in the process multiset for simplicity.
5 TERMINATION SENSITIVE NON-INTERFERENCE

We use the notation •↓l on various domains to remove any information that is not visible to an observer at level l (see Figure 5). For example: S↓l contains only values with labels visible to l, and ps↓l contains only processes with labels visible to l. An event e is visible to l if it starts a process visible to l, or if it outputs on a channel visible to l; otherwise, we say e↓l = nop. We write •1 ≈l •2 to denote that items appear equivalent to an observer at level l, i.e., •1↓l = •2↓l.

Our proof is based on the projection lemma below, which relates the execution of the full system Σ and the portion Σ↓l visible at level l. Every step of Σ has a corresponding step in Σ↓l (part 1) and vice versa (part 2).

Lemma (Projection).

Part 1. If

Σ \xrightarrow{e_1} Σ'_1

then for some Σ'_2 and e_2,

Σ↓l \xrightarrow{e_2} Σ'_2 \quad Σ'_1 ≈l Σ'_2 \quad e'_1 ≈l e'_2

Part 2. If

Σ↓l \xrightarrow{e_1} Σ

then for some Σ'_2 and e_2,

Σ \xrightarrow{e_2} Σ_2 \quad Σ_1 ≈l Σ_2 \quad e_1 ≈l e_2

Proof. See appendix.

Based on this lemma, our proof of single-step and multi-step termination sensitive non-interference is straightforward.²

Theorem (Single step Termination Sensitive Non-Interference).

If

Σ_1 ≈l Σ_2 \quad Σ_1 \xrightarrow{e_1} Σ'_1

then for some Σ'_2 and e_2,

Σ_2 \xrightarrow{e_2} Σ'_2 \quad Σ'_1 ≈l Σ'_2 \quad e_1 ≈l e_2

Proof. By Projection (Part 1):

Σ↓l \xrightarrow{e_1} Σ'_1 \quad Σ'_1 ≈l Σ'_2 \quad e_1 ≈l e_2

for some Σ'_3 and e_3. The l-equivalence assumption implies that Σ↓l \xrightarrow{e_3} Σ'_3. By Projection (Part 2):

Σ_2 \xrightarrow{e_2} Σ'_2 \quad Σ'_3 ≈l Σ'_2 \quad e_3 ≈l e_2

for some Σ'_2 and e_2. Therefore, by transitivity of ≈l, we have Σ'_1 ≈l Σ'_2 and e_1 ≈l e_2, as required.

Corollary (Termination Sensitive Non-Interference).

If

Σ_1 ≈l Σ_2 \quad Σ_1 \xrightarrow{e_1} Σ'_1

then for some Σ'_2 and e_2,

Σ_2 \xrightarrow{e_2} Σ'_2 \quad Σ'_1 ≈l Σ'_2 \quad e_1 ≈l e_2

²When applied to a reactive system as we have here, this notion of termination-sensitive non-interference is often known as progress-sensitive non-interference.
Proof. By induction on the derivation of $\Sigma_1 \xrightarrow{c_{\text{tsni}}} \Sigma'_1$.

Our Coq formalization of these semantics and proofs is available at https://github.com/anonymous-pldi2018-1/faceted-tnsn-coq.

Our TSNI result states that the set of observable outputs of the system under all possible schedules does not depend on inputs that are not visible to the observer. This result does not prevent a malicious scheduler from leaking secrets by prioritizing certain schedules, e.g., by scheduling low-security processes based on high-security secrets. However, as mentioned earlier, we assume that the scheduler is not adversarial in this manner. Prior work [59] has addressed this problem by assuming a round-robin scheduler, but this assumption is not realistic for serverless computing.

6 IMPLEMENTATION AND EVALUATION

6.1 Implementation

In order to evaluate our proposed security architecture and IFC model, we developed an open-source prototype implementation of Trapeze [4]. The implementation is portable and currently runs on the two most popular serverless platforms—AWS Lambda [2] and OpenWhisk [6]. It consists of three components: the sandbox, the security shim, and the authentication service.

Sandbox The Trapeze sandbox encapsulates application code, redirecting all its inputs and outputs through the security shim (Figure 1). The exact sandboxing technology depends on the programming language used. We currently support serverless functions written in JavaScript for the Node.js runtime, which is one of the most common types of serverless functions on both AWS and IBM Cloud Functions, IBM’s public OpenWhisk service. We encapsulate such functions using the VM2 JavaScript sandbox [63, 64]. Many serverless functions rely on the ability to invoke external programs. We encapsulate such external executables using a ptrace-based sandbox [35], which restricts program’s I/O activity to a temporary local directory that gets purged on every serverless function invocation.

Security shim The security shim monitors all inputs and outputs of a function and enforces IFC rules. The shim consists of multiple adapter modules, one for each supported input and output interface. There are three groups of adapters: (1) data store adapters, (2) function call adapters, (3) external channel adapters.

A data store adapter implements faceted store semantics on top of a conventional cloud data store. Trapeze currently supports a single type of data store—a faceted key-value store implemented on top of a relational database. The key-value store implements a standard dictionary with the following operations: put(key, value), get(key), del(key), and keys() (returns all keys in the store). The store is backed by a relational database table with 3 columns, for the key, value, and label. The table contains an entry for each facet of each value in the store. We used MySQL server available in AWS through Amazon Relational Database Service. The security shim passes an additional parameter to every operation—the security label. The get operation performs an SQL query that returns all entries that match the given key, and whose label is less than or equal to the given label. The del operation deletes all facets with labels greater than or equal to the given label. The put operation deletes the same elements a del does, and then inserts the given key-value pair, with the given label. In addition to the faceted version, we also provide a conventional insecure key-value store implementation as a baseline for performance evaluation.

Function call adapters support different ways to invoke serverless functions, making sure that the callee inherits the caller’s label, as required by our IFC model. We support two invocation mechanisms: AWS Step Functions, which run a workflow with multiple serverless functions, controlled by a finite automaton, and Amazon Kinesis, which supports asynchronous communication via real-time event streams.
External channel adapters enable secure communication across the cloud boundary. The supported types of channels are (1) user-initiated HTTP sessions, (2) email communication via the Nodemailer module[50], and (3) connections to external S3 buckets (used to upload large data objects that do not fit in HTTP requests). HTTP sessions obtain their security labels from the authentication service (see below). The Nodemailer adapter uses the user database (see below) to map an email address to a user security label. The S3 adapter inherits the label of the user who provides login credentials for the S3 bucket.

**Authentication service** The authentication service is responsible for associating a correct security label with every external HTTP session. It is implemented on top of a user database that stores credentials, email addresses, and security labels of all users in the system.

The entire Trapeze framework consists of 1174 lines of JavaScript code, including 649 lines in the AWS and OpenWhisk shim modules, 484 lines in the key-value store, and 41 lines in the authentication service.

6.2 Evaluation questions

Our evaluation aims to answer the following questions:

(1) **Security**: Can Trapeze enforce information security in real-world serverless applications? In particular, can confidentiality requirements of such applications be captured in a security policy consisting of a security lattice and trusted declassifiers? Can Trapeze enforce the policy in the presence of buggy or malicious code?

(2) **Transparency**: Can Trapeze secure existing serverless applications with minimal modifications?

(3) **Performance**: Can Trapeze achieve the first two goals with low performance overhead?

6.3 Case studies

To answer the above questions, we carried out three case studies where we used Trapeze to add a security layer to existing serverless applications. We outline each of the case studies below.

**Case study 1: Hello, Retail!** Hello, Retail! is a project from the serverless team at Nordstrom. The goal was to produce a purely serverless, back-end for an e-commerce web site. It has since been open-sourced [51] and won the architecture competition award at serverlessConf Austin’17[45].

We made several changes to Hello, Retail! before applying Trapeze to it. First, we replaced DynamoDB and S3 databases in Hello, Retail! with with calls to Trapeze’s key-value store. Second, we replaced calls to the Twilio SMS messaging service, which is currently not supported by Trapeze, with e-mail communication. Third, we extended the Hello, Retail! project with a product purchase subsystem, which manages online orders and credit card payments. The resulting system consists of 21 serverless functions. Figure 6 shows the high-level architecture of the system.

The system serves several types of users: (1) the store owner, who manages the online catalog and processes orders, (2) photographers, who upload product images to the catalog, (3) customers, who navigate the catalog and place orders, and (4) the VISA credit card authority, which authorizes card payments on behalf of customers. The security lattice (Figure 7a) consists of labels, matching these user categories. Solid lines in the diagram show the partial order of security labels; dashed arrows show declassifiers, with a declassifier \( \langle h, l, D \rangle \) represented by an arrow from label \( h \) to \( l \). Table 1 summarizes the security labels in this case study.

The following scenario illustrates the flow of sensitive information through the Hello, Retail! system. Every step in the scenario is annotated with security label(s) of data involved in this step.

1. \([\text{owner}]\) The owner creates a new product description in the catalog.
2. \([\text{photographer}]\) The owner sends an email to one of the photographers requesting a picture of the product. The request includes information from the product description, declassified with the \( \langle \text{owner}, \text{photographer}, \text{photo}_\text{request}() \rangle \) declassifier, which implements a trusted user interface that request
Fig. 6. The architecture of the Hello, Retail! project. Circles labeled $\lambda$ represent the main functions of this application. Functions whose names end with ‘API’ can be directly invoked via client HTTP requests. Arrows show interactions between different components. Red dashed arrows indicate interactions that carry declassified data.

| label     | description                                                                 |
|-----------|-----------------------------------------------------------------------------|
| owner     | Sensitive information managed by the store owner, including product catalog and photographers’ email addresses. Items in the catalog are only visible to the owner until they are released to the public via the release declassifier. |
| client$\_i$ | Labels online purchases of a specific customer. This information is visible to the customer and the store owner (since client$\_i \subseteq$ owner) |
| clientCC$\_j$ | Customer credit card information that can only be released to a credit card authority |
| VISA      | Labels the external communication channel to the VISA credit card authority |
| photographer$\_i$ | Product photos uploaded by a photographer |

Table 1. Security classes in the Hello, Retail! case study.

owner’s confirmation of the declassification.
3. [photographer$\_i$] The photographer uploads a product image to the catalog.
4. [⊥] Once the owner is ready to make the product publicly available in the online catalog, she declassifies it using the $\langle$owner, ⊥, release()$\rangle$ declassifier.
5. [client$\_i$/clientCC$\_j$] A client orders a product from the catalog. Order information, labeled client$\_i$, is visible to the the client as well as the owner, since client$\_i \subseteq$ owner. Client’s credit card details are labeled clientCC$\_j$, and are hidden from the owner (clientCC$\_j \not\subseteq$ owner).
6. [VISA] Before the order is finalized, credit card information is sent to VISA for payment authorization through an external channel labeled VISA.

7. [client_j] The response received through this channel consists of one bit of information indicating success or failure, which gets declassified by the \( (VISA, client_j, authorize()) \) declassifier, making the outcome of the request visible to the client and the owner.

**Case study 2: gg** gg [35, 37] is a system for running parallel software workflows, such as software compilation and video processing, on serverless platforms. In gg, each unit of work, or thunk, specifies both the executable to run and all its data dependencies. The workflow is synthesized as a direct acyclic graph (DAG) of thunks, and is recursively executed on a serverless platform by gg’s execution engine. gg identifies each dependency in a content-addressed way, using a key-value store as the storage backend. gg consists of a single serverless function, which internally runs arbitrary user-provided executables. Each invocation of the function executes exactly one thunk by fetching the dependencies from the object store, executing the thunk, and storing the output back into the object store.

We use a parallel build framework implemented on top of gg [35] as a concrete use case. The framework extracts a workflow DAG, where every thunk corresponds to an invocation of a build tool (e.g., a compiler or a linker), from the project makefile.

The original gg implementation is single-tenant, with every authenticated user having access to all sources and binaries in the system. We use Trapeze to introduce a secure multi-tenant mode to gg. In this mode, tenants only have access to their own source and compiled code. A thunk running on behalf of the tenant taints all of its outputs with the tenant’s label. A tenant may release some of their sources or compiled binaries to the public, making them available to all other tenants. This is reflected in the security lattice in Figure 7b with mutually incomparable tenant labels and a \( (user_i, ⊥, open_source()) \) declassifier.

Prior to adding the multi-tenant mode to gg, we ported parts of it that were written in Python to JavaScript, as well as modified it to use our key-value store.

**Case study 3: Image feature extraction** This serverless application gives its users access to Amazon’s AWS Rekognition image analysis service [3]. It is based on the ‘Fetch File and Store in S3’ and ‘Analyse Image from S3’ examples from the Serverless Examples collection [57].

The application consists of the upload function that takes an image URL, fetches the image and stores it in the key-value store, and the feature extraction function that uses AWS Rekognition to extract features from the image and send them to the user.

We use Trapeze to add a security layer to this example, enforcing that every user can only access information extracted from images they own. This policy is expressed in the simple security lattice in Figure 7c.
Table 2. Size of the case studies in lines of code (LoCs): (1) LoCs comprising the application, (2) lines added or modified to adapt the application to work with Trapeze, (3) LoCs in trusted declassifiers.

| case study       | app code | modif. code | declassifiers |
|------------------|----------|-------------|---------------|
| Hello, Retail!   | 1,300    | 3           | 104           |
| gg               | 8,800    | 2           | 94            |
| Feature Extraction | 95       | 0           | 0             |

6.4 Security
We employ Trapeze to protect sensitive data in the three case studies. The original implementation of these applications either offered coarse-grained protection, giving every authenticated user access to all data in the system, or implemented ad hoc security policies embedded in application code. For example, the Hello, Retail! system by design only exposes credit card details to the credit card authority. Such protection relies on checks scattered around the application code and is easy to get wrong. Besides, it can be bypassed by any exploit that subverts the application logic.

Trapeze captures the security requirements of each of the three case studies in a security policy consisting of a security lattice and declassifiers, shown in Figures 7a, 7b, 7c. Our policies are simple and concise, consisting of only several classes of labels and few declassifiers. The policies are decoupled from the application logic and its software architecture. For instance, adding new functions to the application, changing its control flow, or even refactoring the database schema, do not affect the security policy.

Furthermore, Trapeze is immune to malicious or compromised application logic. We simulated code injection attacks in our case studies by replacing some of the original functions with malicious functions that attempt to leak secrets to unauthorized users, similar to examples in Figures 2b and 3. As expected, these simulated attacks failed when running the application with Trapeze.

6.5 Transparency
As discussed in Section 3, Trapeze enforces TSNI at the cost of reduced transparency, which may require the developer to refactor the application to work with Trapeze.

Table 2 measures the loss of transparency in our case studies by reporting the size of changes to application code in terms of lines of code (LoCs) required to adapt the application to work with Trapeze. This does not take into account the changes needed to port the application to use our key-value store as well as other compatibility changes that are not fundamental to the Trapeze architecture and can be made unnecessary with some additional engineering effort.

None of the case studies required splitting a function into multiple functions. Hello, Retail! required calling raiseLabel twice, once in order to upgrade the label of the purchase placement function from client to clientCC before saving the customer’s credit card details in the data store, and once to upgrade the label of the payment authorization function from client, to VISA, in order to read credit card details from the store and send them to the credit card authority. In addition, the gg case study required a minor change due to a technicality: the existing code was not fully compatible with the VM2 sandbox.

These results indicate that in practice the loss of transparency is not an issue in serverless applications. This is due to the common software design practices in the serverless world, where each function is assigned a single small task and only accesses the values that are related to this task and are therefore likely to have compatible security labels.

The last column of the table reports the total size of declassifiers used in each case study. This number characterizes the amount of trusted application code in each example.
We measure the overhead of Trapeze by running case studies 1 and 3 on the AWS Lambda serverless platform. We run case study 2 on the OpenWhisk platform in the IBM Cloud (formerly, IBM Bluemix), since AWS Lambda does not support ptrace, which we use to sandbox binary executables in gg (Section 6.1).

Table 3 summarizes the runtime overhead of Trapeze. Since the overhead may depend on the exact workload, we constructed several typical workflows for each case study. We test the Hello, Retail! case study on two workloads: the ‘Build&Browse’ workload, that simulates the construction and browsing of the product catalog, and the ‘Update&Purchase’ workload, that simulates updates to the catalog followed by a series of online purchases. We test gg by using it to compile four open source software packages: mosh, git, vim, and openssh. Finally, we consider two scenarios for the Image Feature Extraction: the ‘Image Upload’ scenario, that uploads a single image to the data store, and the ‘Feature Extraction’ scenario that performs feature extraction for a stored image.

For each workload, we report the total number of serverless function calls (the # column in Table 3). The ‘function runtime’ section of the table reports the total runtime of all functions in the scenario with and without protection and the relative slowdown introduced by protection, averaged across 10 runs. These runtimes do not include additional declassifier calls introduced in the protected execution. Accounting for classifiers increased the total runtime by another 10% in the Build&Browse workload, while not making any measurable impact on other workloads. In our initial experiments we also measured the total time to execute each workload; however we found that, due to the non-deterministic nature and varying resource availability in the serverless environment, these times varied wildly across different runs and did not provide any insights into the performance of Trapeze.

For most workloads, Trapeze adds a modest overhead of up to 12.3% to function runtime. The negative overhead in the gg mosh workload is due to the noisy IBM Cloud environment, where the runtime of a function varies dramatically across different invocations based on the load on the node where the function is scheduled. The overhead is higher in the Hello, Retail! case study, up to 92.33% in the Update&Purchase scenario. Further benchmarking revealed that the bulk of this overhead is due to the startup time of the VM2 sandbox, which adds 100ms on average per function invocation. Since all functions in this example have short runtimes, the startup time becomes a significant contributor to the total runtime. We measured that two thirds of the startup time is spent loading libraries used by the application. In the future, much of this overhead can be eliminated by caching preloaded libraries in memory.

Finally, we evaluate the storage overhead of our secure key-value store. Table 4 compares database sizes (in kilobytes) for an insecure and secure versions of the store for each of the three case studies (we report results
Table 4. Storage overhead of Trapeze.

| case study               | insecure (KB) | Trapeze (KB) | Δ(%)  |
|--------------------------|--------------|--------------|-------|
| Hello, Retail!           | 2,704        | 3,200        | 18.34 |
| gg                       | 15,054,000   | 15,118,496   | 0.43  |
| Feature Extraction       | 8,256        | 8,416        | 1.94  |

for one of the workloads in each case study, as the relative increase in the database size is independent of the workload. The secure database requires more space, as it stores a security label with each value. This overhead is low (under 2%) in examples where the database stores large objects, e.g., images or source files. It is more significant (18.34%) in the Hello, Retail! case study where individual values stored in the database are small.

7 RELATED WORK

The modern technique for using security labels to dynamically monitor information flow was proposed by Denning [25] as the Lattice Model. That work also defines the concept of implicit flow of information. Austin et al. [11] describe three techniques for monitoring such flows, namely Failure Oblivious and No Sensitive Upgrade and Permissive Upgrade. Our work exposes a fourth choice using faceted values specifically to eliminate implicit flows.

Austin and Flanagan [10] introduce faceted values as a full language-based enforcement technique: rather than focusing specifically on controlling implicit flows, they combine the faceted value concept with the concept of multiple executions, which enables more precise enforcement at the cost of more runtime overhead.

Trapeze enforces a strong form of non-interference, TSNI. Most existing IFC systems support only termination-insensitive non-interference (TINI). The few previous systems that enforce TSNI are either too restrictive or too costly for most practical applications. The multilevel security (MLS) model [15] achieves TSNI by statically partitioning all the code and data in the system into security compartments. This model, designed primarily for military-grade systems, is too restrictive for most applications and requires complete re-design of existing software. Smith and Volpano [58] present a security type system that enforces TSNI by imposing a harsh restriction that loop conditions may not depend on secret data. Heintze and Riecke [39] propose a secure typed Lambda calculus called SLam. While SLam only enforces TINI, Sabelfeld and Sands [55] point out that a version of SLam with lazy evaluation semantics would be termination-sensitive. This theoretical result has limited practical implications, as, with the exception of Haskell, none of today’s major programming languages use lazy evaluation.

Indeed, Stefan et al. [59] implemented a Haskell library called LIO, which guarantees TSNI by requiring programmers to decompose their programs into separate threads with floating labels. These are analogous to the processes in our formalism. However, LIO uses the No Sensitive Upgrade rule to prevent implicit flows, while Trapeze uses faceted values instead. They also assume a round-robin scheduler, which would be inappropriate for our application to serverless computing.

Secure multi-execution [27] achieves TSNI by running multiple independent copies of the program, one for each security class. This technique introduces CPU and memory overhead proportional to the number of security classes. While acceptable in systems with few security classes (e.g., Devriese and Piessens [27] consider only two classes, secret and non-secret), this becomes impractical in cloud-scale systems with potentially millions of mutually untrusting users. Faceted execution has the potential to mitigate this drawback, and Bielova and Rezk [16] have proposed a theoretical approach for extending the faceted execution model to enforce TSNI.

The Asbestos OS [29] applies dynamic IFC at the granularity of an OS process, similar to how Trapeze operates at the granularity of a serverless function. Asbestos associates a static security label with each process; however this label only serves as an upper bound on the label of data the process can access. Process’s effective label changes dynamically, which enables the implicit termination channel.
To the best of our knowledge, Trapeze is the first system to apply IFC to serverless applications. Several researchers advocate the use of IFC in the broader context of secure cloud computing [13, 52]; however we are not aware of a practical implementation of these ideas.

8 CONCLUSION
The advent of serverless computing provides the opportunity to rebuild our cloud computing infrastructure based on a rigorous foundation for information flow security. We present a novel and promising approach for dynamic IFC in serverless systems. This approach combines (1) a sandbox and security shim that monitors all I/O operations of each serverless function invocation; (2) static security labels for each serverless function invocation; and (3) dynamic faceted labeling of data in the persistent store.

This combination of ideas provides the strong security guarantee of TSNI, which is necessary in serverless settings to avoid high-bandwidth termination channel leaks via multiple concurrent requests.

Our Trapeze implementation of this approach is lightweight, requiring no new programming languages, compilers, or virtual machines. The three case studies show that Trapeze can enforce important IFC properties with low space and time overheads.

We believe Trapeze represents a promising approach for deploying serverless systems with rigorous security guarantees that help prevent costly information leaks arising from buggy or mis-configured application code or from code-injection attacks.

ACKNOWLEDGMENTS
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A SUMMARY OF AUXILIARY SEMANTIC DETAILS

\( \epsilon \) is the empty sequence and \( + + \) is concatenation.

\texttt{label} : \texttt{OutputChannel} \rightarrow \texttt{Label} \\
\texttt{run} : \texttt{Thread} \rightarrow \texttt{Operation} \\
\texttt{write} : \texttt{LabeledValueSeq} \times \texttt{Value} \times \texttt{Label} \rightarrow \texttt{LabeledValueSeq} \\
\texttt{write}(S, v, l) = (S \setminus \{(v', l') \mid l' \subseteq l\}) + (v, l) \\
\bullet_1 \approx \bullet_2 \text{ means } \bullet_1 \downarrow l = \bullet_2 \downarrow l

B PROOF DETAILS

Lemma (Invisibility).

If

\[
\begin{align*}
l' & \not\subseteq l \\
(\sigma, ps \uplus \{(t, l')\}) & \xrightarrow{\cdot} (\sigma', ps \uplus ps')
\end{align*}
\]
then
\[ \sigma' \downarrow_l = \sigma \downarrow_l \]
\[ e \downarrow_l = \text{nop} \]
\[ ps' \downarrow_l = \{\} \]

Proof. Omitted.

**Lemma (Projection 1).**

(1) If \( \Sigma \xrightarrow{e_1} \Sigma' \),
then \( \exists \Sigma_2' \exists e_2. \Sigma \downarrow_l \xrightarrow{e_2} \Sigma_2' \) and \( \Sigma_1' \approx_l \Sigma_2' \) and \( e_1' \approx_l e_2' \).

Proof.
Let \((\sigma, ps) = \Sigma\).
Let \((\sigma'_1, ps'_1) = \Sigma'_1\).
Proceed by cases (ie inversion) on (1).
Case: \(s\)-start. Let \(t, l'\) be such that:
\[ e_1 = \text{start} (t, l'); \] and
\[ \sigma'_1 = \sigma; \] and
\[ ps'_1 = ps + (t, l'). \]
Proceed by cases.
Case: where \(l' \subseteq l\).
Pick \( \Sigma'_2 = (\sigma \downarrow_l, ps \downarrow_l + (t, l')). \)
Pick \( e'_2 = \text{start} (t, l') \).
QED by \([s\text{-start}]\).
Case: where \(l' \not\subseteq l\).
Pick \( \Sigma'_2 = \Sigma \downarrow_l \) and pick \( e'_2 = \epsilon \).
QED by \([s\text{-skip}]\).
Case: \(s\)-skip. \(e_1 = \epsilon\) and \(\Sigma' = \Sigma\).
Pick \( \Sigma'_2 = \Sigma \downarrow_l \) and pick \( e'_2 = \epsilon \).
QED by \([s\text{-skip}]\).
Last case: any other rule. Let \(t, l', ps_1, ps_2\) be such that:
\[ ps = ps_1 \uplus \{(t, l')\}; \] and
\[ ps'_1 = ps_1 \uplus ps_2; \] and
Proceed by cases.
Case: where \(l' \not\subseteq l\).
\[ \sigma'_1 \downarrow_l = \sigma \downarrow_l \] and \( e_1 \downarrow_l = \epsilon \) and \( ps_2 \downarrow_l = \{\} \) by Invisibility.
QED by \([s\text{-skip}]\).
Last case: where \(l' \subseteq l\).
Resume case analysis on (1).
Case: \(s\)-send. Let \(ch, v, t'\) be such that:
\[ e_1 = \text{output} \ ch \ v; \] and
\[ \sigma'_1 = \sigma; \] and

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\[ \text{Lemma (Projection 2).} \]

1. If \( \Sigma_1 \xrightarrow{e_1} \Sigma_2 \), then \( \Sigma_3 \xrightarrow{e_2} \Sigma_4 \) and \( \Sigma_1 \approx \Sigma_3 \) and \( \Sigma_2 \approx \Sigma_4 \).

\text{Proof.}

Let \( (\sigma_1, ps_1) = \Sigma_1 \).

Let \( (\sigma_2, ps_2) = \Sigma_2 \).

Proceed by cases (ie inversion) on (1).

Case: [s-start]. Let \( t, l' \) be such that:

\[ e_1 = (t, l'); \] and
\[ \sigma_1 = \sigma \downarrow l; \] and
\[ ps_1 = ps \downarrow l \cup (t, l'); \] and
\[ \text{Pick } \Sigma_2 = (\sigma, ps + (t, l')) \text{ and } e_2 = e_1. \]

QED by [s-start].

Case: [s-skip].

Pick \( \Sigma_2 = \Sigma \) and \( e_2 = \epsilon \).

QED by [s-skip].

Case: [s-send]. Let \( t, l', ps_3, ch, v, t' \) be such that:

\[ ps_3 = ps_1 \cup \{(t, l')\}; \] and
\[ ps_1 = ps_3 \cup \{(t', l')\}; \] and
\[ e_1 = \text{output } ch \vee v; \] and
\[ \sigma_1 = \sigma \downarrow l; \] and
\[ \text{run}(t) = \text{send } ch \vee t'; \] and
\[ l' \subseteq \text{label}(ch). \]

QED by [s-send].

Remaining cases omitted.