Towards Practical Integrity in the Smart Home with HomeEndorser

Kaushal Kafle
kkafle@cs.wm.edu
William & Mary
Williamsburg, Virginia, USA

Kirti Jagtap
ktj35@psu.edu
Penn State University
Pennsylvania, USA

Mansoor Ahmed-Rengers
mansoor.ahmed@cl.cam.ac.uk
University of Cambridge
Cambridge, UK

Trent Jaeger
trj1@psu.edu
Penn State University
Pennsylvania, USA

Adwait Nadkarni
apnadkarni@wm.edu
William & Mary
Williamsburg, Virginia, USA

ABSTRACT

Home automation in modern smart home platforms is often facilitated using trigger-action routines. While such routines enable flexible automation, they also lead to an instance of the integrity problem in these systems: untrusted third-parties may use platform APIs to modify the abstract home objects (AHOs) that privileged, high-integrity devices such as security cameras rely on (i.e., as triggers), thereby transitively attacking them. As most accesses to AHOs are legitimate, removing the permissions or applying naive information flow controls would not only fail to prevent these problems, but also break useful functionality. Therefore, this paper proposes the alternate approach of home abstraction endorsement, which endorses a proposed change to an AHO by correlating it with a specific, preceding, environmental change. We present the HomeEndorser framework, which provides a policy model for specifying endorsement policies for AHOs as changes in device states, relative to their location, and a platform-based reference monitor for mediating all API requests to change AHOs against those device states. We evaluate HomeEndorser on the HomeAssistant platform, finding that we can derive over 1000 policy rules for HomeEndorser to endorse changes to 6 key AHOs, preventing malice and accidents for less than 10% overhead for endorsement check microbenchmarks, and with no false alarms under realistic usage scenarios. In doing so, HomeEndorser lays the first steps towards providing a practical foundation for ensuring that API-induced changes to abstract home objects correlate with the physical realities of the user’s environment.

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1 INTRODUCTION

189.4 million households worldwide have at least one smart home device [60]. This popularity can be explained in part due to the convenience of home automation, wherein smart home devices automatically react to changes in the user’s physical environment. For example, the user may configure a security camera to begin recording when they leave home, but turn OFF when they return to preserve their privacy [37]. Such automation is often expressed using trigger-action programs known as routines, that automatically perform a device action (turning OFF the camera) in response to a trigger (e.g., a change from “away” to “home”).

Routines are often enabled via third-party integrations/services, which automate device-actions by leveraging platform APIs. Particularly, third-parties use the APIs to modify two distinct types of objects, device states (e.g., the ON/OFF state of a light bulb), and abstract home objects (AHOs) that are not device-specific (e.g., home/away, hereby referred to as the home AHO). These AHOs are in fact computed in several ways, often through third-party services (e.g., set by the user [33], inferred by querying a combination of device states [25], using some other proprietary approach [57], or inferred from other factors such as geolocation [62]). One particularly dangerous attack vector that emerges from this setting is where adversaries gain privileged access to devices indirectly, by falsifying an AHO that a high-integrity device depends on (via a routine). For instance, consider a situation wherein an adversary may want to disable the security camera to perform a burglary unnoticed, but may not have direct API access to it. As demonstrated by prior work [31], such a camera (e.g., the NEST security camera) can be remotely disabled by compromising a relatively low-integrity integration (e.g., a TP Link Kasa app) and using its privilege to change the home AHO (i.e., from “away” to “home”), thus triggering the routine described previously and turning the camera OFF. Given the widespread vulnerabilities in third-party integrations [31] and the extensive privileges that enable them to modify AHOs [16, 65], this type of lateral privilege escalation is of serious concern.

This problem of lateral escalation is, at its core, an integrity problem analogous to those seen in operating systems: a high-integrity process (here, the security camera) relies on the value of an object (i.e., the home AHO), which can be modified by untrusted parties. Thus, smart home platforms must directly address the lack of strong integrity guarantees for AHOs used in automation. This framing deviates from existing literature where proposed mitigations include restricting over-privilege [35, 48, 65] or restricting permission usage based on the runtime context of an API access [29]. We believe such mitigations may imposes infeasible usability penalties, whilst not addressing the underlying lack of integrity (see Section 2).

Information flow control (IFC) has often been proposed as a method to ensure the integrity of information consumed by sensitive processes [3, 15, 17, 34, 38, 71], through labeling of subjects and
objects, and dominance checks that regulate flows based on labels [3]. For example, the IoT platform may mark the home AHO with a high-integrity label and mark third-party services chosen by the user as low-integrity. However, the enforcement of such a policy may block a service chosen by the user to update home, result in a false denial from the user’s perspective (e.g., 19/33 NEST integrations from a prior dataset [31] would be blocked under such a model).

IFC systems rely on endorsement [5, 34, 70, 71] to overcome this limitation, allowing trusted programs to change labels of objects to permit flows that would normally violate the labeling. However, determining the conditions where an endorsement would be allowable is a challenge; indeed, prior work has often avoided directly addressing this problem, and generally facilitates endorsement by assigning the authority to certain trusted high-integrity processes, thereby delegating the task of determining how to endorse correctly to the programmer or administrator [8, 34, 54, 71]. However, in our case, smart home users may lack information about dependencies among devices and AHOs to do this correctly. So, we ask instead: Is there something else we can rely on to provide endorsement for practical integrity guarantees?

Yes – the cyber-physical nature of the smart home provides us with a unique opportunity for practical endorsement, in the form of ground truth observations from devices (i.e., device state changes) that can be used to validate proposed changes to AHOs. For instance, we can endorse the change to the home AHO (from “away” to “home”) if the door lock was legitimately unlocked (i.e., with the correct keycode) recently, since the lock being unlocked represents the home owner’s intent and attempt to enter the home. Thus, we state the following claim that forms the foundation of this work:

**Contributions:** We introduce the paradigm of home abstraction endorsement to validate changes to AHOs initiated by untrusted API calls, and propose the HomeEndorser framework to enable it. HomeEndorser does not continuously monitor AHOs, but focuses on API-induced changes to specific AHOs, and performs a sanity check using policies that rely on the recent physical state changes in smart home devices. If the check fails, the state change is denied and the user is informed. HomeEndorser’s preemptive action prevents future automation based on maliciously changed AHOs. We make the following contributions in exploring this novel design space:

1. **Home Abstraction Endorsement:** We introduce the paradigm of home abstraction endorsement, which leverages the states of local devices to endorse proposed changes to AHOs. Our approach makes IFC endorsement practical by exploiting the cyber-physical nature of the smart home, and significantly deviates from prior IFC systems that enforce integrity guarantees purely based on opaque labels.

2. **The HomeEndorser Framework:** We design the HomeEndorser framework to provide secure and practical endorsement, consisting of (1) a policy model that allows a unified expression of location-specific device instances within a single policy (e.g., endorsing home via multiple physical entry points), (2) a platform-based reference monitor to enable HomeEndorser to mediate all sensitive state changes using these policies, and finally, (3) a systematic, semi-automated policy specification methodology for experts, that only considers device-states/attributes that can be trusted for endorsement (e.g., read-only, or designated as highly trusted by platforms).

3. **Implementation and Evaluation:** We implement HomeEndorser on HomeAssistant, a popular open-source smart home platform, and evaluate it using experimental and empirical analyses. We first demonstrate that the idea of home abstraction endorsement is feasible, even when using a limited set of trusted device attributes, by generating 1023 policies for endorsing the home AHO. We demonstrate the generality of our policy model by identifying several attributes that my be used to endorse 5 additional AHOs. We then demonstrate the security guarantee enabled by HomeEndorser using a case-study approach. Moreover, we perform 10 realistic home usage scenarios [30] in a smart home (apartment) testbed to demonstrate that HomeEndorser is generally not susceptible to false denials, and in fact, may prevent accidental unsafe situations created through intentional user actions. We demonstrate HomeEndorser’s practical performance overhead with micro/macro benchmarks (9.7-12.2% on average). Finally, we demonstrate that the effort required to specify policies, configure HomeEndorser in end-user homes, and integrate HomeEndorser in popular smart home platforms, would be modest, and acceptable given the benefit of strong integrity enforcement.

### 2 MOTIVATION

Programmable smart home platforms are popular among users for two primary reasons: integration and automation. That is, platforms such as SmartThings [59] and NEST [39] provide permission-protected APIs that enable seamless integration of a diverse array of third-party services, ranging from software support (e.g., cloud and mobile apps) for a variety of smart home devices (e.g., TP Link Kasa [22], Wemo [23]), to third-party automation platforms that hook into the smart home and enable user/developer-provisioned automation routines (e.g., IFTTT [26] and Yonomi [69]).

Platform-provided API access allows the caller (i.e., the third-party service) to read/write to two broad categories of “states” in the home: (1) device states, i.e., values associated with individual devices such as the security camera (e.g., the ON/OFF state, battery status), and (2) abstract home objects (AHOs) that are not associated with any specific device, and instead may be computed in several ways, often by taking into account the user’s choice. For example, an object that stores whether the user is home or away is an AHO (i.e., the home AHO), and a third-party service designated by the user may compute it in several ways, i.e., based on the location of the user’s phone [62], based on the certain device states in the home [25], using a proprietary/undisclosed method/device [57], or through a direct command from the user [33]. The use of AHOs by third-party services, and in routines that control security-sensitive devices in the home, may lead to severe consequences for security and safety, and particularly, the integrity of the home, as we discuss in the following motivating example inspired from prior attacks [31, 32].
Alice is a smart home user who has installed a security camera to deter burglars. For automated monitoring when she is away, Alice has configured two routines for the camera (similar to routines enabled by SimpliSafe [56] and NEST [40]): (1) the camera should turn ON when Alice leaves (i.e., goes away), and (2) the camera should turn OFF when Alice returns (i.e., returns home). Additionally, Alice has also integrated several third-party services such as the TP Link Kasa app (which allows her to control her Kasa switch).

We now introduce our adversary Bob, who seeks to burglarize the house when Alice is away, \textit{without being monitored by the camera}. Bob knows what third-party services are connected to Alice’s home, and any vulnerabilities they may have (e.g., SSL misuse in the TP Link Kasa app). Thus, we assume that Bob either exploits one or more vulnerabilities in a connected third-party service to control it, or steals an authorization token belonging to a service, which allows Bob to access the APIs with the permissions assigned to the service.

Using these abilities, Bob can disable the camera \textit{without API access} to it in the manner shown in Figure 1: Bob uses the access he has obtained from the compromised service (e.g., a stolen authorization token from Kasa [31]) to set the \textit{home} AHO to the value “home”, falsely suggesting that Alice is home. This false change triggers the routine described previously, and turns the security camera OFF.

This problem is not just limited to the home AHO. Consider another AHO, the \textit{security.state}, which is often used in routines [1, 49] to control security-related devices such as cameras and glass break detectors. That is, the security devices are armed when the \textit{security.state} is set to “deter”, and disarmed/ignored when the \textit{security.state} is set to “ok” (similar to routines from Ring [49] and TotalConnect [1]). If Bob can obtain control over an integration that has access to the \textit{security.state}, Bob can set it to “ok” and disable the camera just as well. That is, the adversary may falsify \textit{one of many AHOs} to \textit{transiently} manipulate a highly sensitive device.

### 2.2 The Need for Proactive Integrity Checks

As shown in Figure 1, Bob transitively attacks a high-integrity device, \textit{i.e.}, by modifying AHOs to trigger routines that manipulate a high-security device such as a camera, which Bob \textit{cannot compromise or modify} (via API) \textit{directly}. In other words, this problem is a smart home-specific instance of the classical \textit{OS integrity problem} (e.g., Biba integrity [3]), wherein a high-integrity process (\textit{i.e.}, the camera) relies on an object (\textit{i.e.}, the home AHO) which can also be modified by low-integrity process (\textit{e.g.}, the Kasa integration).

As high-integrity devices rely on such AHOs, traditional wisdom dictates that low-integrity (or third-party) integrations must be disallowed from writing to these objects. However, recall that in existing platforms (\textit{e.g.}, SmartThings and NEST), AHOs are often \textit{computed} by third-party services chosen by the user, and such integrations may genuinely need to modify AHOs to perform their functionality. Thus, disallowing \textit{the user’s choice} of third-party integration from writing to AHOs is bound to break numerous useful services that the user relies on (\textit{e.g.}, IFTTT, Yonomi, Kasa), which is a prohibitive cost in terms of user experience that platforms may find undesirable. For example, in 2019, Google announced an end to its “Works with NEST” developer program in favor of a more restricted “Works with Google Assistant” program that would only be open to vetted partners [20], but immediately backtracked [9, 21, 63] given significant opposition from both users and third-party integrations/developers [11, 12, 27, 64, 66], eventually offering a more flexible program that would allow a broader set of partners access to internal home states (including AHOs) [21]. It is important to note that even when such partners may be vetted, prior work has demonstrated that such vetting is often ineffective, as even vetted integrations may flout security/privacy-design policies [31, 32, 36]. This is particularly true in the case of smart home platforms, as integrations are often hosted \textit{outside of the purview of the platform}, \textit{i.e.}, on third-party clouds, and any security assessment by the platform given this limited visibility is bound to be only partially effective.

Therefore, there is a need for a solution that is (1) \textit{backwards compatible} or practical, \textit{i.e.}, does not break functionality by preventing third-parties from accessing AHOs, and (2) \textit{effective}, \textit{i.e.}, which enables integrity guarantees for devices that rely on AHOs. To this end, this paper proposes the moderate route of proactive integrity checking, \textit{i.e.}, \textit{runtime validation of proposed changes} to AHOs, which will enable reasonable integrity guarantees while being compatible with platform design and integration choices.

### 3 OVERVIEW

This paper introduces the novel paradigm of \textit{home abstraction endorsement} that provides a strong \textit{integrity guarantee} for AHOs, defined as follows: In the event that an untrusted service uses the platform API to modify a critical AHO, \textit{e.g.}, \textit{home} or \textit{security.state}, the modification will be allowed iff it is consistent with the \textit{local state of the home}, composed of the physical device states. Our approach builds upon the concept of trusted “guards” in the Biba integrity model [3]. That is, in a system operating under Biba integrity, a high integrity subject cannot receive input from a low integrity subject unless it is endorsed by a trusted guard. Similarly, in the smart home, we envision that endorsement policies that apply trusted device states will serve as the trusted guards, ensuring the validity of API requests to change the AHOs that high-integrity devices rely on.

Figure 2 provides an overview of our approach. When a third party service attempts to modify an AHO, the platform first enforces a permission check. We envision an additional \textit{integrity check}
for endorsing the proposed change, performed using an endorsement policy corresponding to each AHO-change that we plan to endorse. This policy leverages the recent changes in specific device-attributes/states for arriving at an endorsement decision. For example, for endorsing a proposed change in the home AHO from “away” to “home”, one possible policy would be as follows: if the door-lock has been unlocked recently (i.e., using the correct keycode), then ALLOW the change, else DENY. To build a system that enables our vision of home abstraction endorsement, we first define a set of key design goals, followed by the threat model.

3.1 Design Goals
The following goals guide our design of an effective, backwards compatible, framework for home abstraction endorsement:

**G1** Expressive and Grounded Endorsement Policies. The endorsement policy structure must be designed in a way that allows it to express common deployment factors in smart homes that may affect the endorsement, such as device availability and locality. Moreover, when policies are specified using this design, the specification methodology must be grounded in real smart home devices and their characteristics for practical relevance.

**G2** Complete Mediation. Third party services are generally deployed in cloud environments outside the platform’s control, as simple cloud end-points that can make REST API calls (e.g., the “Works with Google Assistant” platform [19], or SmartThings v3 [59]). Hence, the reference monitor should be app-agnostic, i.e., should not depend on the analysis/instrumentation of app/services, but should provide complete mediation for all API calls that modify AHOs, irrespective of app logic.

**G3** Tamperproofness. While our endorsement approach relies on device states, several device states may be modifiable by untrusted services using the platform API. We need to build a reference monitor that only relies on trusted reports from devices.

**G4** Freshness. The task of endorsing an AHO change may require the reference monitor to examine recent changes in the states of physical devices, rather than simply reading the current state (e.g., as sensor states may reset after apprising the platform of an event). Hence, the reference monitor must have trusted access to historical states and timestamps.

**G5** Minimal Performance and Management Overhead. Implementing physical state endorsement is likely to introduce several additional performance costs to API accesses. The framework should minimize any performance delay perceivable by the user, as well as the effort required to deploy and manage policies.

3.2 Threat Model
We consider a network-based adversary with the ability to compromise any third-party integration/service connected to the target’s home (e.g., as demonstrated by prior work [16, 31]). The attacker’s objective is to indirectly modify or disable high integrity devices (e.g., security camera) using compromised or malicious third-party services. The adversary may issue API commands to the target’s home that may affect device states; however, the adversary does not have the ability to compromise devices in the home by other means (i.e., which is a standard assumption in work that deals with API misuse [7, 13, 14]). The adversary cannot compromise the platform and the platform app; explicitly, the adversary cannot censor notifications sent from the platform to the user. Devices may be offline; however, we do not account for byzantine fault tolerance, but point to complementary prior work [4] that verifies reported device states.

4 THE HOMEENDORSER FRAMEWORK
We propose HomeEndorser, a framework that enables home abstraction endorsement by developing the methods and systems necessary to achieve the design goals G1→G5. We first define a policy model that can express deployment-considerations such as device locality and availability (G1). HomeEndorser automatically instantiates the policies defined within this model in the context of the end-user’s home, i.e., considering the devices available as well as install locations, thereby reducing deployment-time configuration effort (G5). HomeEndorser’s reference monitor is integrated into the user’s smart home platform in the form of an endorsement check in the platform subsystem responsible for executing all API calls, thereby ensuring complete mediation (G2). When a third-party makes an API call to modify an AHO-change that HomeEndorser endorses, HomeEndorser invokes the corresponding policy, and uses a state machine to retrieve the most recent change in each relevant device state/attribute included in the policy (G4). We consider the most recent change, rather than the current state of the device attribute, as the two may be different (since most sensors reset after a change), and because the most recent device state changes provide the context for endorsing the proposed AHO change. This design decision is instrumental in eliminating unnecessary false denials (see Section 6.4).

We formulate a policy specification methodology that allows experts to specify endorsement policies in a systematic, ground-up manner (G1). Our approach derives a mapping of smart home devices and their attributes (i.e., fields that indicate specific device states), which are further filtered to a set of endorsement attributes: device-attributes that can be trusted for endorsement, due to being either read-only or treated as highly restricted by platforms (G3). Once the trusted attributes are identified, we use systematic open coding to identify inferences drawn from them that can endorse specific AHOs. These inferences, when expressed in our policy model, form deployment-independent endorsement policy templates that are automatically instantiated in the user’s deployment-context.

The rest of this section describes the three design components, starting with the policy model (Section 4.1), followed by the runtime enforcement (Section 4.2), and the data-driven policy specification and instantiation methodology (Section 4.3). We use the endorsement scenario in Section 2.1 as the running example.

4.1 Policy Model
A key challenge for HomeEndorser is designing a policy model that can alleviate two practical constraints. First, unlike our motivating example where a single device-attribute (i.e., the UNLOCKED state of the door lock) was used for endorsing home, in practice, endorsement policies may consist of more than one device-attribute that must be checked simultaneously. Second, the device location is an important factor in deciding what they can endorse. For example, while a door lock on the front door as well as a door lock on the back door can both indicate that the user is home, the two endorsements are naturally mutually exclusive. We account for these constraints
with a policy design that can be expressed as a Disjunctive Normal Form (DNF) boolean formula, as follows:

**Definition 1 (Endorsement Policy).** The policy for endorsing a change in AHO \( x \) to value \( y \), \( P_X(y) \), is a DNF formula composed of one or more location-specific predicates \( (L_i) \), i.e., \( P_X(y) = L_1 \lor L_2 \lor \cdots \lor L_n \), where a location-specific predicate is defined as follows:

**Definition 2 (Location-specific Predicate).** A location-specific policy predicate \( L_i \) for location \( i \) (e.g., entryway), i.e., \( L_i = d_j \land d_k \land \cdots \land d_m \), is a conjunction of one or more device-attribute checks \( d_j \), defined as follows:

**Definition 3 (Device-attribute Check).** A device-attribute check \( d_j \) is a condition \( d_j \equiv s \), where \( s \) is a physical state that the particular device-attribute must have exhibited in the recent past, for the device-attribute check to return \( true \).

To illustrate, let us express the policy from the motivating example for endorsing the home AHO’s change to the value “home”. We express the policy using a door lock and a motion sensor at the entry way, as well as the same devices at the rear entrance, as follows:

\[
P_{\text{home}}(\text{entryway}) = (\text{door-lock\_lock} = \text{UNLOCKED} \land \text{motion\_sensor} = \text{ACTIVE})_{\text{front\_door}} \lor (\text{door-lock\_lock} = \text{UNLOCKED} \land \text{motion\_sensor} = \text{ACTIVE})_{\text{back\_door}}
\]

The above policy considers both the door lock being unlocked, and motion being sensed, to prevent false negatives. That is, for both the conditions above to be true, a user would have to unlock the door and then enter, i.e., proving that they are home beyond doubt. On the contrary, if the user unlocks but leaves without entering, this policy condition would correctly result in a denial (as shown in Section 6.4). Similarly, the disjunction between the location-specific predicates enables their independent evaluation, thereby allowing the AHO-change as long as either one evaluates to a \( true \) result. Finally, we define two policy actions: ALLOW and DENY, corresponding to the \( true \) or \( false \) values that the DNF formula results in, respectively.

For Bob to circumvent HomeEndorser’s defense, Bob could attempt to modify home at the very moment when Alice is performing what are semantically completely opposite actions, but sufficient for the endorsement of home. For instance, Alice could be leaving, which would also involve (1) unlocking the door, and (2) triggering the door-way motion sensor. A naive implementation of our policy model would be susceptible to this attack, as it would consider the above device state changes, even if performed in the opposite sense, to be evidence that Alice is returning home, because it matches \( P_{\text{home}}(\text{entryway}) \). However, smart home devices provide unique device attribute values even for similar actions, i.e., the state value for unlocking the door using the keypad is different relative to simply unlocking it from the inside (i.e., “owner” in the former case, and “manual” in the latter). Our policy specification 4.3 and enforcement (Section 4.2) consider device-attribute values at this precise granularity, preventing such an attack.

### 4.2 Secure and Practical Enforcement

We integrate HomeEndorser’s enforcement into the smart home platform, to enable it to mediate all API commands from third-parties before they are executed \((G2)\). This decision is influenced by how third-party services are currently integrated, i.e., as cloud endpoints that use RESTful APIs to interact with the platform, but execute on their own proprietary servers, without a way for the platform to inspect them \((e.g., \text{NEST and SmartThings v3})\). Therefore, our decision ensures that the endorsement check will occur regardless of how the integration is implemented, or where it is deployed. We now describe our platform-level enforcement in terms of its three design components, as shown in Figure 3.

**1. Deployment-aware Policy Instantiation:** HomeEndorser enforces policies specified as per the policy model described previously \((we\ describe\ the\ specification\ process\ in\ Section\ 4.3)\). However, it cannot directly enforce the general policies without first contextualizing them to a user’s home, for three key reasons: (1) A typical user’s setup is unlikely to have all the devices specified in the policy, i.e., the most restrictive policy consisting of the most number of devices would always deny the state change. (2) The policies need to be configured as per the different locations in which devices are placed in the home, and (3) The enforced policies need to adapt as the user’s smart home evolves \((e.g., through device addition/removal), to provide the enforcement applicable to the current setup. Thus, we treat the specified policies as templates that HomeEndorser automatically instantiates in the deployment-context of a particular home.

To elaborate, when HomeEndorser is first set up in a home, it leverages the platform’s internal bookkeeping systems to extract all the devices and device-locations. Then, for each state the user decides to endorse, it uses the policy templates specified previously to instantiate the most restrictive but feasible policy, i.e., the policy that contains the largest aggregate of device-attributes \((with\ the\ assumption\ that\ including\ more\ device-attributes\ would\ make\ the\ inference\ stronger)\), but which is also supported given the devices present in the home and their locality. This most restrictive policy is then marked for enforcement. Finally, HomeEndorser also updates its policy instances upon a configuration change, such as the addition, removal, or relocation of a new device.

**2. The Endorsement Check:** HomeEndorser mediates all API requests, but only invokes the endorsement check if one of the AHOs selected by the user for endorsement is about to be modified, in a manner similar to performance-preserving hook activations as previously proposed for Android \((G2)\). The check consists of retrieving the policy for the specific AHO-change being endorsed and collecting state information from the device-attributes in the policy. As described previously in Section 4.1, if the policy decision is ALLOW, then the proposed change is allowed to go through; else, it is denied, and the user is notified. A key component of this
check is HomeEndorser’s platform state machine that retrieves the device-attribute values, which we now describe in detail.

3. Retrieving the most recent changes using the Platform State Machine: A naive approach of executing an endorsement check would be to query each device for its current state at the time of endorsement. However, such a check would most certainly fail and lead to a false denial because most sensors detect and report a change, and then reset to a predefined neutral state. For example, recall the endorsement policy predicate to endorse home consisting of the door lock and the motion detector (assuming one location for simplicity):

\[
door-lock\_lock \equiv UNLOCKED \land motion\_sensor \equiv ACTIVE
\]

Unless the endorsement check happens exactly at the moment the user enters, the motion detector will reset to its INACTIVE state immediately after detecting motion, resulting in a false denial. Therefore, for correct endorsement, we check the most recent but fresh change in the physical device states (G4), i.e., the last state change before the state automatically reset, within a certain configurable time threshold to ensure freshness (e.g., one minute).

A state machine that keeps track of the state changes in all the devices provides HomeEndorser’s reference monitor with this data, by tracking changes through callbacks placed in the entities that represent devices on the platform (e.g., device handlers in SmartThings, or device-integrations in HomeAssistant). Every time the physical state of a device changes, the state machine callback is invoked to store the most recent state change along with the timestamp. The timestamp helps HomeEndorser discard states that are older than the preconfigured threshold, thereby preventing old states from causing false allows (G4). Finally, we note that this state machine abstraction does not have to be developed from scratch, and can be built on top of the platform’s subsystem that keeps track of device states.

4.3 Data-driven Policy Specification

Figure 4 provides an overview of our data-driven methodology to allow experts (e.g., security researchers, platform vendors) to specify endorsement policy templates that are representative of what real device states can enable (G1), which HomeEndorser automatically instantiates in the context of end-user homes (as previously described in Section 4.2). We begin by creating a device-attribute map, i.e., a comprehensive mapping between device types (e.g., cameras, door locks) and the attributes they embody. We then define the endorsement attributes to be used for tamperproof endorsement, and describe our approach for identifying them (G3). Finally, we use an open coding methodology for identifying the observations and inferences that can be made from the endorsement attributes, which are then used to specify policy templates (using the model from Section 4.1). Note that although we develop a methodology to specify policies, we assume optimal device placement and sensor configuration to be out of scope, and direct the reader to complementary related work that informs users on optimal deployment [30].

1. Generating the Device-Attribute Map: We develop a semi-automated methodology to create a realistic device-attribute map from platform documentation and existing device-abstractions such as SmartThings “device handlers”. We select the following information sources for building the map, based on platform popularity, and the potential of obtaining realistic mappings: (1) a device-resource map from the Open Connectivity Foundation (OCF) specification [43], used by the open source platform IoTivity [28], (2) the NEST data store [41], (3) the SmartThings capability reference [58], and (4) SmartThings device handlers [52]. As each of these sources exhibits a unique representation of devices and attributes, we develop customized, automated, methods for extracting device-attributes from each source. To elaborate, OCF explicitly specifies a device types, the attributes associated with each device type in a JSON document [44], which we automatically analyze to obtain a device-attribute map for OCF. Similarly, the NEST data store provides a mapping of device-attributes in JSON-like format, which we similarly query. SmartThings provides a capability reference [58], which lists attributes (i.e., capabilities) that devices may choose to exhibit, via developer-defined device handlers, which are software proxies for devices that facilitate device-interaction with the platform. To extract a device-attribute map from SmartThings, we automatically analyze the 334 device handlers from the SmartThings repository [52], and capture the device-attribute relationships evident in the preamble (seen in Figure 6 in the Appendix).

2. Identifying Trusted Endorsement Attributes for Tamperproof Endorsement: We observe that similar to AHs, several device-attributes are modifiable by third-parties through the platform APIs, either for legitimate purposes or due to over-privilege. Therefore, for ensuring tamperproof endorsement, HomeEndorser must be able to trust the information received from the participating endorsers i.e., device-attribute pairs (G3). We achieve this goal by defining a trusted subset of device-attributes to be used for our checks, i.e., endorsement attributes. We propose two categories of endorsement attributes: (1) read-only attributes, i.e., which are only writable by devices, and not via API calls, rendering them read-only from the third-party API caller’s perspective (e.g., motion sensor reading), and (2) designated attributes, which are writeable in theory, but are considered high-integrity by platforms and prior security research [10, 61] alike (e.g., locking the door lock), and hence, heavily restricted. For example, NEST allows its own platform app to unlock the locks integrated with it (e.g., the Nest X Yale Lock [18]), but does not allow third-party apps to do the same. Therefore, both read-only and designated device attributes would have a higher integrity level than a state such as home, and hence, would be trusted to endorse it.

We identify read-only device-attributes in a manner similar to our approach for extracting the device-attribute map, i.e., by parsing platform documentation and device handler code. For identifying designated attributes, we leverage the rationale of popular platforms for assigning integrity levels to attributes only writable by the platform app, particularly those belonging to security-sensitive devices.
3. Generating Endorsement Policies from Attribute Inferences: We now address the question of how the endorsement attributes are used to endorse a specific AHO, by designing a holistic inference study. We begin by identifying 5 additional AHOs, by considering the objects that have been previously examined and found to be susceptible to transitive attacks [13, 31], and by considering AHOs not mentioned in prior work, but which we encountered when building our device-attribute map (e.g., the security_state from NEST, which prior work does not account for). Then, we consider each device-attribute, and identify the type of information sensed or observed by that device-attribute, which we then translate to an inference that could be used for endorsing an integrity-sensitive change in one or more of the AHOs. For example, the device-attribute pair <security-panel, disarmed> indicates that the security panel/keypad was recently disarmed, which may indicate that the user recently arrived home, and hence, provide an inference to endorse the home AHO’s proposed change to “home”. As a key principle in the construction of policies is the combination of device inferences, we combine inferences to construct deployment-independent policy templates using the structure defined in Section 4.1. An example set of inferences discovered using this process are shown in Table 1.

5 IMPLEMENTATION

This section describes our policy specification study, as well as the reference monitor implemented in HomeAssistant.

1. Policy Specification Study: We automatically generated a combined device-attribute map from all the data sources consisting of 100 device-types and 510 device-attribute pairs. Of these, we identified 41 endorsement attributes, i.e., read-only or designated device-attributes. Two authors then independently identified the inferences that could be drawn from these endorsement attributes to endorse changes in one or more of our 6 AHOs. When identifying inferences, the coders disagreed on 12 out of the 510 device-attribute pairs (2.4% disagreement rate), which were resolved through mutual discussion. The inferences specified for these endorsement attributes led to 1023 policies for the home AHO alone. Note that the generation of the device-attribute map was fully automated and directly derived from platform sources, and hence, did not result in any disagreements. Our data is available in our online appendix [2].

2. Implementation on HomeAssistant: We implemented HomeEndorser in HomeAssistant, a popular open-source smart home platform, for two main reasons: (1) the availability of source code, and (2) the centralized execution of automation and state changes. Similar to the platform state machine described in Section 4.2, HomeAssistant has a state machine component that saves and updates all the devices and their states within HomeAssistant. In fact, all state changes to the devices occur through the state machine. HomeEndorser modifies this state machine to keep track of the most recent state changes and their timestamps. It also hooks into the state machine to intercept the incoming state change requests, to mediate all API accesses. Furthermore, HomeAssistant has a component known as an Event Bus, which announces and logs the addition/removal of devices, among other events. HomeEndorser adds callbacks in the Event Bus and re-instantiates the endorsement policies in response to any change in device deployment. Finally, HomeEndorser keeps track of device-connectivity using HomeAssistant’s built-in mechanisms, and falls-back to the next most restrictive policy in case a device becomes unavailable at runtime. Note that no such loss of connectivity was noticed throughout our evaluation.

6 EVALUATION

Our evaluation is guided by the following research questions:

- **RQ1:** (Feasibility of the policy model.) Is it feasible to specify endorsement policies using only a small subset of trusted endorsement attributes, i.e., only the read-only and designated device attributes?
- **RQ2:** (Generalizability of the policy model) Do feasible endorsement policies exist for endorsing AHOs other than home?
- **RQ3:** (Security.) Does HomeEndorser prevent an attacker from escalating privilege to a high-integrity device (e.g., a camera) using one or more shared objects?
- **RQ4:** (False Denials.) What is the rate of false denials in typical benign usage, i.e., when users intentionally cause AHO changes?
- **RQ5:** (Runtime Performance.) What is the performance overhead introduced by HomeEndorser?
- **RQ6:** (Integration Cost.) How much effort is required to integrate and deploy HomeEndorser?

We evaluate RQ1→RQ6 using a diverse array of empirical and experimental methods. We first derive 1023 endorsement policies (i.e., templates) for endorsing the home AHO using the approach described in Section 4.3, which demonstrates that the proposed approach is feasible with even a limited endorsement attributes (RQ1). Further, we demonstrate that HomeEndorser may generally apply to 5 additional AHOs drawn from platform documentation and prior work, as these AHOs may be endorsed using policies composed of 5 device attributes on average (RQ2). We then deploy 11 devices (7 real, 4 virtual) in a real home, and perform a case study wherein we assume that the attacker’s goal is to disable the security camera by tampering with state variables that the camera depends on. Our experiments demonstrate that HomeEndorser correctly endorses the two AHOs that can be tampered with to disable the camera, thus demonstrating its effectiveness (RQ5).

We perform 10 additional realistic scenarios obtained from (or inspired by) prior work [30], which represent the various logical ways in which the user would intentionally change the AHOs endorsed in the case study. Our evaluation demonstrates that HomeEndorser correctly allows all of the intentional AHO changes, resulting in no false denials (RQ4). We also measure the performance overhead incurred by HomeEndorser’s hooks using macro and microbenchmarks, demonstrating practical performance overheads (RQ5).

Finally, we evaluate the effort required to configure HomeEndorser and integrate it into other platforms. Particularly, we demonstrate that policy specification is a feasible, one-time effort performed by security experts, and HomeEndorser automatically instantiates policies in the context of the user’s home (i.e., as described

| AHO               | Endorsement attributes                                      |
|-------------------|------------------------------------------------------------|
| home              | <security-panel, disarmed>                                 |
| home              | <motion-sensor, active>                                    |
| fire              | <temperature-sensor, temperature>                          |
| fire              | <smoke-detector, smoke-alarm-state>                        |
| safety_state      | <co-detector, co-alarm-state>                              |
| illuminance       | <blind, openLevel>                                         |

**Table 1: AHOs inferred from Endorsement Attributes**
Figure 5: Layout of the physical device placement

Table 2: Sample policies for endorsing home AHO (“away”→“home”)

| Policy (location independent) |
|-------------------------------|
| 1.  \(\text{<security-panel, disarmed> \&<motion-sensor, active>}\) |
| 2.  \(\text{<doorlock, unlocked> \&<presence-sensor, active> \&<beacon, active>}\) |
| 3.  \(\text{<garage-doorlock, unlocked> \&<beacon, active>}\) |
| 4.  \(\text{<security panel, disarmed> \&<thermostat, motion, active>}\) |

in Sec. 4.3), drastically minimizing user effort. Moreover, we distilled the key properties that a platform would need to exhibit in order to integrate HomeEndorser, qualitatively analyze 4 popular smart home platforms, and demonstrate that it is feasible to integrate HomeEndorser with modest engineering effort (RQ1).

Experimental Setup: We integrated HomeEndorser into HomeAssistant (v0.112.0.devo), running on a Macbook Pro machine with 16GB of RAM. Further, we connected 7 smart home devices to our smart home, and created 4 other virtual devices (see Table 5 in Appendix A for full list). Our choice of devices was limited by devices compatible with HomeAssistant, with a bias towards known/popular brands, as well as device types that would allow us to evaluate HomeEndorser’s endorsement policies. We installed these devices in a room as shown in Figure 5, influenced by effective deployment recommendations from prior work [30]. To elaborate, we placed the August door lock and the Aotec door sensor on the main door, and the motion sensor in the hallway directly past the door. The motion sensor was placed such that it would not be triggered by the opening or closing of the door but would be triggered if someone walked down the hallway to get into the room. The Blink camera was placed inside the room. We interacted with the real devices physically and with the virtual devices through the HomeAssistant UI.

6.1 Feasibility of the Policy Model (RQ1)

We do not expect users to possess all possible device-combinations that may endorse a specific AHO. Instead, our approach must enable the specification of a large and diverse set of candidate policies (i.e., templates), to increase the possibility of finding at least one policy that contains the limited set of devices the user may possess. Thus, our approach would be feasible if such a set of policies is possible, given the small number of trusted endorsement attributes.

Using the approach specified in Section 4.3, we were able to specify 1023 unique policies for endorsing the home AHO (i.e., the change from “away” to “home”), consisting of 5 device-attributes on average, with the largest containing 10. Table 2 contains 5 example policies generated using HomeEndorser (our online appendix [2] provides the full list). These policies were constructed from 10 device-attribute pairs that provide some inference for the home AHO change, of which 3 provide particularly strong endorsement of the user entering the home, as they denote authenticated entry (i.e., the door lock being unlocked, the garage door opened, and the security panel disarmed). As a result, even if the user had one of these 3 devices, they would be able to endorse home; the remaining 7 devices would only make the endorsement stronger. Further, even if we include the policies that only have only 1 of these 3 device-attribute pairs (and other device-attributes), we get a total of 255 policies. For example, as shown in Table 2, a user who has a door lock and motion sensor, or another who has a security panel, or another who has a garage doorlock and a presence sensor, would all be able to endorse home using HomeEndorser. This demonstrates that our approach is feasible, i.e., we can define a large number of diverse policies for an AHO (i.e., home), using a limited set of endorsement attributes, and hence, support a diverse array of device-deployment scenarios (RQ1).

6.2 Generalizability of the Policy Model (RQ2)

To demonstrate the generalizability of our policy model, we consider 5 additional AHOs (i.e., security_state, fire, water leak, illuminance, and safety_state). For each AHO, we identified endorsement attributes from the device-attribute map and then generated inferences using the process described in Section 4.3. Our process resulted in 41 inferences (cumulatively) that would be useful for endorsement, with each AHOs being endorsed using at least 3 device-attributes (examples provided in Table 1 in Section 4.3). This demonstrates that our approach is generalizable to AHOs other than home, i.e., similar policies are feasible for 5 other AHOs, as demonstrated by the substantial availability of applicable and trusted device-attributes (RQ2).

6.3 Case Study: Protecting the Security Camera from Privilege Escalation (RQ3)

HomeEndorser enables the following guarantee: given the attacker’s goal to tamper with a high-integrity device that they cannot directly access (e.g., a security camera), HomeEndorser’s endorsement checks prevent the attacker from affecting malicious changes to any AHO that the aforementioned device depends on. We demonstrate HomeEndorser’s effectiveness, with respect to the guarantee, using the attack described in the motivating example (Section 2.1). As the camera depends on both the home and security_state AHOs, we experimentally demonstrate HomeEndorser’s effectiveness at preventing malicious modifications to both, using two scenarios:

Malicious Scenario 1 - Bob modifies home: We deploy a malicious third-party service controlled by the attacker, Bob. We assume that Alice has granted to the service the permission (i.e., a REST API token) to write to the home AHO. When Alice is out of the home, Bob writes to the value “home” to home, to disable the camera. Without HomeEndorser, the home AHO will change, allowing Bob to remotely disable the security camera; however, we consider that Alice uses HomeEndorser with the policy \(P_{\text{home}}(\text{home})\) enabled:

\[
P_{\text{home}}(\text{home}) = (\text{door-lock\_lock} == \text{UNLOCKED} \land \text{motion\_sensor} == \text{ACTIVE})\land \text{front\_door}
\]

Thus, when Bob writes to home, the policy \(P_{\text{home}}(\text{home})\) is checked as follows: HomeEndorser queries the state machine, and obtains the most recent change in the state of the door lock as well as the entryway motion detector. Since the door lock was not unlocked, and
The motion detector has also not detected motion recently, the policy returns a DENY decision, and Bob’s access is denied, preventing the attack. It is also important to note that Bob could attempt to circumvent HomeEndorser’s policy by satisfying one of the two conditions in it, e.g., by sliding a thin object (e.g., a card) through the door to trigger the motion sensor; however, the conjunction among device-attributes prevents this attack variation.

**Malicious Scenario 2 – Bob modifies security_state:** We deploy a malicious third-party service controlled by Bob, to which Alice has granted the permission to write to the security_state AHO. Bob will attempt to set the security_state to “ok” (as opposed to “deter”), which will trigger a routine that turns off the camera. Without HomeEndorser, the security_state state will successfully change, allowing Bob to disable the camera; however, we consider that Alice uses HomeEndorser with the policy $P_{\text{security state, ok}}$ enabled:

$$P_{\text{security state, ok}}(\text{ok}) = (\text{security panel} == \text{DISARMED} \land \text{motion sensor} == \text{ACTIVE})_{\text{front-door}}$$

When Bob writes to security_state, $P_{\text{security state, ok}}$ is checked. Since the security panel wasn’t disarmed and the motion sensor wasn’t active recently, the policy returns a DENY decision, preventing the attack. To summarize, HomeEndorser successfully endorses both of the AHOs on the transitive attack path to the security camera, thereby preventing Bob from disabling the camera via a lateral privilege escalation.

### 6.4 Endorsing Intentional State Changes (RQ4)

We experimentally evaluate the behavior of HomeEndorser when users intentionally request state changes. Users may themselves choose to change AHOs (e.g., by manually selecting home mode in their platform mobile app after getting home), or by using a third-party service that automatically requests appropriate state changes based on the user’s location (e.g., when the user arrives home). We derive a set of 10 realistic user behavior scenarios from prior work [30] to use as our benign examples, and enact those scenarios in our apartment testbed. Note that HomeEndorser can provide endorsement policies to endorse all 10 scenarios, even when they are exemplary of HomeEndorser’s decisions in response to benign user behavior, with the rest available in Table 6 in Appendix B.

**Scenario 1 – Entering the house:** Alice returns home, unlocks the front door lock and opens the door. She then closes the door and enters, triggering the motion sensor near the door. Around the same time, her home/away tracker service requests a state change from away to home using REST API. In response to the request, HomeEndorser gathers the recent states of the devices to check against the active policy (i.e., $P_{\text{home, (home)}}$).

$$P_{\text{home, (home)}} = (\text{motion sensor} == \text{ACTIVE} \land \text{door sensor} == \text{ACTIVE})_{\text{front-door}}$$

Since the door lock was manually unlocked and the sensors were active recently, the policy is satisfied and HomeEndorser allows the change, as Alice intended.

**Scenario 2 – Unlocking the house, and then leaving:** Alice returns home and opens the front door after unlocking the front door lock. However, she gets a call from her office and leaves immediately without entering the house, accidentally also leaving the door open in the process. Regardless, Alice’s home/away service accidentally requests the home AHO to change to “home” (i.e., even when Alice has actually left), which would disable the camera and leave the home in an unmonitored state.

In response to the request, HomeEndorser gathers the recent states of the devices to check against the active policy (i.e., $P_{\text{home, (home)}}$). The policy constraints are partially satisfied, as the door lock was recently manually unlocked, and the door sensor’s state changed to “open”. However, as Alice did not enter, the motion sensor did not detect any motion, and the policy results in a correct denial, preventing an unsafe situation in which the camera is turned off while the home is vulnerable (i.e., the door is unlocked). That is, HomeEndorser’s composite policy design leverages additional devices such as the motion detector to provide stronger endorsement, and hence, is useful for preventing accidental but unsafe changes.

**Scenario 3 – A home without a smart door lock:** Alice does not possess a smart door lock, but enables the following policy based on the devices in her home:

$$P_{\text{home, (home)}} = (\text{motion sensor} == \text{ACTIVE} \land \text{motion sensor} == \text{ACTIVE})_{\text{front-door}}$$

Alice comes home and enters through the front door, triggering the motion sensor and the presence sensor in the hallway. At the same time, her service requests a change to home. In response, HomeEndorser gathers the recent device states to check against the active policy, $P_{\text{home, (home)}}$. Since both the sensors were recently active, the policy is satisfied and the state change is correctly allowed. That is, HomeEndorser’s policy structure enables us to specify a variety of endorsement policies containing a diverse array of devices, which supports several home configurations, and prevents false denials due to the absence of certain devices.

**Scenario 4 – Disarming the security panel and entering:** In this scenario, Alice returns home and inputs the key-code in the security panel near the door, disarming the home. She then enters the home, triggering the motion sensor. At the same time, a home security service requests change to the security_state object on Alice’s behalf, from “deter” to “ok”, which if allowed, would disable the security camera, as well as any other security devices (e.g., alarms).

HomeEndorser gathers the recent states of the devices to check against the active policy, $P_{\text{security state, ok}}$ (provided previously in Section 6.3). Since the security panel was manually disarmed and the motion sensor was active recently as well, the policy is satisfied and the state change is correctly allowed.

**Scenario 5 – Direct state change request:** Alice returns home, and manually changes the home AHO to “home” using the HomeAssistant dashboard. HomeEndorser identifies that the request was not made through the REST API, and correctly allows it without checking the policy, thereby honoring the user’s explicit intent.

Our evaluation demonstrates that HomeEndorser does not cause false denials under benign behavior. That is, it generally does not deny state changes intended by the user, and when it does, its denials prevent accidental and harmful state changes by users (i.e., and hence, are correct) (RQ4). We further observed that in several cases, by the time the endorsement was requested (i.e., time of REST
API call), the relevant devices (e.g., motion sensors) had reverted to their default states (e.g., the motion sensor reverted to the “inactive” state). This means that if we had only checked the current state of the devices, i.e., the state at the time of endorsement, the endorsement check would have resulted in a false denial. However, HomeEndorser’s approach of checking the most recent change prevents such potential false denials. Finally, we did not observe any device or automation crashes/failures in the home in response to HomeEndorser’s endorsement (see Appendix C for details).

6.5 Runtime Performance (RQ₅)

We measure the performance of HomeEndorser using a combination of macro and microbenchmarks (RQ₅).

Methodology: We compute microbenchmarks to capture each aspect of the platform that HomeEndorser affects, in particular, the time taken for (1) policy instantiation (i.e., additional delay at boot time), (2) policy update during runtime (i.e., overhead of device addition/removal) (3) the endorsement hook invocation cost (i.e., overhead of an API call to a state not being endorsed), and, (4) the endorsement check (i.e., overhead of an API call to a state being endorsed). Furthermore, we perform 2 macrobenchmarks to assess the overall end-to-end impact of HomeEndorser on the execution times of remote IoT services that leverage the REST API for (5) executing an automation involving an AHO being endorsed, and (6) executing an automation involving an AHO not being endorsed. We measure the worst-case performance by performing all measurements with the largest policy, i.e., the policy involving the maximum number of device-attributes that can be instantiated in our device deployment (i.e., $P_{109}$, online appendix [2]).

We compute baselines for the benchmarks using an unmodified build of HomeAssistant with the same devices. We perform each experiment 50 times in both environments i.e., 50 executions each on HomeAssistant with HomeEndorser and HomeAssistant without HomeEndorser. Table 3 shows the mean results with 95% confidence intervals.

Results: As seen in Table 3, HomeEndorser has negligible performance overhead for operations that do not involve the AHO being endorsed, i.e., the hook invocation cost when calling an API that modifies a non-endorsed AHO (microbenchmark), as well as executing an automation that changes a non-endorsed AHO (macrobenchmark), with the overhead falling within the error margin (which explains the negative overhead for operation 6).

For endorsed AHOS, HomeEndorser adds only 0.916ms (9.69% overhead) to an AHO-change invoked via an API call (microbenchmark), and adds 2.016ms (12.16% overhead) to the overall execution time of an automation execution that changes an endorsed AHO (macrobenchmark). In fact, the maximum overhead of 9.818ms (41.16%) that HomeEndorser adds is to the overall bootup time of HomeAssistant, which is not that frequent, and not perceivable by the user. This is primarily due to the fact HomeEndorser’s Policy generator is called repeatedly as HomeAssistant adds devices during bootup. After the bootup, the overhead to update policies when devices get added or removed is only 4.350 ms. Finally, we note that the endorsement check overhead may not be dependent on the policy size, as we have confirmed via inspecting HomeAssistant’s code that its state machine obtains device state changes in parallel.

6.6 Effort Required to Integrate and Configure HomeEndorser (RQ₆)

This section describes the effort that may be required to deploy and integrate HomeEndorser. Particularly, we demonstrate that (1) experts may specify a large number of endorsement policies for HomeEndorser using the systematic semi-automated methodology defined in Section 4.3 with minimal effort and time, (2) HomeEndorser can automatically instantiate its policies in end-user homes as per the availability and placement of devices, which significantly reduces configuration effort, and finally (3) most platforms may directly integrate HomeEndorser without any design-level extensions, which indicates its practicality, and promise of future deployment (RQ₆).

1. Policy specification: HomeEndorser’s policies are specified by experts, and automatically instantiated in the end-user’s home based on the devices deployed at various locations. The semi-automated, data-driven, process for specifying policies is a one-time effort, as described in Section 4.3, and policies only need to be updated when new functionality emerges in an entire category of devices such as door locks (i.e., and not individual brands), or when an entire new category of device is introduced to the market. To generate the 1023 policies for endorsing home, as well as the 510 device-attributes that could help endorse 5 other states, it took 2 authors around 4 workdays, which is feasible given that the policies will provide endorsement in user homes with diverse device configurations.

2. Deployment in the User’s Home: The user deploys HomeEndorser by simply deploying the smart home platform that it is integrated into (e.g., HomeAssistant, as implemented in the paper). The deployed platform comes with pre-specified policies built-in, which are instantiated in the context of the user’s device setup (as described in Section 4.2). Most platforms already require the user to provide device-location for functionality, and HomeEndorser simply piggy-backs on this information to instantiate policies. The only additional effort on the user’s part is selecting the AHOS that they would like to endorse. Finally, HomeEndorser seamlessly updates the policy configuration with minimal performance overhead when new devices are added or existing devices removed.

3. Platform integration: Through lessons learned during our implementation of HomeEndorser in HomeAssistant, we distill 4 key platform-properties that are necessary to successfully integrate HomeEndorser in a smart home platform, in a way that satisfies the general purpose of physical home endorsement, as well as certain enforcement-related design goals (G2 → G4). We then discuss these identified properties in the context of 4 popular platforms, namely IoTivity [28], OpenHAB [45], SmartThings [59], and NEST/Google Assistant [19], and estimate the effort that would be required for the wide-spread integration of physical home endorsement, across all platforms. We now describe the properties, followed by our qualitative analysis of platforms in terms of ease of integration.

Property 1 (Prop₁) - Ability to obtain device states: In order for HomeEndorser to correctly enforce the policies, it has to be able to obtain states from all devices involved in the policies. Ideally, the platform
should have a Platform State Machine that can readily provide device state information. This property is necessary for the general correctness of enforcement, and no design goal in particular.

**Property 2 (Prop2) - Complete mediation of state changes:** For HomeEndorser to intercept all incoming API requests that seek to change AHOs, and trigger endorsement checks (G2), the platform must have a central component that intercepts all the API requests. Furthermore, this component must be unmodifiable by third parties (G3).

**Property 3 (Prop3) - Timestamp information of device states:** HomeEndorser requires fresh devices state information in order to remove any false positives that can occur because of devices reporting cached states or the platform itself reporting the last known state as the current state because of a non-responsive device (G4).

**Property 4 (Prop4) - Ability to monitor device changes:** HomeEndorser needs the ability to dynamically adapt its policies based on the current setup of the smart home, and hence, the platform needs to monitor the addition, removal, and change in placement of devices.

Table 4 shows the results of our platform analysis based on Prop1 → Prop4, and particularly, demonstrates that only IoTivity requires a design-level extension for integrating HomeEndorser (in terms of Prop3), and all other platforms may feasibly integrate HomeEndorser, sometimes with negligible engineering efforts. Each integration may require minor adjustments, e.g., for HomeAssistant, we modified the state machine for complete mediation, whereas in OpenHAB, we would need to implement a reference monitor across various bindings (i.e., hook into services exposed as bindings), in a manner similar to how extensible access control has been previously implemented in OSes such as Linux [68] and Android [24]. While IoTivity provisions states to the reference monitor (Prop2), a state machine with the ability to collect fresh information will need to be implemented (Prop3), which would be a design-level extension.

We mark certain properties for NEST and SmartThings as in Table 4 because while we can almost certainly say that they possess the required properties to integrate HomeEndorser with minimal engineering efforts, we would need source code to confirm. NEST is a particularly interesting example, because while it does exhibit all of the properties, making it an ideal platform to integrate HomeEndorser into, it currently supports Prop1 for only a limited set of devices, i.e., the NEST-owned devices that are in its data store (e.g., the NEST camera, NEST smoke alarm). However, this may be easily remedied by allowing third-party devices to be integrated into the data store as well, so that they can report their states for the platform to access. Further, while SmartThings does not protect AHOs (e.g., home) with permissions, it does provide a permission framework that mediates most similar accesses (and hence, has the ability to protect AHOs). Hence, integrating HomeEndorser would simply require the placement of endorsement checks alongside the permission enforcement, which is engineering effort similar to what we observe for OpenHAB in terms of Prop3. Furthermore, as an app can be configured to support multiple devices and observe their states (Prop4) and as it can also obtain the state change timestamps from the platform logs (Props), we can say that SmartThings may be able to perform these actions at the platform-level.

### Table 3: Performance overhead of HomeEndorser (in comparison with the unmodified HomeAssistant baseline)

| No. | Operation                          | HomeAssistant Baseline (ms) | HomeEndorser (ms) | Overhead (ms) | Overhead (%) |
|-----|-----------------------------------|----------------------------|------------------|---------------|-------------|
| 1.  | Policy Instantiation (Boo up time) | 23.851 ± 1.738             | 33.669 ± 5.042   | 9.818         | 41.6        |
| 2.  | Policy update during runtime       | 4.350 ± 0.511              | 9.916 ± 0.814    | 0.062         | 0.63        |
| 3.  | Changing non-endorsed AHO (Hook invocation cost) | 9.854 ± 0.723        | 10.36 ± 0.482   | 0.916         | 9.8         |
| 4.  | Changing endorsed AHO (Endorsement check cost) | 9.451 ± 0.605       | 2.016            | 12.16        |
| 5.  | Automation execution with endorsed AHO | 16.582 ± 2.388      | 0.477            | -2.04        |
| 6.  | Automation execution with non-endorsed AHO | 14.809 ± 1.026      | 0.477            | -2.04        |

Table 4: The (minimal) cost of Integrating HomeEndorser with respect to the properties identified in Section 6.6

|               | HomeAssistant | IoTivity | OpenHAB | SmartThings | NEST |
|---------------|---------------|---------|---------|-------------|------|
| Prop1         | ✓             | ✓       |         |             |      |
| Prop2         | ✓             | ✓       |         |             | C    |
| Prop3         | ✓             | ✓       | ✓       |             | C    |
| Prop4         | ✓             | ✓       | ✓       |             | C    |

✓ = Directly portable, C = Directly portable, but needs confirmation from source code, G2 = design-level constraint/extension

7. RELATED WORKS

Much prior work in smart home security has focused on reducing the misuse of sensitive APIs, through improvements to the platform permission model (e.g., risk-based permissions [48], functionality-based enforcement [35]), providing users with context of an API access (e.g., ContexIoT [29]), enforcing least privilege using context from the app’s description (e.g., SmartAuth [65]), and, when all else fails, forensic analysis by integrating fine-grained provenance tracking into apps (e.g., ProvThings [67]). At first glance, our problem may also seem to be one of over-privilege or API misuse; however, we assert that addressing this problem as API misuse by retrofitting existing defenses would be both ineffective and impractical. The approach of removing privileges (or completely preventing third-parties from accessing AHOs) would be impractical because several third-party integrations may truly need access to AHOs, and denying access may come at prohibitive usability costs, as we previously discussed in Section 2.2. Instead, HomeEndorser presents a more direct solution to the lack of integrity for AHOs in the smart home.

An alternate approach to securing shared states (including AHOs) is centralizing them and only allowing trusted third parties to modify them, as Schuster et al. explored using “environmental situation oracles” [53] or ESOs. The ESO model is mainly geared towards providing privacy (and not integrity), i.e., to prevent several parties from persistently accessing the user’s private information (e.g., location) to generate a shared state (e.g., home), by only allowing one dedicated trusted app per shared state. The key difference between ESOs and HomeEndorser’s endorsement is that our approach does not require a trusted party to take upon itself the responsibility of accurately generating the value for a shared state, which may introduce compatibility issues by requiring a single app for every state to be approved by various stakeholders such as users, platform vendors, and device vendors. Instead, HomeEndorser applies an endorsement policy that can sanity check a proposed AHO modification based on consistency with expected device states.
Prior work has also studied transitive problems occurring in the smart home, mostly in the context of app chaining/interactions [61], where the premise is that two or more applications could accidentally (or maliciously) trigger one another, putting the system in an overall unsafe state [6, 7, 10, 42, 61]. Prior defenses against app-chaining attacks involve static analysis (e.g., Soteria [6], IoTSan [42]), or runtime rule-based enforcement (e.g., IoTGuard [7]). Further, Ding and Hu demonstrated that such chains can also exploit the physical interactions among devices in the home [13] and build the IoTSafe system to predict application interactions at runtime [14]. HomeEndorser differs from prior work on app chains (whether or not they involve physical interactions) in two key ways. First, prior defenses are geared towards preventing attacks that involve two apps (i.e., app interaction), and are not designed to defend against arbitrary API calls that modify high-integrity AHOs, which is a complementary research goal. Second, prior work relies on the ability to view and/or instrument apps, whereas HomeEndorser is app-agnostic, only relying on local observations of device states. This is a prudent decision, as most popular platforms no longer host third-party services, as instead such services are hosted from their own cloud environments and access the users’ platforms via platform APIs.

HomeEndorser relies on trusted endorsement attributes, i.e., attributes that cannot be modified by the adversary through API calls, but HomeEndorser does not account for byzantine faults in devices. However, there is prior work in the area of validating states reported by devices, particularly the recent Peeves system by Birnbach et al. [4]. Peeves generates fingerprints of device events, in the form of physical changes that they cause, which are sensed by other trusted sensors, which attest to the validity of the reported device state. However, note that HomeEndorser and Peeves validate orthogonal types of states in the home, which lie at different levels of abstraction, and hence, have distinct design goals. That is, while Peeves focuses on sensor fingerprint accuracy and precision, HomeEndorser focuses on building expressive policies that involve a variety of device states to ensure compatibility with most end-user deployments (G1), and on realizing key reference monitor properties (G2, G3, G4). The device states that Peeves validates form the building block of HomeEndorser’s endorsement policies that endorse higher-level, abstract home attributes (e.g., home.security_state). Hence, HomeEndorser will benefit from the additional robustness and fault tolerance enabled by complementary approaches such as Peeves, although neither system promises byzantine fault tolerance.

Finally, a related problem of endorsing operations has also been explored in Android. Android devices contain many sensors (e.g., camera and microphone) that apps may use if authorized. Android depends on users to authorize the sensors that apps may use, but a malicious app may access a sensor at will once authorized [55]. To address this problem, researchers have explored methods to endorse authorized sensor operations by comparing the context of the sensor operation request to authorized contexts. For instance, user-driven [50, 51] access control requires that applications use system-defined GUI gadgets associated with particular operations to endorse the sensor operation associated with a user input event unambiguously. The AWARE [47] and EnTrust [46] systems permit applications to choose their own GUI gadgets, but restrict applications to employ the same GUI configuration (e.g., layout) to endorse a sensor operation. For IoT systems, rather than GUI contexts, we find that state changes are associated with physical events, enabling them to be endorsed based on properties of those physical events.

### 8 THREATS TO VALIDITY

With HomeEndorser, we seek to lay the groundwork for secure and practical endorsement for abstract home objects in the smart home, through our systematic and data-driven approach. However, there are certain threats to the validity of our evaluation and results, as we discuss below:

1. **Byzantine Fault Tolerance:** We rely on devices to not be compromised and to report correct states, as stated in Section 3.2 (although HomeEndorser does dynamically adapt to devices that may be offline/non-responsive). That said, while HomeEndorser does not account for Byzantine fault tolerance, it is complementary to prior efforts [4] that aim to validate device states via fingerprinting, and combining the two approaches is a promising future direction.

2. **Completeness and Rigor of Policy Specification:** The device-attribute map used for identifying endorsement attributes was automatically constructed from platform-provided resources (Section 4.3). This map, consisting of 510 device-attribute-pairs, is an evolving dataset that is as complete as the information sources used to derive it (e.g., device handlers, capability maps), and new device attributes/types that emerge may be integrated into it with minimal effort. Furthermore, we used a systematic, 2-author, open coding approach to identify the endorsement attributes from this map that would enable endorsement of each of the 6 AHOs (Section 5). This approach resulted in negligible disagreements (i.e., only 2.4%), illustrating high confidence in the identified inferences (our online Appendix 2 provides the complete dataset). We note that our expert-defined policies are only meant to be a seed-list, which can be expanded upon with community support.

3. **Multi-user smart homes:** Similar to most prior work in the area of smart home API misuse [29, 35, 48, 67], HomeEndorser does not claim to address multi-user scenarios, which are a novel but orthogonal design challenge. Further, we note that certain AHOs (e.g., fire) may be independent of the number of users, and moreover, HomeEndorser’s location-specific policy-predicates (Section 4.1) may also mitigate the implications of multiple simultaneous device-interactions, although we do not make formal claims.

4. **Device Availability and Placement:** HomeEndorser’s policies (i.e., at least the seed list specified in this paper) consist of a diverse range of devices. Hence, the user does not need to have all the devices, as HomeEndorser can automatically choose the most restrictive policy that is applicable to a user’s home based on device-availability and placement information obtained from the platform (Section 4.2). However, as stated in Section 4.3, we assume optimal device placement and sensor configuration to be out of scope, and direct the reader to complementary related work that informs users on optimal deployment [30].

### 9 CONCLUSION

In this paper, we presented the HomeEndorser framework, which validates proposed changes in high-integrity abstract home objects (AHOs) in correlation with device states. HomeEndorser aims to
address the threat posed by compromised/malicious services that may use their authorized API access to change AHOs in a way that causes high-integrity devices to behave unsafely. To do this, HomeEndorser leverages the insight that the changes in AHOs are inherently tied to a home’s physical environment, enabling each sensitive change to be validated, or endorsed, by correlating to changes in physical device states. HomeEndorser provides a policy model for specifying endorsement policies in terms of device state changes, and a platform reference monitor for endorsing all API requests to change AHOs. We evaluate HomeEndorser on the HomeAssistant smart home platform, finding that we can feasibly derive policy rules for HomeEndorser to endorse changes to 6 key AHOs, preventing malicious and accidents with feasible performance overhead. Finally, we demonstrate that HomeEndorser is backwards compatible with most popular smart home platforms, and requires modest human effort to configure and deploy.

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Figure 6: Specification of device-attributes in the SmartThings device handler preamble.

Table 5: Real and Virtual Devices in Evaluation

| Device                                      | real/virtual | Number |
|---------------------------------------------|--------------|--------|
| August Door Lock                           | real         | 1      |
| Blink Camera                               | real         | 1      |
| Philips Hue Motion+Illuminance+Temp. Sensor | real         | 1      |
| Aotec Door Sensor                          | real         | 1      |
| Security Panel                             | virtual      | 1      |
| Presence Sensor                            | virtual      | 1      |
| Beacon Sensor                              | virtual      | 1      |
| Thermostat                                 | virtual      | 1      |
| Wemo Switch                                | real         | 1      |
| Philips Hue Lamp                           | real         | 1      |
| Google Home                                 | real         | 1      |

A DEVICE LIST FOR EVALUATION

Table 5 shows the real as well as the virtual devices we integrated into HomeAssistant to conduct the experiments.

B SCENARIOS

Table 6 shows the remaining realistic scenarios (from Section 6.4).

C BACKWARDS COMPATIBILITY

One of our key objectives is to build a practical framework that does not crash or in any other way impede legitimate functionality. Therefore, we evaluate the backwards compatibility of HomeEndorser with automation developed by real users or app developers (i.e., IoT apps or user-driven routines).

Methodology: We randomly selected 20 automations from the SmartThings repository [52]. We then leveraged our existing deployment of HomeEndorser and set up 10 of these automations in HomeAssistant that were applicable to the devices in our deployment, filtering out the remaining 10 for which we did not have devices. We then triggered the automations throughout the day, in a random order and at random times, while constantly monitoring for system crashes, dropped or delayed device actions, or any other unusual device, automation, or platform failures. Note that since this is an automated experiment, certain automated triggers may be denied due to endorsement checks; we consider these denials as legitimate, and not failure cases.

Results: We did not observe any crashes or device failures. Note that the selection of routines included one involving home shared state changing from away to home that was denied throughout the day, i.e., when user is home, disarm the security panel. On the other hand, routines that were changing states not endorsed by HomeEndorser were allowed throughout the day.
### Table 6: Realistic Scenarios used in evaluation of HomeEndorser

| Scenario | User Behavior | State change request | Policy involved | HomeEndorser behavior |
|----------|---------------|----------------------|----------------|-----------------------|
| 56: Entering the house without closing the door | Alice comes home and opens the front door after unlocking the front door lock manually. She leaves the door open, and comes in by triggering the motion sensor in the hallway. | An app requests a state change from away to home using REST API. | $P_{home2} = (door-lock \_lock == UNLOCKED \land motion\_sensor == ACTIVE \land door\_sensor == ACTIVE)_{front-door}$ | HomeEndorser gathers the recent states of the devices. Since the door-lock was manually unlocked and the sensors were active recently, the policy is satisfied and the state change is endorsed. |
| 57: Unlocking the home and leaving | Alice comes home and opens the front door after unlocking the front door lock manually. She steps outside immediately after entering and closes the door behind her, thereby triggering the door sensor again. | An app requests a state change from away to home using REST API. | $P_{home2}$ | HomeEndorser gathers the recent states of the devices. The door lock was manually unlocked and the door sensor was triggered both when opening and closing the door. However, the motion sensor was not active recently so the policy is not satisfied and the state change is denied. |
| 58: Diverse device setup1 | Alice comes home and opens the front door after unlocking the front door lock manually. She comes in by triggering the motion sensor and the beacon sensor in the hallway. | An app requests a state change from away to home using REST API. | $P_{home3} = (door-lock \_lock == UNLOCKED \land motion\_sensor == ACTIVE \land door\_sensor == ACTIVE \land beacon\_sensor == ACTIVE)_{front-door}$ | HomeEndorser gathers the recent states of the devices. Since the door-lock was manually unlocked and the sensors were active recently, the policy is satisfied and the state change is endorsed. |
| 59: Diverse device setup2 | Alice comes home and inputs the keycode in the security panel near the door, disarming the home. She then enters the home triggering the motion sensor in the hallway. | An app requests a state change from away to home using REST API. | $P_{home4} = (security-panel == DISARMED \land motion\_sensor == ACTIVE \land presence\_sensor == ACTIVE)_{front-door}$ | HomeEndorser gathers the recent states of the devices. Since the security panel was manually disarmed and the motion sensor was active recently as well, the policy is satisfied and the state change is endorsed. |
| 510: Home with just 2 devices | Alice comes home and unlocks the front door lock manually. She comes in by triggering the motion sensor in the hallway. | An app requests a state change from away to home using REST API. | $P_{home5} = (door-lock \_lock == UNLOCKED \land motion\_sensor == ACTIVE)$ | HomeEndorser gathers the recent states of the devices. Since the door lock was manually unlocked and the motion sensor was active recently, the policy is satisfied and the state change is endorsed. |