Walnut: A low-trust trigger-action platform

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Abstract

Trigger-action platforms are a new type of system that connect IoT devices with web services. For example, the popular IFTTT platform can connect Fitbit with Google Calendar to add a bedtime reminder based on sleep history. However, these platforms present confidentiality and integrity risks as they run on public cloud infrastructure and compute over sensitive user data. This paper describes the design, implementation, and evaluation of Walnut, a low-trust trigger-action platform that mimics the functionality of IFTTT, while ensuring confidentiality of data and correctness of computation, at a low resource cost. The key enabler for Walnut is a new two-party secure computation protocol that (i) efficiently performs strings substitutions, which is a common computation in trigger-action platform workloads, and (ii) replicates computation over heterogeneous trusted-hardware machines from different vendors to ensure correctness of computation output as long as one of the machines is not compromised. An evaluation of Walnut demonstrates its plausible deployability and low overhead relative to a non-secure baseline—3.6× in CPU and 4.3× in network for all but a small percentage of programs.

1 Introduction

The platforms that manage heterogeneous Internet of Things (IoT) devices have become mainstream [23, 43, 44, 56, 60, 69]. However, these platforms undermine user confidentiality and integrity as they compute over sensitive user data. Therefore, a relevant question is: how can we build a system that can manage IoT devices without incurring the security risks?

To expand on the motivation above, consider the case of trigger-action platforms [43, 44, 47, 60]. They connect IoT devices with web services through simple customizable programs. For example, a user can set up programs to sync Fitbit with iOS Health [35], adjust home temperature when they request an Uber to take them home [73], tweet Instagram photos [46], turn off oven if the smoke alarm detects an emergency [31], and even move money from checking to savings depending on daily step count [45].

Besides providing connectivity across devices and online services, trigger-action platforms are easy to use. They run in the cloud and require no local, in-home installation or maintenance. Furthermore, they allow a user to go offline indefinitely after setting up a program. Finally, their interfaces are so simple that an average internet user can specify programs for them with only a few clicks. Indeed, popular trigger-action platforms like IFTTT [43] run tens of millions of programs daily on behalf of their users [58, 59].

However, this connectivity and convenience comes at a cost (§2). When users opt to run programs on these platforms, they must provide unobstructed access to sensitive data needed by the programs (and generated or consumed by the devices or services). Furthermore, the users assume that the platforms correctly perform actions on their behalf: adjust thermostat to the right temperature, post the intended tweet, do not tamper with health data, and remove the right amount of money from the checking account.

The security risks affect not just the users: when platform providers operate on user data, they become liable for protecting it. Indeed, under new privacy regulations in California and EU [1, 2], a business can be subject to a class action lawsuit or large fine (for example, up to 4 percent of global annual revenue) for data breaches and misuse.

Given the popularity of trigger-action platforms, there is prior work targeting improved security for them [25, 26, 78]. However, as we discuss later (§9), these works provide confidentiality or integrity exclusively, and suffer from a fundamental weakness that shifts security risks from the platform to the connected services.

In this paper, we address these limitations and demonstrate that we do not need to compromise significantly on security to support the automation provided by trigger-action platforms. We present Walnut, a trigger-action platform that provides the same functionality as IFTTT, but with much stronger confidentiality and integrity protection. Furthermore, this added protection does not affect the security at the connected services, and comes at a modest resource cost.

To begin with, Walnut splits the platform into two parts that run in separate administrative domains (Microsoft Azure and IBM Cloud) such that no part can access sensitive data (§3.1). To obtain such a split, Walnut employs a two-party secure computation protocol (2PC) called Yao’s garbled circuits [80, 81], which allows two parties to perform arbitrary computation on their secret inputs without revealing their inputs to each other. Yao’s protocol is powerful as it supports arbitrary computation but it is also expensive in terms of CPU time and network transfers.

Walnut makes two observations. First, typical programs on trigger-action platforms perform simple computations: they either pass a sensitive string from one device or service to another without modification, or substitute strings from a dictionary of sensitive strings into a user-supplied template string. Second, the names of the keys in the dictionary are publicly known. Based on these observations, Walnut designs

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a custom two-party secure computation protocol for the typical trigger-action platform programs. Walnut’s protocol leaks coarse-grained information such as the approximate positions in the template string where the strings from the dictionary get substituted. However, it significantly reduces overhead relative to Yao’s protocol; in particular, it eliminates network overhead between the two parties in the protocol (§4).

The 2PC protocol described so far allows Walnut’s platform to compute over sensitive data but does not prevent the platform from deviating from the protocol and producing arbitrary program output. To efficiently add integrity guarantees, Walnut extends the protocol to use trusted-hardware machines such as those with Intel SGX [20] and AMD SEV [50] capabilities. These machines provide a trusted execution environment (TEE) that can load and execute a computation such that an external entity cannot tamper with its execution. However, a limitation of using TEEs is that they introduce a large trusted computing base (TCB), consisting of both a software component and a hardware component.

The software part can be moved out of the TCB by formally verifying that the software meets its required specification [10, 14, 27, 28, 39]. However, the hardware itself (the root of trust) can be tampered, for example, through physical attacks [20, 32, 33, 52].

Walnut addresses this limitation by employing multiple, heterogeneous TEEs from different vendors. In particular, it runs a copy of the 2PC protocol described above over three pairs of TEEs, where each counterpart in a pair resides in one of the two domains (for example, Microsoft Azure or IBM Cloud). Walnut’s protocol does not guarantee an output; however, if it does produce an output, then the output is correct as long as one of the TEEs is not compromised (§5). Recently, Chandran et al. [13] explored this idea of multiple TEEs to obtain theoretical feasibility results in cryptography; however, this idea has not been explored in practical systems.

Besides using the two techniques above, Walnut’s 2PC protocol composes cryptographic primitives such as end-to-end encryption, digital signatures, and hash-chaining of OAuth authentication tokens. The latter, in particular, allows a user of Walnut to go offline indefinitely after uploading a program to run on the Walnut platform (§6).

We have implemented (§7) and evaluated (§8) a prototype of Walnut. Our prototype runs on Microsoft Azure and IBM Cloud. For sparsely-used programs for which Walnut resorts to using Yao’s protocol, it incurs a high CPU and network overhead: 54× for CPU and 1883× for the network relative to a non-secure baseline that mimics IFTTT. However, for typical programs that run on IFTTT (a manual inspection of 50 most popular programs per the dataset of Mi et al. [59] reveals that 98% of them fall in this category), Walnut incurs 3.6× CPU and 4.3× network overhead relative to the non-secure baseline. We also implemented 30 programs from IFTTT (15 from the set of 50 most popular ones per Mi et al. [59], and 15 selected randomly) on Walnut, demonstrating that Walnut is plausibly deployable.

Walnut’s limitations include coarse-grained leakage from its customized 2PC protocol. Nevertheless, we believe Walnut is useful: it provides a benefit to both users and platform providers, as they can enjoy trigger-action automation with significant improvement in data confidentiality and integrity, at low resource cost.

2 Overview of IFTTT (IF-This-Then-That)

Walnut aims to mimic IFTTT’s functionality as IFTTT is a popular trigger-action platform [8, 26, 59, 72, 74]. This section gives an overview of IFTTT and describes the confidentiality and integrity risks it presents.

Figure 1 depicts IFTTT’s architecture, which consists of three key components: services, platform, and applets.

Services are either IoT device management services such as the Fitbit service or online-only web-services such as Google calendar. These services expose user information and provide an ability to update that information through HTTP-based RESTful APIs. For example, the Fitbit service exposes an API that returns the sleep duration of a user. Similarly, the Google calendar service exposes an API to add a reminder to a user’s calendar.

The IFTTT platform runs in the public cloud (AWS currently). It aggregates APIs from all services and presents them to applets. It is also responsible for executing these applets. Applets are programs that stitch together two service APIs. They are the core abstraction that IFTTT exposes. For example, the “When you sleep less than the desired amount, add a reminder on your calendar to go to bed early tomorrow” applet connects the sleep duration API from Fitbit with the add reminder API from Google calendar. An applet contains a TypeScript code that takes the output of the first API and manipulates it before feeding into the second API. For instance, the applet depicted in Figure 1 takes the user’s sleep...
duration string “6 hrs” returned by the Fitbit API and adds it to the title of the reminder. An applet also contains OAuth authentication tokens \([38]\) that allow the platform to access the APIs on user behalf.

**Confidentiality and integrity risks.** IFTTT acts as a delega-
tee and runs applets on user behalf; this arrangement naturally
creates both confidentiality and integrity risks. In particular,
when a user creates an applet and loads it to the IFTTT plat-
form, or when the IFTTT platform executes the applet, the
platform learns sensitive information such as the APIs the
user intends to use, the parameters the user wants to send to
the APIs, and the information returned by the APIs. Similarly,
the IFTTT platform creates integrity risks because it may not
run an applet as intended. For instance, it may set an incorrect
time for reminder in the Fitbit and Google calendar example
discussed above. In other examples, it may cause more dam-
age: turn oven on instead of off, move an incorrect amount
of money from a user’s checking to savings account, drop malware into user’s Dropbox account, etc.

The confidentiality and integrity risks described above are
significant; however, the current design of the IFTTT platform
and the connected services exacerbates them. The connected
services give out OAuth access tokens with broad scope, so
that a user can authenticate with a service once and use the
token across applets that call different APIs at the service \([24–
26]\). Thus, if the platform misbehaves, it can create malicious
applets using the (broad) OAuth tokens.

Thus, our goal is to design mechanisms that address these
risks, that is, enable the IFTTT platform provider to keep user
data confidential while operating on it as intended by the user,
at low resource costs (CPU, network, etc.). We are not saying
that the IFTTT platform provider is inherently untrustworthy.
However, the platform provider runs the platform on a public
cloud. Besides, there are many cases of both internal and
external adversaries, such as rogue system administrators and
hackers, that can get into cloud infrastructure and steal and
tamper with user information \([7, 19, 30, 75, 83]\). On top of
that, the platform provider is incentivized to reduce risk for
user data due to the risk of significant fines and lawsuits under
modern privacy regulation \([1, 2]\).

3 Overview of Walnut

3.1 Architecture

Figure 2 shows Walnut’s architecture. Walnut has the same
key components as IFTTT, namely the platform, services, and
applets, but makes modifications, particularly, to the platform
and the services.

Walnut’s platform runs over two servers, \(S_0\) and \(S_1\), in sep-
arate administrative domains such as Microsoft Azure and
IBM Cloud. Each server is logically centralized but physically
distributed; it contains trusted-hardware machines from dif-
fferent vendors (denoted as “TEE-A”, “TEE-B”, and “TEE-C”
in Figure 2) and general-purpose compute machines (labeled
collectively as \(M_0\) and \(M_1\) in Figure 2).

The services implement the HTTP APIs. Today, they send
or receive plaintext data (over secure channels) to or from
the platform. Therefore, some change is necessary to sup-
port a secure Walnut platform. Walnut expects these services
to implement logic for basic cryptographic primitives such
as encryption, signatures, and secret-sharing (described be-
low), and to be aware of and hold public keys for Walnut’s
two servers and their TEEs. This logic is agnostic of the
API implementation, and thus can be implemented once and
distributed to all the services (for example, by the Walnut
platform provider).

In Walnut, as in IFTTT, the applet is the core programming
abstraction. Walnut does not make any change to this core
abstraction. Each applet consists of URLs for two APIs: a
trigger API and an action API. We denote the inputs to
the APIs as \(trigInp\) and \(actInp\), respectively, and the output from
the trigger API as \(trigOut\) (the action API does not produce
an output). Each of \(trigInp\), \(trigOut\), and \(actInp\) is a set of key-
value pairs. \(filterCode\) is the code component of the applet
that produces \(actInp\) based on \(trigOut\).

Walnut’s protocol to delegate execution of an applet to Wal-
nut’s platform has four phases: setup, trigger-polling, action-
generation, and action-execution.

- **Setup.** This phase (marked 1 in Figure 2) runs once per
applet. During this phase, the user creates the applet \(App\)
and gives its parts to the two servers: part \(App_0\) to \(S_0\) and
part \(App_1\) to \(S_1\). Each part contains signed ciphertexts or
secret-shares of the sensitive applet data. Secret-sharing
refers to the technique of splitting a secret \(s\) into two strings,
\(sh_0^{(s)}\) and \(sh_1^{(s)}\), such that each string appears uniformly
random, but \(sh_0^{(s)} + sh_1^{(s)} = e\).

- **Trigger-polling.** As in IFTTT, this phase (marked 1 in
Figure 2) runs periodically (every 15 minutes) or in re-
response to a real-time notification from the service imple-
menting the trigger API. In this phase, server \(S_0\) calls the
trigger API in the applet. In return, server \(S_0\) for each
\(b \in \{0, 1\}\) gets a signed secret-share of \(trigOut\).

- **Action-generation.** This phase (marked 2 in Figure 2)
follows the trigger-polling phase. In this phase, each Walnut server uses its outputs from the two phases above, and runs a cryptographic protocol with the other server to obtain its secret-share of the input to the action API. That is, $S_b$ obtains $sh_b^{\text{actInp}}$. Server $S_b$ also generates a proof that it computed $sh_b^{\text{actInp}}$ correctly. This phase uses the TEE machines at the two servers.

- **Action-execution.** Finally, in the action-execution phase (marked $\circ$ in Figure 2), the two servers send their output from the action-generation phase to the service implementing the action API, who performs checks on the proofs, merges the shares of the API input, and executes the API.

3.2 Threat model and security definitions

We consider two settings for Walnut, passive and active, depending on the power of the adversary. In the passive setting, the adversary is honest-but-curious, meaning that it follows the protocol description but tries to infer sensitive user data by inspecting protocol messages. In this setting, Walnut uses only the general-purpose machines at $S_b$, which are collectively denoted as $M_b$ for $b \in \{0, 1\}$. The adversary can compromise one of $M_b$ for some $b \in \{0, 1\}$.

In the active setting, the adversary is malicious and can arbitrarily deviate from the protocol. In this setting, each server $S_b$ uses three types of TEEs (made by three different vendors) besides the general-purpose machines; we denote $S_b$’s three types of TEEs by $T_b^{(i)}$ for $i \in \{0, 1, 2\}$. The adversary can compromise one of $M_b$ for $b \in \{0, 1\}$, and at most two of $T_b^{(0)}, T_b^{(1)}$ and $T_b^{(2)}$.

We define security notions for the two settings separately.

**Definition 3.1 (Passive security).** A passive Walnut scheme consisting of setup, trigger-polling, action-generation, and action-execution phases is said to be $L$-secure if for any honest-but-curious (passive) probabilistic polynomial time (PPT) adversary $A$ corrupting $M_b$ for some $b \in \{0, 1\}$, for a leakage function $L$, for every large enough security parameter $\lambda$, there exists a PPT simulator $\hat{S}_b^{\text{actInp}}$ with access to the leakage function, such that the output distribution of the simulator is computationally indistinguishable from the adversary’s view in the real protocol.

**Definition 3.2 (Active security).** An active Walnut scheme consisting of setup, trigger-polling, action-generation, and action-execution phases is said to be $L$-secure with abort if, for any malicious (active) probabilistic polynomial time (PPT) adversary $A$ corrupting $M_b$, $T_b^{(i)}$, $\chi_b$ for some $b \in \{0, 1\}$ and $i, j \in \{0, 1, 2\}$, with black-box access to TEE $T_b^{(k)}$ implementing functionality $F_b^{(k)}$, for $k \in \{0, 1, 2\}$ and $k \neq i, k \neq j$, for a leakage function $L$, for every large enough security parameter $\lambda$, there exists a PPT simulator $\hat{S}_b^{\text{actInp}}$ with access to the leakage function, such that the output distribution of the simulator is computationally indistinguishable from the adversary’s view in the real protocol.

Essentially, the definitions say that the view of the adversary in an execution of Walnut’s protocol can be simulated by knowing just the inputs to the simulator, which is defined by the leakage function. Furthermore, the protocol aborts if the adversary in the active setting deviates from the protocol.

For Walnut, the leakage function is defined as $L(App)$, which equals $\{K(App), P(App), F(App)\}$. $K(App)$ equals $\{K_1, K_2, \ldots, K_m\}$, where $m$ is the number of key-value pairs in the actInp parameter to action API, and $K_i = \{key_1, key_2, \ldots, key_k\}$ contains the key names of key-value pairs in trigOut that go into computing the $i$-th key-value pair of actInp. $P(App)$ equals $\{pos_1, pos_2, \ldots, pos_m\}$, where $pos_i = \{index_1, index_2, \ldots, index_k\}$ is the set of positions in the $i$-th key-value pair in actInp where the key-value pairs in trigOut get inserted. $F(App)$ is the filterCode for the applet and the URLs of trigger and action APIs.

3.3 Key techniques

Walnut’s protocol consisting of the four phases (setup, trigger-polling, action-generation, action-execution) and meeting the security definitions stated above uses three key techniques.

**Tailored 2PC for IFTTT-like applets.** Walnut’s protocol, in the action-generation phase, uses a tailored two-party secure computation (2PC) cryptographic sub-protocol to enable its servers to obtain secret-shares of actInp. Walnut’s 2PC protocol is tailored to the common filterCode that generates actInp fields via string substitutions, for instance, by substituting the value of duration in the template string “Slept $\{${duration}$\}$.” Sleep early.” Although Walnut’s protocol leaks a small amount of information, captured in the leakage function above, it is significantly more efficient than a general-purpose 2PC protocol [80] (§4).

**Proof replication across heterogeneous TEEs.** Walnut, during the action-generation phase, uses trusted hardware machines to generate hardware attestations (which we call proofs for simplicity) that the code to generate action API input is executed inside a trusted execution environment (TEE). However, relative to a solution that would use a single TEE for proof generation, Walnut replicates proof generation over heterogeneous TEEs such that as long as one TEE works correctly, an adversary cannot pass a proof check and result in an incorrect invocation of the action API (§5).

**Chaining of OAuth tokens.** Walnut, as in IFTTT, ensures that a user can go offline after executing the setup phase. To enable this behavior, Walnut creates signed tuples of the expirable OAuth token supplied by the user during the setup phase and fresh OAuth tokens generated by the services (§6).

Besides these three techniques, Walnut uses standard cryptographic primitives such as encryption, hashing, and signatures. The next three sections (§4–§6) dive into the details of Walnut’s protocol. We begin by making a simplifying assumption that the OAuth tokens do not expire. Under this assumption, we first present Walnut’s design that meets the security definition for the passive setting described above.
Walnut’s protocol for the passive security setting

• This protocol has four parties: a user, Walnut’s platform consisting of machines $M_0$ and $M_1$ in separate administrative domains, a trigger service $TS$, and an action service $AS$. The protocol allows the user to install an applet and the platform to execute it.
• The protocol assumes that each entity has a (public, private) key pair $(pk_p, sk_p)$, for $p \in \{User, M_0, M_1, TS, AS\}$.

Setup phase

1. (Encrypt OAuth tokens) The user receives OAuth access tokens $at-TS$ and $at-AS$ from $TS$ and $AS$, respectively. The user encrypts these tokens, that is, computes $C_{at-TS} \leftarrow \text{Enc}(pk_{TS}, at-TS)$ and $C_{at-AS} \leftarrow \text{Enc}(pk_{AS}, at-AS)$.
2. (Encrypt trigInp) The user encrypts the trigInp input parameter, that is, computes $C_{\text{trigInp}} \leftarrow \text{Enc}(pk_{TS}, \text{trigInp})$.
3. (Secret-share actInp) For each key-value pair $(k, v)$ in install-time value of actInp, the user does the following:
   - Splits $v$ into blocks $(t_1, \ldots, t_i)$ at spaces and punctuation marks. For instance, splits “Slept {\{duration\}}”. Sleep early” into (“Slept”, “ ””, “{\{duration\}}”, “ ””, “Sleep”, “ ””, “early”).
   - For each $t_i$, if $t_i$ is like “{\{key-name\}}”, sets $sh_{(b)}^{(v)} = t_i$. Else, secret-shares $t_i$ into $sh_{0}^{(v)}$ and $sh_{1}^{(v)}$, s.t. $sh_{0}^{(v)} \oplus sh_{1}^{(v)} = t_i$.
   - Sets $sh_{\text{actInp}}^{(v)}[k] = (sh_{0}^{(t_i)}, \ldots, sh_{1}^{(t_i)})$.
4. The user sends $App_b = \{T, A_b, fc\}$ to $M_b$, where $T$ equals $(\text{triggerEndpoint}, C_{\text{at-TS}}, C_{\text{trigInp}})$, $A_b$ equals $(\text{actionEndpoint}, C_{\text{at-AS}}, sh_{\text{actInp}})$, and $fc$ is the applet filterCode.

Trigger-polling phase

5. (Call trigger API) Machine $M_0$ sends $T$ to the trigger service $TS$ (whose name is in triggerEndpoint URL in $T$).
6. (Generates shares of trigOut) $TS$ decrypts and checks the OAuth token, executes the trigger API, and generates trigOut. Then, for each $(k, v)$ in trigOut, $TS$ generates $sh_{\text{trigOut}}^{(v)}[k]$ following step 3 above.
7. $TS$ sends $sh_{\text{trigOut}}^{(v)}$ to $M_b$.

Action-generation phase

8. (Generates shares of runtime value of actInp) $M_b$ generates $sh_{\text{actInp}}^{(v)} \leftarrow \text{GenerateAI}(sh_{\text{trigOut}}^{(v)}, sh_{\text{actInp}}^{(v)}, fc)$. GenerateAI further calls either Yao’s 2PC protocol or Walnut’s string substitution function (Figure 4) depending on filterCode.

Action-execution phase

9. $M_b$ sends $(\text{actionEndpoint}, C_{\text{at-AS}}, sh_{\text{actInp}})$ to $AS$, who reconstructs actInp, validates $at-AS$, and executes the action API.

This protocol further calls Yao’s protocol [80] or the function in Figure 4.

4 Design for passive security

Figure 3 shows Walnut’s protocol for the passive security setting discussed in the previous section (§3.2). This protocol is optimized, in terms of performance, for the common types of applets on IFTTT that perform simple substitutions: set the value of a key-value pair in actInp by replacing parts of a template string with values from trigOut. We briefly describe each phase of the protocol below; the protocol figure contains precise details.

Setup phase. First, the user obtains OAuth tokens for the two services and encrypts them with their public keys (step 1 in Figure 3). Second, the user encrypts trigInp as a single blob with the trigger service’s public key (step 2 in Figure 3). Third, the user splits the setup-time values in actInp into blocks and secret-shares each block (step 3b in Figure 3).

Trigger-polling. In this phase, $M_0$ sends encrypted blob of trigInp to the trigger service implementing the trigger API. The trigger service generates secret-shares of trigOut in the same way as the user generates shares of actInp in the setup step (step 6 in Figure 3). For instance, if one of the trigOut key-value pairs is ‘duration’: ‘6 hrs’, then the trigger service partitions the value ‘6 hrs’ into blocks (“6”, “”, “hrs”) and secret-shares them.

Action-generation. $M_0$ and $M_1$ call Yao’s garbled circuits protocol to run the applets’ filterCode over shares of blocks from trigOut and (setup-time value of) actInp; the call to Yao happens inside the GenerateAI function in step 8 in Figure 3. Yao’s protocol is general-purpose and can handle any arbitrary filterCode. However, when the filterCode involves simple string substitutions, $M_0$ and $M_1$ locally run the function $\text{string_sub}$ shown in Figure 4. The $\text{string_sub}$ procedure returns a single block for each key-value pair of actInp.

Action-execution. $M_0$ and $M_1$ send their outputs from action-generation phase along with OAuth tokens to the action ser-
# 'actInp_shr' is a list of block shares from user.
# shr(pad(str)) denotes a share of a padded block.
actInp_shr = [{"type": TEXT, "value": shr(pad("Sleep")) + pad(" ")},
               {"type": TEXT, "value": shr(pad("early")) + pad(" ")},
               {"type": FIELD, "key-name": "duration"},
               {"type": TEXT, "value": shr(pad(".") + pad(" ")
               + pad("Sleep") + pad(" ") + pad("early"))}]

# Input 'trigOut_shr' from the trigger service.
# Func. maps trigOut key-names to shares of actInp.

def string_sub(trigOut_shr, actInp_shr):
    output = []
    for part in actInp_shr:
        if part.type == FIELD:
            # lookup key-name
            output += trigOut_shr[part.key-name]
        else:
            output += part.value
    return "

Figure 4: Walnut’s custom function for string substitution. This function assumes that secret-shares of block of strings are both padded and concatenated (explained further in text).

Concentration and padding. One issue with the protocol described above is that it reveals to Walnut the length of each block in the strings in trigOut and actInp. Walnut mitigates this leak by concatenation and padding. First, both the user and the trigger service apply padding to each block separately. This padding is configurable: each block can be padded to a pre-determined maximum size, or each block can be padded to the next higher size from a set of allowed predetermined sizes (for example, multiples of five, or powers of two). Second, the user and the trigger service concatenate padded adjacent blocks that do not contain key names. For instance, ("Sleep", ",", "duration"), ("","","Sleep", "", "early") becomes three blocks ("SleepXXXX", ("duration")), ".XXXX XXXXSleep XXXXearly"), and ("6", ",", "hrs") becomes a single block ("6XXXX XXXXhrsXX"), where "X" denotes padding.

Security analysis. The protocol described above meets the passive security definition in §3.2. Appendix C.2 contains a proof. But, at a high-level, the protocol encrypts OAuth tokens and trigInp with the trigger service’s public key so that they remain hidden from both Walnut servers. The protocol also only reveals, to each Walnut server, secret-shares of large blocks that are formed by padding and concatenating smaller blocks; this leakage is captured in the definition in §3.2.

Notably, unlike prior work [25][26], Walnut’s protocol ensures that the trigger and action service learn strictly the same information as they do in IFTTT. In particular, the trigger service handles request to the trigger API; it learns neither about the action API nor how trigOut is used to invoke the action API. Similarly, the action service learns only the actInp parameter needed to execute the action API. Specifically, padding both trigOut and actInp in the same way ensures that the action service cannot outrightly distinguish parts of a string that come from trigOut versus setup-time value of actInp (just how it is in IFTTT). Thus, Walnut does not increase data liability at the services—in line with the data minimization or least privilege principle [1][2][22][68].

Performance analysis. The setup phase runs once and thus its cost gets amortized across multiple executions of an applet. Here, we focus on the costs of the other phases.

In the trigger-polling phase, the use of encryption and secret-sharing adds CPU and network overhead at the platform and the services. However, this overhead is small, as encryption and secret-sharing are cheap operations which take less than a millisecond (§6).

In the action-generation phase, if the protocol invokes Yao’s protocol, then the CPU and network overhead for Walnut’s two servers increases significantly, as Yao represents the filterCode as a low-level, verbose Boolean circuit (a network of Boolean gates such as AND and XOR), and incurs cryptographic operations for each gate in the circuit [55][71][82]. However, majority of the time, Walnut calls the string_sub protocol, which performs cheap local computation. Indeed, in the top-50 popular applets in the dataset of Mi et al. [59], only one uses custom filterCode while the others use string substitution. Similarly, in the 15 randomly selected applets we implement (§8.4), none require custom filterCode.

The action-execution phase is also efficient like the trigger-polling phase as it uses the cheap decryption and secret-sharing operations.

5 Design for active security

Walnut’s protocol in the previous section assumes a passive (honest-but-curious) adversary who can monitor protocol messages but not tamper with protocol execution. In particular, the protocol in Figure 3 assumes:

(i) machine $M_0$ does not corrupt the trigger part of the applet $T$ before sending it to trigger service (step 5 in Figure 3),

(ii) $M_0$ and $M_1$ do not tamper with trigOut or the applet parts that feed into action-generation (step 8 in Figure 3),

(iii) $M_0$ and $M_1$ run GenerateAI correctly,

(iv) $M_0$ and $M_1$ do not tamper with the message sent to the action service (step 10 in Figure 3), and

(v) machines $M_0$ and $M_1$ do not replay requests to action service (requests to a trigger service are idempotent).

One way to relax these assumptions is to extend the protocol with zero-knowledge proofs [64][70][76] that allow proving the correctness of code execution without revealing the sensitive data that the code is operating on. However, these protocols are expensive. Instead, Walnut uses digital signatures and trusted execution environments (TEEs)—recall, in the active setting, each Walnut server has three TEE machines (§3.1). At a high-level, signatures enable services to verify that the information they are receiving has not
Walnut’s protocol for the active security setting

• This protocol assumes each Walnut server \( S_b \) has a general-purpose machine \( M_b \) and three TEEs \( T_b^{(0)}, T_b^{(1)}, \) and \( T_b^{(2)} \).
• The protocol assumes that each entity has a key-pair that it uses to sign messages and allow others to verify signed messages.

**Setup phase**

1. The user runs steps [1 to 3] in Figure [3] to create \( \text{App}_b = \{ T, A_b, fc \} \), for all \( b \in \{0, 1\} \).
2. (Sign request to trigger API) The user appends a unique identifier \( TID \) to \( T \), and asks \( TS \) to sign \( T \). The user obtains \( \sigma_T \leftarrow \text{Sign}(sk_{TS}, T) \).
3. The user adds \( \sigma_T \) and public key of trigger service \( pk_{TS} \) to \( \text{App}_b \), and sends \( \text{App}_b \) to each of \( M_b, T_b^{(0)}, T_b^{(1)}, \) and \( T_b^{(2)} \).

**Trigger-polling phase**

4. (Call trigger API) \( M_0 \) sends \( \langle \text{App}_b, T, \sigma_T \rangle \) to trigger service \( TS \).
5. (Generate signed shares of trigOut) \( TS \) verifies \( \sigma_T \) and runs step 6 in Figure 3 to get \( sh_b^{(\text{trigOut})} \). \( TS \) then samples a unique identifier \( RID \) for response, constructs \( tout_b \leftarrow \langle \text{RID}, TID, sh_b^{(\text{trigOut})} \rangle \), and computes \( \sigma_{tout_b} \leftarrow \text{Sign}(sk_{TS}, tout_b) \) \( \forall b \in \{0, 1\} \).
6. \( TS \) sends \( \langle tout_b, \sigma_{tout_b} \rangle \) to \( M_b \).

**Action-generation phase**

7. (Generate signed actInp shares) \( M_b \) sends \( \langle tout_b, \sigma_{tout_b} \rangle \) to each TEE \( T_b^{(i)} \), who does the following:
   (a) Checks \( tout_b \) is from the correct \( TS \) and for the correct trigger API:
      i. Asserts \( \text{Verify}(\text{App}_b, pk_{TS_1}, tout_b, \sigma_{tout_b}) \) is True.
      ii. Asserts \( TID \) in \( tout_b \) equals \( \text{App}_b.T.TID \).
   (b) (Generate actionFields shares) Runs step 8 in Figure 3 with \( T_b^{(i)} \) to generate \( sh_b^{(\text{actInp})} \).
   (c) (Sign request to action service) Constructs \( \text{ain}^{(i)}_b \leftarrow \langle tout_b, \text{RID}, \text{actionEndpoint}, C_{\text{as}^\text{AS}}, sh_b^{(\text{actInp})} \rangle \), where \( \text{actionEndpoint} \) and \( C_{\text{as}^\text{AS}} \) are part of \( A_b \) in \( \text{App}_b \). Then, \( T_b^{(i)} \) computes \( \text{proof}-T_b^{(i)} \leftarrow \text{Sign}(sk_{T_b^{(i)}}, \text{ain}^{(i)}_b) \), gives \( \text{proof}-T_b^{(i)}, \text{ain}^{(i)}_b \) to \( M_b \).

**Action-execution phase**

8. (Send request) \( M_b \) sends \( \text{ain}^{(i)}_b \) from any one of its TEEs to AS. \( M_b \) also sends \( \text{proof}-T_b^{(i)} \) for all \( i \in \{0, 1, 2\} \).
9. (Check proofs) For all \( b \in \{0, 1\} \), and for all \( i \in \{0, 1, 2\} \), AS asserts \( \text{Verify}(pk_{T_b^{(i)}}, \text{ain}^{(i)}_b, \text{proof}-T_b^{(i)}) \) equals True.
10. AS checks \( R\text{ID} \) in \( \text{ain}^{(0)}_b \) and \( \text{ain}^{(1)}_b \) is equal and unique, reconstructs \( \text{actInp} \), validates OAuth token, and executes action API.

Figure 5: Walnut’s protocol for the active security setting. This protocol uses the TEE machines at Walnut’s two servers.

been tampered. Meanwhile, TEEs such as Intel SGX [48], AMD SEV [50], ARM TrustZone [5], provide a tamper-proof sandbox for executing computation. Figure 5 shows Walnut’s protocol that incorporates these integrity primitives; we now briefly describe each phase and reflect on the protocol’s security guarantees and performance.

**Setup and trigger-polling.** The main difference in these phases (relative to the passive security protocol) is the addition of signatures (steps 2 and 5 in Figure 5) to the input and output of the trigger API. Besides signatures, these phases add unique IDs, particularly to the output of the trigger API.

**Action-generation.** This phase uses the TEE machines at the two servers. Each TEE \( i \) matches the response from the trigger service to the correct applet (step 7a in Figure 5), (ii) runs the GenerateAI function, and (iii) signs its part of the request to the action service (step 7c in Figure 5). This signature becomes a proof that the action service should act on the request. However, since all but one of the TEE machines may be compromised (§3.2), the action service acts on the request only if proofs from all the TEEs are valid.

**Action-execution.** The action service checks the proofs, ensures the uniqueness of the identifier in the request, and executes the action API.

**Security analysis.** The protocol described in Figure 5 meets the active security definition in §3.2. Appendix C.3 contains a proof. But, briefly, the cryptographic binding guarantees of digital signatures ensure that the messages the services receive are not tampered. Besides, the use of TEEs and equality checks ensures that \( \text{actInp} \) are computed correctly. Finally, the use of unique IDs ensures that requests to action service are not replayed.

**Performance analysis.** As with the protocol for passive security, the cost of setup phase gets amortized across many
invocations of an applet. Therefore, we focus on the costs of the other phases.

The protocol adds (relative to the passive security protocol) low CPU and network overhead in the trigger-polling phase, for two reasons. First, signature generation and checking takes less than a millisecond ($\S 8$), and each signature is 64 bytes with elliptic-curve cryptography. Second, the trigger service sends its output (step 6 in Figure 5) once to each server; in contrast, a naive design would make the trigger service send a copy of trigOut to each TEE separately.

In the action-generation phase, the main overhead is due to the replication of GenerateAI function three times on the three TEEs (step 7b in Figure 5). When GenerateAI further calls Yao’s protocol, this increase is significant as Yao’s CPU and network costs are high. However, when GenerateAI calls Walnut’s efficient string_sub procedure, then the impact on the protocol is small.

In the action-execution phase, the protocol adds low CPU and network overhead. Again, the protocol sends only one copy of actInp from each server to the action service. Each TEE does send a separate signature but signatures are small in size (64 bytes each) and signature verification takes less than a millisecond of CPU time.

6 Supporting OAuth tokens with expiry

So far, we have assumed that OAuth tokens do not expire (the user puts tokens in applet during the setup phase and goes offline). However, in practice, some IFTTT applets use OAuth that do expire. This section first quickly reviews how expirable tokens work, and then describe Walnut’s protocol.

Expirable tokens in OAuth protocol. The OAuth protocol uses two tokens: an access token and a refresh token. Each token has an expiration time. The holder of these tokens includes the access token in regular GET and POST requests to HTTP endpoints. However, if the access token is expired, the endpoint returns a HTTP 401 unauthorized error. Then, the token holder sends a refresh request to an OAuth endpoint consisting of both the access token and the refresh token; if the refresh token has not expired, the endpoint returns a new access token and refresh token.

Walnut’s protocol to support OAuth token refresh. One way for Walnut to support expirable tokens is to use the TEEs at the two servers, who could initiate the refresh tokens request and update the tokens in an applet. However, Walnut uses a protocol that avoids the use of TEEs. Walnut’s high-level idea is to use a signed chain of encrypted tokens—to link the original user-supplied tokens with new tokens.

Assume that time is split into epochs, beginning with the 0-th epoch. Also, let $a_k$ be the valid access token in the $k$-th epoch, and define $\langle \text{Enc}(pk, a_k), \sigma_k \rangle$ as the token-chain for the same epoch; here, encryption is under the key of the entity issuing the tokens (a trigger or action service) and $\sigma_k$ is a signature by the same entity over the ciphertext. Then, during a regular HTTP request to a trigger or action API in the $k$-th epoch (steps 4 and 8 in Figure 5), machines $M_0$ and $M_1$ at Walnut’s platform append the $k$-th token-chain to the request. When the service receives the request, it verifies the signature, and matches the $a_0$ part of the chain to the original user-supplied access token in the request. If there is a match, then the service replaces the original token in the request with $a_k$ (this replacement is done in the API-agnostic logic added to the services; $\S 3.1$).

A question is: how does Walnut’s machines $M_0$ and $M_1$ obtain the token-chain for the $k$-th epoch? The user supplies the chain for the 0-th epoch, that is, $\langle \text{Enc}(pk, a_0), \sigma_0 \rangle$, as part of the applet during setup. To enable $M_0$ and $M_1$ to get the chain for the $k$-th epoch, Walnut extends the refresh token request to the OAuth endpoind. As mentioned above in the background, normally the token holder sends the refresh and access tokens for the $k$-th epoch and receives refresh and access tokens for the $(k+1)$-th epoch. In Walnut, $M_0$ includes the token-chain for the the $k$-th epoch, that is, $\langle \text{Enc}(pk, a_k), \sigma_k \rangle$, in the refresh request. The service verifies that the token $a_k$ in the chain matches the token in the regular part of the refresh request, and sends the chain for the $(k+1)$-th epoch, that is, $\langle \text{Enc}(pk, a_{k+1}), \sigma_{k+1} \rangle$.

Security analysis. Walnut’s protocol with the extension described above meets the active security definition in $\S 3.2$. Appendix C.3 contains a proof. But, briefly, Walnut’s protocol keeps tokens (both original and in the chain) for each epochs encrypted with the services’ keys. Also, the Walnut platform makes a successful request to a trigger and action API if it has a valid chain and a valid (but expired) user-supplied token. Finally, Walnut’s servers get a chain for a new epoch only if they possess the expiring (but valid) chain.

Performance analysis. The protocol extension affects mainly the trigger-polling and action-execution phases. In particular, the addition of token-chain to the requests to the trigger and action APIs (steps 4 and 8 in Figure 5) adds CPU. The protocol extension de-
For applets with custom filterCode (≈1-2%), Walnut increases platform-side \(CPU\) and network costs by \(54 \times\) and \(1883 \times\) over a non-secure baseline. However, for common applets, Walnut increases these costs by \(3.6 \times\) and \(4.3 \times\).

For all applets, Walnut increases \(CPU\) and network costs at trigger and action services by up to \(3.2 \times\) and \(2.52 \times\), respectively, relative to a non-secure baseline.

Walnut’s dollar cost for running the common applets is \(3.74 \times\) of a non-secure baseline.

One can program existing IFTTT applets on Walnut with ease.

### 8 Evaluation

Walnut’s evaluation answers the following questions:

1. What are Walnut’s overheads relative to a non-secure baseline that mimics IFTTT?
2. How much overhead do Walnut techniques (§4–§6) incur?
3. For what kinds of applets is Walnut practical?

Figure 6 summarizes our evaluation results.

#### Method and setup

We compare Walnut to the following baseline systems. NoSec is our Python-based reference implementation of IFTTT (IFTTT itself is closed-source). NoSec uses Flask as a web server, MongoDB as a data store for applets, and the Python requests framework \([29]\) for HTTP requests. W-Yao, W-C, and W-I are intermediate baselines between NoSec and Walnut. W-Yao implements Walnut’s protocol for the passive security setting. It provides confidentiality but no integrity guarantees. Further, it uses Yao’s protocol only for secure computation (§4). W-C builds on W-Yao and adds Walnut’s custom protocol for string substitution for the common types of applets on IFTTT (§4). W-I builds on W-C and adds the use of digital signatures and TEEs for integrity guarantees (§5). Walnut (W) builds on W-I and adds the use of token-chains for refreshing OAuth tokens (§6).

We perform a series of experiments to answer the evaluation questions. In each experiment, we deploy a system, execute an applet (described below), and measure \(CPU\) time, wall-clock time, network transfers, and storage space use. We measure \(CPU\) time and network transfers using kernel accounting frameworks /proc/pid/stat and /proc/net/dev, respectively. We measure wall-clock time by instrumenting code with Python’s time.time(), and storage space use by reading statistics returned by MongoDB’s collStats.

We execute the “Get a daily 6:00 AM email with the weather report” applet from Weather Underground [77]. We choose this applet because it is both popular (installed over 30K times) and representative of the common IFTTT applet. We run this applet with three types of filterCode. The “passing around” filterCode sets the body of the email to the value of the key-value pair with key “new_weather_type” in trigOut.

The “string sub” filterCode sets the body of the email to the value of \{new\_weather\_type\} in trigOut as described in Section 4. We configure Walnut to pad each block in a string to a power-of-two length.

For all applets, Walnut increases \(CPU\) and network costs at trigger and action services by up to \(3.2 \times\) and \(2.52 \times\), respectively, relative to a non-secure baseline.

Walnut’s dollar cost for running the common applets is \(3.74 \times\) of a non-secure baseline.

One can program existing IFTTT applets on Walnut with ease.

**Figure 7:** Machines used in Walnut’s experiments.

**Figure 8:** CPU times and network transfers for cryptographic operations in Walnut and the baselines. The key-sizes of elliptic curve-based ECIES and ECDSA are 256 bits. The elliptic curve used is secp256k1. The overheads of Yao depend on the function being computed inside Yao; integer comparison compares two 32-bit integers, and the string substitution function replaces the braces in the template string “This is a substitution \{\}” with another string of length 100 bytes.

We execute the “Get a daily 6:00 AM email with the weather report” applet from Weather Underground [77]. We choose this applet because it is both popular (installed over 30K times) and representative of the common IFTTT applet. We run this applet with three types of filterCode. The “passing around” filterCode sets the body of the email to the value of the key-value pair with key “new_weather_type” in trigOut.

The “string sub” filterCode sets the body of the email to the value of \{new\_weather\_type\} in trigOut as described in Section 4. We configure Walnut to pad each block in a string to a power-of-two length.

Our testbed (Figure 7) is a set of VMs on Google Cloud, Microsoft Azure, and IBM Cloud. We run the trigger and action services on Google Cloud, and Walnut’s two servers on Azure and IBM. Within Azure and IBM, we use both general-purpose and TEE machines. Cloud providers currently offer only Intel SGX-based TEEs [66]; we use three such machines as the three TEEs for W-I and Walnut. However, the TEE availability on cloud providers is improving [4][66], and in a real deployment, Walnut would use three different TEEs.

**Microbenchmarks.** Figure 8 shows CPU and network costs for common cryptographic operations in Walnut and the baselines on machines of type B1.1x2 (Figure 7). Walnut uses elliptic curve-based encryption and signature schemes (ECIES and ECDSA) and uses Yao’s protocol only for secure computation (§4). W-Yao builds on W-C and adds the use of digital signatures and TEEs for integrity but no integrity guarantees. Further, it uses Yao’s protocol only for secure computation (§4). W-C builds on W-Yao and adds Walnut’s custom protocol for string substitution for the common types of applets on IFTTT (§4). W-I builds on W-C and adds the use of digital signatures and TEEs for integrity guarantees (§5). Walnut (W) builds on W-I and adds the use of token-chains for refreshing OAuth tokens (§6).

We perform a series of experiments to answer the evaluation questions. In each experiment, we deploy a system, execute an applet (described below), and measure CPU time, wall-clock time, network transfers, and storage space use. We measure CPU time and network transfers using kernel accounting frameworks /proc/pid/stat and /proc/net/dev, respectively. We measure wall-clock time by instrumenting code with Python’s time.time(), and storage space use by reading statistics returned by MongoDB’s collStats.

We execute the “Get a daily 6:00 AM email with the weather report” applet from Weather Underground [77]. We choose this applet because it is both popular (installed over 30K times) and representative of the common IFTTT applet.
8.1 Platform-side overheads

CPU overhead. Figure 9 (a) shows platform-side CPU overhead while varying the system and the filterCode in our workload applet. At a high level, the CPU overhead increases as the complexity of filterCode increases. For instance, Walnut’s CPU time is 62.0 ms for pass arnd, 62.9 ms for string sub, and 950.3 ms for custom filterCode.

For all three filterCode types, NoSec consumes the least CPU, while W-Yao and Walnut consume the most. For instance, for the string sub filterCode, W-C, W-I, Walnut, and W-Yao consume 2.9×, 3.5×, 3.6×, and 17.7× the CPU time of NoSec. This trend is expected as NoSec operates over plaintext data and does not provide integrity properties, while W-C adds secret-sharing, encryption, and tailored string substitution over shares of strings (Figure 3 in §4). W-I further adds signature verification and generation inside TEEs (Figure 5 in §5), and Walnut adds token-chain to W-I (§6). W-Yao consumes high CPU as it performs string substitution over an encrypted Boolean circuit (§4).

Meanwhile, the CPU times connect back to microbenchmarks (Figure 8). For instance, Walnut adds 12.7 ms of CPU time relative to W-C for the string sub filterCode. This is primarily due to three pairs of signature generation and six pairs of signature verification using OpenSSL inside TEE machines; each signature generation and verification takes ≈0.7 ms and ≈0.55 ms, respectively.

Network overhead. Figure 9 (b) shows platform-side network overhead for the various systems and filterCodes. The network trends resemble those for CPU. The costs increase with filterCode complexity, and for each type of filterCode, W-C, W-I, Walnut, and W-Yao incur successively increasing cost over NoSec, except for the custom code filterCode where W-C behaves like W-Yao.

Walnut incurs overhead over NoSec because it transfers serialized ciphertexts, secret-shares, signatures, and token-chains during the trigger-polling, action-generation, and action-execution steps of Walnut’s protocol (§4–§6). As an example, consider the trigger-polling message from Walnut’s first server to the trigger service. In NoSec, the header of the message is 219 bytes, while it is 383 bytes in Walnut. The header increases by 164 bytes because the 64 byte OAuth token in NoSec is ECIES-encrypted to a 161-byte ciphertext, and then serialized to a final size of 228 bytes (step[4] in Figure 5). Similarly, the body of the polling message is 150 bytes in NoSec and 826 bytes in Walnut, due to the addition of several fields including 231 bytes of encrypted trigInp, 126 bytes of a signature over trigInp, and 403 bytes of a token-chain.

Latency overhead. Figure 10 shows the time it takes for the various systems to execute an applet. Our wall-clock timing begins when the platform initiates the trigger-polling request to the trigger service, and ends when the action services receive the action details. Walnut’s latency is 1.3×, 1.3×, and 32.7× of NoSec’s latency for the three types of filterCode. The latency increase for the custom filterCode is high because it calls the expensive Yao’s protocol.

Storage overhead. Figure 11 shows Walnut’s and NoSec’s storage space use for the applet with the string sub filterCode. Overall, Walnut’s applet takes 5.8× the storage space required by the NoSec applet. This extra storage is due to the additional...
components in Walnut’s applet, such as secret-shares of setup-time values of actInp, and the overhead of encrypting, signing, and serializing the components.

8.2 Service-side overheads

Trigger service overheads. Figure 12(a) shows CPU time for the various systems and the three types of filterCodes in our workload applet. The CPU times have two notable aspects. First, Walnut’s CPU time is $3.2 \times$ that of NoSec. The overhead comes from confidentiality techniques (decryption of trigInp ciphertexts and creation of trigOut secret shares) and integrity design (verification and generation of signatures). Second, the overhead does not vary with filterCode. This trend is expected as the trigger components of the three applets are the same.

Figure 12(b) shows the trigger service’s network overhead. This overhead is $2.5 \times$ that of NoSec. Also, as with the CPU costs, the network traffic is independent of the filterCode.

Action service overheads. Figure 13 shows action service’s CPU and network overhead for the various systems and filterCodes. Similar to the trigger service overheads, the CPU costs are dependent on the system used. The CPU overhead of Walnut relative to NoSec is due to the decryption and merging of actInp shares, and signature verification for the “proofs” from TEEs and the token-chain (§5, §6).

The network overhead also increases with the security provided by the system, and with the filterCode. The variation across filterCodes is due to the fact that different filterCodes result in actInp of different lengths. Finally, we notice that for NoSec the action service-side network transfers (9.3 KB) are larger than the platform-side network transfers (3.7 KB; Figure 9(b)). This is because the action service also communicates with Gmail to authenticate and send emails.

8.3 Dollar Cost

Walnut’s added overheads (§8.1) increase dollar cost for the platform provider for running an applet. In this section, we estimate these costs by converting Walnut’s raw resource overheads into a dollar amount using a pricing model derived from machine and data transfer prices of Microsoft Azure (Appendix A). This model charges CPU at $0.198/hour and network transfers at $0.087/GB.

Figure 14 shows the resulting dollar costs for the three types of filterCodes (passing around, string substitution, and custom code). For the common filterCodes (passing around and string substitution), Walnut increases cost by $3.7 \times$ and $3.74 \times$. However, for the custom code filterCode, Walnut increases cost by $510.4 \times$.

8.4 Compatibility

One of Walnut’s goals is to run any IFTTT applet. To study whether Walnut can meet this requirement, we implemented, using Walnut, (i) 15 randomly selected IFTTT applets from the 50 most popular applets in the dataset of Mi et al. [59], and (ii) 15 IFTTT applets whose applet IDs were randomly generated (Appendix B). We found that IFTTT applets can be implemented on Walnut in a short time—it took us 96 developer-hours to implement and test these applets.
passing around
NoSec 17.6 ms 3.6 KB 1×
Walnut 62.9 ms 15.7 KB 3.74×

string substitution
NoSec 17.6 ms 3.7 KB 1×
Walnut 62.9 ms 15.7 KB 3.74×

custom filterCode
NoSec 17.6 ms 3.7 KB 1×
Walnut 950.3 ms 6966.6 KB 510.4×

Figure 14: Dollars spent to run an applet on NoSec, Walnut.

9 Related work

Confidentiality and integrity risks in IoT middleware. Xu et al. [78] study SmartThings, which is the Samsung platform for managing Samsung smart devices, and report the movement of sensitive information from SmartThings to IFTTT.

Fernandes et al. [24] also report security issues with SmartThings, in particular, over-privilege of access tokens. For example, a SmartThings application may get a capability for locking and unlocking a Samsung device even if it needs to only call lock. Like SmartThings, IFTTT exhibits over-privilege: 75% of IFTTT services issue broad-scoped OAuth tokens [25][26], as discussed earlier (§2).

Walnut is inspired by these works. It focuses on limiting the exposure of sensitive data at the platform and ensuring that the platform does not misuse tokens (that is, always performs the precise action intended by the user).

Reducing risks in trigger-action platforms. Almond [12] is a virtual assistant that connects trigger and action services. Unlike IFTTT, it allows the users to program applets using natural language (rather than mouse clicks that build automation programs). Almond preserves confidentiality but makes strong trust assumptions: it runs inside a single trusted device.

Xu et al. [78] use a filter-and-fuzz approach to provide confidentiality. The filter part enables the trigger service to eliminate parameters that are either not needed by an applet or do not result in the firing of an action. The fuzz part adds dummy trigger outputs to drown real outputs that cannot be filtered. Filter-and-fuzz approach has a limited applicability as it assumes that the trigger service has knowledge of the actions. Indeed, Xu et al. apply their approach to Samsung’s SmartThings where trigger and action services are in the same domain. Furthermore, the approach adds high CPU and network overhead to transfer and process dummy events.

DTAP [25][26] eliminates over-privilege of OAuth tokens by using applet-specific access tokens. In DTAP, a trigger service signs trigOut, the platform processes the output in plaintext to generate actInp, and the action service verifies both the signature over trigOut and the correctness of actInp. DTAP does not hide sensitive data from the platform. Besides, it sends the entire trigOut structure to the action service to verify signature and action-correctness.

Walnut also targets security improvements for a trigger-action platform. However, relative to prior work, it provides both confidentiality and integrity guarantees (Figure 15). Furthermore, in line with the principle of least privilege [22][68] (also called data minimization in modern privacy regulation [2]), Walnut ensures that the services learn only the information that is input to the trigger and action APIs.

Reducing risk in other types of IoT middleware. Bolt [37] targets applications for smart homes (e.g., finding a lost pet in a neighborhood). It stores data on an untrusted cloud provider but runs applications on trusted in-home devices.

BeeKeeper [84] targets a streaming scenario in which an IoT device streams data to a blockchain-based “leader” who runs a query on it. BeeKeeper uses secret-sharing and secure multi-party computation [36] to provide confidentiality, and threshold-cryptography to provide integrity. However, BeeKeeper does not target trigger-action scenarios; instead, it computes quadratic polynomials (mean, variance, and standard-deviation). Jayaraman et al. [49] target the same scenario as BeeKeeper. However, in contrast to BeeKeeper, they use Paillier encryption and do not provide integrity.

General-purpose crypto primitives for security. Secure computation [36][80] and homomorphic encryption [34][67] are vibrant areas of research [16][17][40][41][53][54][57][71][82]). These general-purpose primitives support arbitrary computation but are expensive. Walnut uses Yao’s two-party protocol but only for a small fraction of applets (§4).

Zero-knowledge proof systems have also seen tremendous development [6][9][11][15][21][64][70][76]. However, the party generating the proof incurs a large CPU time.

Walnut instead uses a mix of digital signatures and TEEs for proving execution integrity at low overhead (§5).

10 Conclusion

Trigger-action platforms like IFTTT have gained traction due to their convenience and connectivity. However, these cloud-hosted platforms present confidentiality and integrity risks. This paper asked the question, can we build a fortified alternative to IFTTT at a low resource cost, and found the results to be encouraging. In particular, one can gain significantly on security while restricting resource (CPU, network) overhead to 4.3× for all but a small fraction of programs. Walnut’s enabler is a new secure computation protocol that is tailored for common computation on IFTTT and that distributes trust...
over heterogenous trusted-hardware machines from different vendors. By demonstrating these promising results, Walnut provides a benefit to both users and platform providers—they can enjoy trigger-action automation with significant improvement in data confidentiality and integrity.

A Pricing model

To get the dollar-cost of running an applet, we take the CPU and network cost from our benchmarks and add them linearly (§8.3). That is, if $C$ is the hourly CPU cost and $D$ is the price for transferring one GB of data over the network, the dollar cost to run each applet is of the form $\alpha C + \beta D$, where $\alpha$ is the CPU time required to run the applet and $\beta$ is the amount of data transferred to or from the Walnut platform during execution. Our goal in this appendix is to estimate the values of $C$ and $D$.

The network cost is taken from the “outbound data transfer” costs for Microsoft Azure which gives $D = 0.087$ (dollars per GB) [61]. Meanwhile, estimating CPU cost is not straightforward. Machine prices on cloud providers are set using several factors including maintenance and running expenses, market demand, and peripheral costs such as DDoS protection and load-balancing. Therefore, we make a simplifying assumption that the machine cost on cloud providers is dominated by the cost of CPU. We take the hourly cost of a DC4s.x2v2 SGX machine on Microsoft Azure [62] that we use in our experiments and divide by 4, which is the number of cores on this machine. This method gives $C = 0.198$ (dollars/hour).

B Compatibility study applets

- The following 15 applets were randomly selected from the set of 50 most popular applets from the dataset of Mi et al. [59]:
  1. “Get a daily 6:00 AM email with the weather report” (https://ifttt.com/applets/Zv56ZxWw)
  2. “Update your Android wallpaper with NASA’s image of the day” (https://ifttt.com/applets/yNhX9VQ)
  3. “Sync all your new iOS Contacts to a Google Spreadsheet” (https://ifttt.com/applets/45cQ5A6)
  4. “Automatically change your Twitter profile pic when you update your Facebook photo” (https://ifttt.com/applets/qFZqXrvs)
  5. “Automatically back up your new iOS photos to Google Drive” (https://ifttt.com/applets/90254p)
  6. “Send a text message to someone with your Android and Google Home” (https://ifttt.com/applets/fNDgJfwy)
  7. “Sync your Amazon Alexa to-dos with your reminder” (https://ifttt.com/applets/ieCE52WK)
  8. “Track your work hours in Google Calendar” (https://ifttt.com/applets/cFk2W4r)
  9. “Quickly create events in Google Calendar” (https://ifttt.com/applets/192007p)
  10. “Press a button to track work hours in Google Drive” (https://ifttt.com/applets/227069p)
  11. “Back up new iOS photos you take to Dropbox” (https://ifttt.com/applets/103376p)
  12. “Backup your new Instagram photos to Dropbox” (https://ifttt.com/applets/25679p)
  13. “Post your Instagram photos to Tumblr” (https://ifttt.com/applets/131p)
  14. “Post your Instagram photos as native Twitter photos when #twitter is in the caption” (https://ifttt.com/applets/68915p)
  15. “Tell Alexa to email you your shopping list” (https://ifttt.com/applets/284243p)

- The following 15 applets were randomly selected from a set of 78 randomly generated applet IDs:
  1. “bloggin’ via Instagram: STEP 2 Flickr -> Tumblr” (https://ifttt.com/applets/7p)
  2. “End Harmony Activity using MESH” (https://ifttt.com/applets/6163)
  3. “Receive a notification when occupancy is detected” (https://ifttt.com/applets/3820)
  4. “Turn on Wemo Smart Plug using MESH” (https://ifttt.com/applets/6190)
  5. “bloggin’ via Instagram: STEP 1 Instagram -> Flickr” (https://ifttt.com/applets/6p)
  6. “Tweet your newest uploaded Flickr pictures.” (https://ifttt.com/applets/29p)
  7. “Carry important file everywhere!” (https://ifttt.com/applets/86p)
  8. “Record each time you connect to your TP-Link network in a Google Spreadsheet” (https://ifttt.com/applets/6997)
  9. “Test ifttt 1” (https://ifttt.com/applets/09018)
  10. “Switch on a socket with Amazon Alexa” (https://ifttt.com/applets/6569)
  11. “Flickr favorites to Evernote” (https://ifttt.com/applets/33p)
  12. “Get an email when motion is detected at your front door” (https://ifttt.com/applets/3726)
  13. “Sing a love song to IFTTT Voicemail, send it straight to my sweetheart” (https://ifttt.com/applets/11p)
  14. “Daily Forecast” (https://ifttt.com/applets/2950p)
  15. “Post your new Instagram videos with a specific hashtag to a Telegram chat” (https://ifttt.com/applets/4657)

C Security proofs

We first introduce definitions for the basic cryptographic primitives such as secret-sharing, encryption, and signatures that Walnut’s protocol builds on. We then present the proofs for the passive and active security settings (§3.2).
C.1 Basic cryptographic primitives

Secret-sharing. Walnut uses a 2-out-of-2 XOR secret-sharing scheme, where both the shares are required to reconstruct the secret. This scheme consists of two algorithms.

- **Share** \( s \in \{0, 1\}^\ell \rightarrow (k, k') \) takes as input a \( \ell \)-bit string and generate two secret-shares of the string: \( k \) and \( k' \). Internally, the procedure first samples \( k \in_R \{0, 1\}^\ell \) and then computes \( k' \leftarrow k \oplus s \).
- **Reconstruct** \( (k, k') \) outputs \( s \leftarrow k \oplus k' \).

Correctness of the scheme requires the shares produced to be reconstructable. Security requires that an adversary cannot distinguish between the shares of two different input strings of the same length.

Encryption scheme. Walnut relies on an encryption scheme that is IND-CPA and IND-CCA2 secure. It consists of two algorithms.

- **Enc** \((pk, m) \rightarrow C^m\) takes in the public key, and the plaintext message and outputs a ciphertext.
- **Dec** \((sk, C^m) \rightarrow m\) takes in the secret key and a ciphertext and outputs the plaintext message.

Correctness requires that ciphertexts produced from the scheme can be decrypted to obtain back the original plaintext. Security requires that the ciphertexts produced for two different plaintext messages are indistinguishable. Walnut's implementation uses the elliptic-curve based ECIES encryption scheme (§8).

Signature scheme. Walnut relies on a standard signature scheme which consists of two algorithms.

- **Sign** \((sk, m) \rightarrow \sigma_m\) takes in a secret key and a message and outputs a signature.
- **Verify** \((pk, m, \sigma_m) \rightarrow \{\text{True, } \perp\} \) takes in the public key, the message, and the signature, and returns either True or \( \perp \) to indicate whether the signature on the message is valid or not.

Correctness requires that a signature produced from the scheme can be successfully verified by the verification algorithm. Security requires the unforgeability of a valid signature by an adversary, that is, an adversary cannot (without the secret key) produce a signature that outputs True from the verification algorithm.

We now move to the proofs for Walnut’s protocol.

C.2 Proof for passive security

Our goal here is to prove that the protocol described in Section 4 (Figure 3) meets the passive security definition in Section 3.2.

We prove the security of the protocol using the simulation proof technique. Essentially, in this technique, there is an ideal world adversary called the simulator which resides in the ideal world (which is secure by definition). The real world adversary interacts with the simulator, and the simulator simulates the messages output by the honest parties in the protocol. The simulator has access to the signing keys of the honest parties. The protocol is said to be secure if such a simulator exists and the adversary cannot distinguish between the real execution of the protocol and the simulated execution.

Suppose there exists a PPT adversary \( A \) that compromises the general purpose machine \( M_b \) for some \( b \in \{0, 1\} \). The honest parties in the passive setting are trigger service \( TS \), action service \( AS \), and the general-purpose machine \( M_{1-b} \).

We then construct a PPT simulator \( \hat{S} \) as follows:

1. \( \hat{S} \) chooses a uniform random tape for the corrupted party \( M_b \). \( \hat{S} \) simulates the honest parties \( TS, AS, M_{1-b} \).

2. In Setup phase:
   
   (a) \( \hat{S} \) sends encryptions of zeros as access tokens and trigInp. That is, \( C_{\text{Sim}}^{\text{AT-TS}} \leftarrow \text{Enc}(pk_{\text{TS}}, 0^{\ell-\text{AT-TS}}) \), \( C_{\text{Sim}}^{\text{AT-AS}} \leftarrow \text{Enc}(pk_{\text{AS}}, 0^{\ell-\text{AT-AS}}) \), and \( C_{\text{Sim}}^{\text{TrigInp}} \leftarrow \text{Enc}(pk_{\text{AS}}, 0^{\ell-\text{TrigInp}}) \).
   
   (b) \( \hat{S} \) replaces each \( s_{b}^{(i)} \) not of the form \( \{\text{key-name}\} \) in each \( s_{b}^{(\text{actInp})}[k] \) with \( \text{Share}(0^{\ell})[b] \).

3. In trigger-polling phase: \( \hat{S} \) replaces each \( s_{b}^{(t)} \) in each \( s_{b}^{(\text{actInp})}[k] \) with \( \text{Share}(0^{\ell})[b] \).

4. In action-generation phase: depending on the filter-Code, \( \hat{S} \) runs the simulator of Yao’s protocol or the custom string substitution protocol (described shortly below). In either case, the simulator is programmed to output shares of the action input parameter \( s_{b}^{(\text{actInp})} \) chosen uniformly at random.

5. In action-execution phase: \( \hat{S} \) does nothing.

We now show that the distribution of the messages in the real protocol and the outputs of the simulator are computationally indistinguishable using the standard hybrid technique. This technique refers to the strategy of proving that two tuples of distributions \( (D_1, \ldots, D_n) \) and \( (D'_1, \ldots, D'_n) \) are computationally indistinguishable, if all the \( D_i \)'s (respectively, \( D'_i \)'s) are independently generated, and \( D_i \) is computationally indistinguishable from \( D'_i \). The strategy is to consider a sequence of hybrid distributions \( (D_1, \ldots, D_{i-1}, D'_i, \ldots, D'_n) \) and proving every consecutive tuples of distributions are computationally indistinguishable.

1. \( \text{Hyb}_0 \): This corresponds to the real world distribution where trigger service \( TS \), action service \( AS \) and machine \( M_{1-b} \) execute the protocol as described in Section 4.

2. \( \text{Hyb}_1 \): In this hybrid, we change the ciphertexts of tokens and trigInp sent to \( TS \), and ciphertext of tokens sent to \( AS \). More specifically, we replace the encryption of tokens and trigInp with a bit strings chosen uniformly at random. \( \text{Hyb}_0 \approx_{c} \text{Hyb}_1 \) due to the semantic security of
the encryption scheme.

3. $Hyb_2$: In this hybrid, we change the shares of actInp and trigOut. More specifically, each $sh_b^{(\text{actInp})}[k]$ not of the form \{\{key-name\}\} in each $sh_b^{(\text{actInp})}[k]$ and $sh_b^{(\text{origOut})}[k]$ is replaced with bit strings chosen uniformly at random. $Hyb_1 \approx_c Hyb_2$ due to the security of the secret sharing scheme.

4. $Hyb_3$: In this hybrid, the simulators for either Yao’s protocol or custom string substitution protocol is invoked which outputs honest shares of action input parameter $sh_b^{(\text{actInp})}$. $Hyb_2 \approx_c Hyb_3$ due to the security of the secret sharing scheme.

5. $Hyb_4$: In this hybrid, we replace $sh_b^{(\text{actInp})}$ output from either Yao’s protocol or custom string substitution protocol with bit strings chosen uniformly at random. $Hyb_3 \approx_c Hyb_4$ due to the security of secret-sharing.

6. $Hyb_5$: This corresponds to the output distribution of $Sim$. Hybrids $Hyb_4$ and $Hyb_5$ are identically distributed.

**Proof of security for custom string substitution.**

**Definition C.1.** The custom string substitution protocol described in Figure 4 is said to be $C$-secure if for any honest-but-curious (passive) probabilistic polynomial time (PPT) adversary $A$ corrupting $M_b$ for some $b \in \{0, 1\}$, for a leakage function $L$, for every large enough security parameter $\lambda$, there exists a PPT simulator $Sim$ with access to the leakage function, such that the output distribution of the simulator is computationally indistinguishable from the adversary’s view in the real protocol.

The simulator for string-sub is constructed as follows:

1. $Sim$ replaces each $sh_b^{(c)}$ in each $sh_b^{(\text{origOut})}[k]$ with Share($0^{(b)}|b]$.
2. Similarly, $Sim$ replaces each $sh_b^{(t)}$ not of the form \{\{key-name\}\} in each $sh_b^{(\text{actInp})}[k]$ with Share($0^{(b)}|b]$.
3. $Sim$ replaces each $sh_b^{(c)}$ in each $sh_b^{(\text{actInp})}[k]$ output from GenerateAI with Share($0^{(b)}|b]$ and outputs $sh_b^{(\text{actInp})}$.

We now show that the distribution of the messages in the real protocol and the outputs of the simulator are computationally indistinguishable using the hybrid technique.

1. $Hyb_0$: This hybrid corresponds to the real world distribution of the execution of string-sub function by machine $M_b$. That is, \{\{string-sub($sh_b^{(\text{origOut})}$, $sh_b^{(\text{actInp})}$)\}\}.

2. $Hyb_1$: In this hybrid, we change the share of trigOut to secret shares of zero. More specifically, each $sh_b^{(c)}$ in each $sh_b^{(\text{actInp})}[k]$ is replaced with Share($0^{(b)}|b]$).

3. $Hyb_2$: In this hybrid, we change the share of actInp input parameter to secret shares of zero. More specifically, each $sh_b^{(c)}$ not of the form \{\{key-name\}\} in each $sh_b^{(\text{actInp})}[k]$ is replaced with Share($0^{(b)}|b]$).

4. $Hyb_3$: This corresponds to the output distribution of $Sim$. Hybrids $Hyb_2$ and $Hyb_3$ are identically distributed.

**C.3 Proof for active security**

Our goal here is to prove that the protocol described in Section 5 (Figure 5) and Section 6 meets the active security definition in Section 3.2. We first formalize the notion of token-chains (\S 6) and then present the proof.

**Definition C.2 (Token-chains).** Let $at-TS_b$ and $rt-TS_b$ denote the access and refresh token for trigger service $TS$ in epoch $\ell$, and let $at-AS_b$ and $rt-AS_b$ denote the access and refresh token for action service $AS$ for epoch $\ell$. We define $chain^{TS}_\ell$ equal to $Enc$(pk$_{TS}$, $at-TS_0[|at-TS_\ell]$) as the token chain for the trigger service $TS$ for epoch $\ell$, and $\sigma^{AS}_\ell \leftarrow$ Sign(sk$_{TS}$, $chain^{TS}_\ell$) as the signature over the chain. Similarly, we define $chain^{AS}_\ell$ and $\sigma^{AS}_\ell$. Walnut’s protocol for active security adds $chain^{TS}_\ell$, $\sigma^{TS}_\ell$, $chain^{AS}_\ell$, and $\sigma^{AS}_\ell$ to App$_b$.

Suppose there exists a PPT adversary $A$ that compromises the general purpose machine $M_b$ for $b \in \{0, 1\}$ and TEE machines $T_b(i)$ and $T_b(j)$ for some $i, j \in \{0, 1, 2\}$. Then the honest parties in the active setting are trigger service $TS$, action service $AS$, TEEs $T_b(k)$, $T_b(i)$, $T_b(j)$, $T_b(k)$, and the general purpose machine $M_{1-b}$. Let $k$ be such that $k \neq i$ and $k \neq j$. We then construct a PPT simulator $Sim$ simulating the behavior of the honest parties as follows.

1. **In setup phase:**
   
   (a) $Sim$ sends encryptions of zeros as access tokens and trigInp, that is, $C_{Sim}^{TS} \leftarrow Enc$(pk$_{TS}$, $0^{(\text{actInp})}$), $C_{Sim}^{AS} \leftarrow Enc$(pk$_{AS}$, $0^{(\text{actInp})}$), and $C_{Sim}^{\text{origOut}} \leftarrow Enc$(pk$_{TS}$, $0^{(\text{origOut})}$).
   
   (b) $Sim$ replaces each $sh_b^{(c)}$ not of the form \{\{key-name\}\} in each $sh_b^{(\text{actInp})}[key]$ with Share($0^{(b)}|b]$).
   
   (c) $Sim$ sends encryptions of zeros as the token chains, that is, $chain'^{TS}_{Sim} \leftarrow Enc$(pk$_{TS}$, $0^{(chain^{TS})}$), $chain'^{AS}_{Sim} \leftarrow Enc$(pk$_{TS}$, $0^{(chain^{AS})}$).
   
   (d) $Sim$ generates simulated signatures $\sigma^{TS}_{Sim}$, $\sigma^{AS}_{Sim}$, $\sigma_T$ for the uniform random ciphertexts $chain'^{TS}_{Sim}$, $chain'^{AS}_{Sim}$, and simulated $T$, respectively.

2. **In trigger-polling phase:**
   
   (a) $Sim$ asks $A$ for its inputs to the trigger service $TS$: $T$, $\sigma_T$, $chain'^{TS}_{Sim}$, $\sigma^{TS}_{Sim}$. $Sim$ additionally aborts the protocol if signature verification of $\sigma_T$ and $\sigma^{TS}_{Sim}$ fails.
   
   (b) $Sim$ simulates trigger output tout$_b$ by generating simulated shares of $sh_b^{(\text{origOut})}$. replacing each $sh_b^{(c)}$
We now show that the distribution of the messages in the real protocol and the outputs of the simulator are computationally indistinguishable using the hybrid technique.

1. **Hyb₀**: This hybrid corresponds to the real world distribution where trigger service $TS$, action service $AS$, machine $M_{1-b}$, and TEE machines $T_{1}^{(k)}$ and $T_{0}^{(k)}$ execute the protocol described in Figure 5.

2. **Hyb₁**: In this hybrid, we change the ciphertexts of tokens and trigInp sent to $TS$, and ciphertext of tokens sent to $AS$. More specifically, we replace the encryption of tokens and trigInp with bit strings chosen uniformly at random. The signatures $\sigma_{T}$, $\sigma_{TS}$, and $\sigma_{AS}$ are also updated accordingly. $Hyb₁ \approx_c Hyb₀$ due to the semantic security of the encryption scheme.

3. **Hyb₂**: In this hybrid, the shares of trigOut in $touṭ_b$ obtained as the output of trigger-polling phase $sh_{b}^{(trigOut)}$ is replaced with a bit string sampled uniformly at random. The signature $\sigma_{touṭ}$ is updated according to the simulated value of $touṭ_b$. $Hyb₂ \approx_c Hyb₁$ due to the security of secret-sharing.

4. **Hyb₃**: This hybrid is same as $Hyb₂$ but $Sim$ verifies $\sigma_{T}$, $\sigma_{TS}$, and $\sigma_{AS}$ in the trigger-polling phase and aborts if the verification fails. $Hyb₃$ is identically distributed to $Hyb₂$.

5. **Hyb₄**: In this hybrid, the action generation output of $T_{b}^{(k)}$, $sh_{b}^{(actInp)}$, is replaced with a bit string sampled uniformly at random. The signature proof-$T_{b}^{(i)}$ is updated according to the simulated value of $ain_{b}^{(i)}$. $Hyb₄ \approx_c Hyb₃$ due to the security of the secret-sharing scheme.

6. **Hyb₅**: In this hybrid, the simulator of Yao’s protocol that outputs honest shares $sh_{b}^{(actInp)}$, $sh_{b}^{(actInp)}$ is invoked. $Hyb₅ \approx_c Hyb₄$ due to the simulation security of Yao’s protocol.

7. **Hyb₆**: In this hybrid, the shares $sh_{b}^{(actInp)}$, $sh_{b}^{(actInp)}$ output from the simulator of Yao is replaced with bit strings chosen uniformly at random. The signatures proof-$T_{b}^{(i)}$ and proof-$T_{b}^{(j)}$ are updated according to the simulated value of $ain_{b}^{(i)}$, $ain_{b}^{(j)}$. $Hyb₆ \approx_c Hyb₅$ due to the security of the secret-sharing scheme.

8. **Hyb₇**: In this hybrid, $Sim$ additionally runs signature checks mentioned in step 7a of Figure 5 and aborts if verification fails. $Hyb₇$ is identically distributed to $Hyb₆$.

9. **Hyb₈**: In this hybrid, $Sim$ additionally runs checks mentioned in step 9 of Figure 5 and aborts if verification fails. $Hyb₈$ is identically distributed to $Hyb₇$.

10. **Hyb₉**: This hybrid corresponds to the output distribution of $Sim$ in the ideal execution. $Hyb₉$ and $Hyb₈$ are identically distributed.

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