Enabling Security-Oriented Orchestration of Microservices

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Abstract
As cloud providers push multi-tenancy to new levels to meet growing scalability demands, ensuring that externally developed untrusted microservices will preserve tenant isolation has become a high priority. Developers, in turn, lack a means for expressing and automatically enforcing high-level application security requirements at deployment time.

In this paper, we observe that orchestration systems are ideally situated between developers and the cloud provider to address these issues. We propose a security policy framework that enables security-oriented orchestration of microservices by capturing and auditing code properties that are incorporated into microservice code throughout the software supply chain. Orchestrators can leverage these properties to deploy microservices on a node that matches both the developer’s and cloud provider’s security policy and their resource requirements. We demonstrate our approach with a proof-of-concept based on the Private Data Objects [1] confidential smart contract framework, deploying code only after checking its provenance.

1 Introduction
Microservices are emerging as a dominant software design paradigm for distributed applications easing deployment effort for developers, and enabling cloud providers to meet increasing resource demands while providing component-level fault isolation. However, three major trends in distributed computing introduce new security challenges for deployment.

1. Shift towards lightweight containers. Cloud providers improve microservice performance and increase multi-tenancy using lighter weight, finer grained execution environments that rely on software-based techniques for security and isolation (e.g., [29, 33]). However, this means cloud providers can no longer rely on VM-like mechanisms to protect their resources and strongly isolate co-tenant microservices.

2. Multiplicity of principals and locations. Distributed applications are becoming increasingly data-centric keeping data stationary as costs to move large troves of data have become prohibitive. This shift often results in data being spread across multiple organizations (e.g., for federated learning or decentralized data analytics) and locations (e.g., cloud and edge). Thus, microservice deployments may span multiple geographically and institutionally distributed compute resources, each with their own security features and requirements.

3. On-demand deployment. Cloud providers are primarily relying on orchestration frameworks to select on-demand which compute nodes are most suitable to deploy particular microservices. Yet, today’s orchestrators (e.g., [3, 10, 27, 35]) select nodes optimizing for compute resource usage, but do not consider microservice security in this decision.

The core problem. Microservice deployments must adhere to a multitude of security requirements imposed by mutually distrusting application principals—software developers, data owners, and cloud providers. Although application principals wish to enforce their individual security requirements, they do not currently have a common way of easily identifying, expressing and automatically enforcing these requirements end-to-end from source code to deployment.

Because cloud providers have intimate knowledge of available compute platforms they can specify fine-grained requirements about unknown microservice code they deploy (e.g., the code must provide memory bounds checks). In contrast, developers/data owners may not have a priori knowledge about the platform hosting their code expressing only coarse-grained policies (e.g., the code must be deployed in a sandboxed execution environment).

Since orchestration systems interpose on microservice deployments for scheduling and resource management, we see an opportunity to leverage their central position in front of the compute nodes at the cloud provider to address this issue.

Our Proposal. We introduce the concept of security-oriented orchestration: Selecting a suitable host platform for a workload requires evaluating multi-principal security policies, and ensuring that the execution environment preserves all principals’ security requirements in addition to meeting performance and latency requirements. We propose CDI (Code Deployment Integrity), a security policy framework designed to enable such security-oriented orchestration.

Our key insight is that even if application principals do not trust each other directly, they can establish trust in a microservice if they trust who was involved in creating the final executable that is deployed at a cloud provider. This is possible since microservice-based deployments rely very heavily on a complex software supply chain to preserve certain code security properties during the creation of a microservice. That is, even if the code is transformed or inspected through various tools, if those tools operate as expected, a final executable
microservice is expected to provide specific properties (e.g., compilation inserts stack canaries for memory safety).

Thus, CDI captures properties about the operations performed throughout the software supply chain on a piece of software and binds this metadata to the artifact in a cryptographically verifiable manner. CDI then uses this metadata to establish an auditable provenance chain between the developer’s source code and the executable microservice that the orchestrator receives for deployment.

By evaluating the CDI metadata attached to a microservice, an orchestrator can perform two security-oriented tasks. First, it can map cloud provider requirements to developer or data owner policies bridging the gap between coarse and fine-grained security requirements. Second, the orchestrator can use the metadata to identify an execution environment that minimizes performance costs (e.g., a lightweight runtime) while trusting the microservice to meet all security requirements (e.g., the code is sandboxed).

However, a plethora of attacks have undermined the integrity of entire applications by compromising one or more operations of the software supply chain [5, 8, 11, 13, 14, 18, 24, 26, 30–32]. To protect this vital ecosystem, our design provides integrity for the supply chain by employing trusted execution environments (TEEs) (e.g., [2, 20, 21, 25]) for their hardware-enforced code integrity and authentication features.

Crucially, CDI does not directly evaluate or guarantee the correctness or security of microservice code. Instead, the provenance information obtained throughout the software supply chain provides an orchestrator with the history of transformations and inspections performed to create a given microservice. Because of the code properties associated with specific supply chain operations, as long as the orchestrator can establish trust in the provenance of a microservice, it can gain assurances about the security properties of the code by proxy of its history.

We demonstrate our approach with a proof-of-concept based on the Intel SGX [20, 25] TEE and the Private Data Objects [1] confidential smart contract framework, which deploys code only after verifying its provenance.

2 Related Work

Orchestration and security. Today’s orchestration frameworks (e.g., [4, 9, 28, 36]) largely place the burden of enforcing application security requirements on developers through complex, low-level per-container configuration. Kubernetes [34] allows cloud providers to advertise available platform-specific security features such as TEEs, but developers must still reason about each hardware feature and manually request a specific platform in their deployment configuration.

Several frameworks [9, 15, 17, 28] provide the ability to only deploy verified trusted container images. These approaches share techniques with CDI, providing access control to the platform and vulnerability-based security policy enforcement, and could be used in combination with CDI to build a more security-oriented orchestration system.

Supply chain security. Cloud providers [12, 16] and academics [37] have proposed solutions that offer end-to-end security metadata collection and policy enforcement throughout the software supply chain. However, these approaches do not easily enable an orchestrator to leverage these policies to make security decisions about the deployment itself.

Concurrent work in Craciun et al. [8] proposes mitigations for attacks that circumvent Intel SGX integrity checking by injecting malicious code into the enclave binary between the enclave build and signing stages. Since the proposed approach shares techniques with CDI, we imagine these mitigations may be used in combination with CDI in confidential computing scenarios.

3 Overview

Our goal for CDI (Code Deployment Integrity) is to enable security-oriented microservice orchestration that enforces security policies imposed by different application principals: cloud providers, software developers, and data owners.

3.1 Terminology

The software supply chain is a directed acyclic graph (DAG) of operations performed to create a deployable executable bundle. An operation by a supply chain tool transforms or inspects one or more input software artifacts generating one or more output artifacts, which may in turn be passed in as input artifacts to subsequent software supply chain operations. Thus, artifacts comprise materials such as source code files, intermediate code representation such as bytecode, configuration files, test results, log files, executable binaries, shared libraries, a Docker image, or Python package.

As CDI collects security metadata about the transformation or inspection performed by a given tool for later evaluation by an orchestrator, this metadata is attached to the generated artifacts essentially providing an annotated software supply chain DAG, which serves as an auditable trace. Thus, we refer to an executable bundle as an artifact that can be deployed at a cloud provider with the attached CDI metadata.

3.2 Principals & Assumptions

To optimize resource usage, cloud providers may run application code in a multi-tenant environment, requiring hosts to protect applications from one another, while also appropriately protecting their own resources against unauthorized access or tampering. At the same time, a developer may want to ensure that their microservice is deployed in a way that meets their application security policies and configuration. However, we assume that developers may not know a priori the specific compute platform (and specifically its exact hardware features) their microservice will be deployed on.
In addition, we treat the data owner as a separate application principal; owners of large-scale datasets may for example loan out access to the data (or a subset thereof) to software developers wishing to run analytics on the data. We also assume that the data owner may not fully trust the developer, imposing confidentiality, usage or regulatory constraints on the data that are expected to be enforced at deployment time.

Since microservices are created through a complex software supply chain, application principals expect each tool that transforms or inspects an artifact to preserve specific security properties in the code as part of its operation. However, because the cloud provider or software developer may each be responsible for configuring (parts of) the software supply chain for a given microservice, we assume individual tools may not be fully trusted by one of the participants.

3.3 Design Goals

The design of CDI meets the following three goals.

G1: Any application principal must be able to validate the full provenance of the code. By digitally signing the CDI metadata bundled with a microservice at each stage of the software supply chain, CDI provides an auditable trace of the operations a piece of code has undergone from its source at the developer to its executable form at the cloud provider, attributing each stage to the responsible tool.

G2: Orchestrators can establish trust in the code at deployment time without an a priori knowledge of the tools that created it. CDI achieves this goal by enabling independent vetting authorities to validate and certify that specific tools properly provide the expected security properties. Then, as long as orchestrators are able to establish a chain of trust between a vetting authority and a given tool, the signed CDI metadata is sufficient for the orchestrator to dynamically gain trust in the deployed microservice.

G3: Application principals need not rely on a single centralized root of trust. Developers, data owners and cloud providers may independently select the vetting authorities they trust to properly certify tools in the software supply chain ecosystem. A security-oriented orchestrator, then uses this information when enforcing the principals’ policies.

4 CDI Design

At a high level, CDI enables principals in distributed applications to express security policies, and allows an orchestrator to enforce these policies through metadata about the software supply chain. In CDI, vetting authorities are entities that independently vet and digitally certify that a given tool performs a transformation (e.g., compilation) or inspection (e.g., unit testing) that preserves specific code security properties in the microservice bundle (see §4.1).

To capture these properties at every software supply chain operation, each tool generates a digitally signed statement summarizing its operation over the artifacts, which we call a CDI report (see §4.2). Dedicated policy engines, which can be incorporated into an orchestration framework, then evaluate the CDI reports to verify the provenance of the microservice and ensure the deployment will adhere to all principals’ security policies prior to execution.

For example, if the cloud provider has a WebAssembly (Wasm)-based lightweight container available (e.g., as in [?] ) and wants to ensure that deployed microservices cannot violate software-based isolation, the CDI report allows the orchestrator to check if a microservice was created by a Wasm build toolchain that the host trusts to preserve the Wasm-mandated memory bounds checks needed for code sandboxing. Then, if the orchestrator can establish trust in the provenance of the code, it can confidently deploy the microservice in the more efficient execution environment. Meanwhile, the microservice developer only needed to specify a policy requesting deployment in a Wasm-based container.

To protect the integrity of vetting authorities and individual tools, CDI employs trusted execution environment (TEE) technology such as Intel SGX [20, 25] for its hardware-enforced security properties (see §4.3). We summarize the CDI architecture for a simple Wasm-based supply chain in Fig. 1.

4.1 Vetting Authorities

To avoid requiring application principals to have full knowledge of the software supply chain prior to deployment, CDI vetting authorities act as trusted intermediaries between application principals and individual supply chain tools. Specifically, vetting authorities are responsible for certifying that a given tool properly implements or preserves specific security properties in the artifact, e.g., gcc inserts stack canaries into compiled binaries for memory safety.

CDI requires vetting authorities to produce a tool certification $C$ signed with the vetting authority’s signing key $SK_{VA}$ indicating the security properties provided by a given tool:

$$C = \text{Sign}_{SK_{VA}}(T||P)$$

where $T$ is a representation of the tool’s attributes (e.g., name, version, tool owner’s release signing key) including its public report verifying key $PK_T$ and $P$ a string-representation of the certified properties later used for policy enforcement.

In practice, we expect each vetting authority to determine the exact process by which to vet individual software supply chain tools. This vetting process may be as basic as asserting institutional trust in a particular tool or as complex as performing formal verification of tool. However, given the large number of software supply chain tools available to developers and hosting services today, our design assumes that a number different of vetting authorities will be needed to vet different types of tools.

Thus, our design supports creating a hierarchy of vetting authorities akin to how traditional certificate authorities operate
today. A CDI vetting authority VA may thus also certify other vetting authorities establishing a chain of trust between root vetting authorities and tool vetting authorities via a signature chain $SIG_{VA}$, consisting of the following fields:

$$SIG_{VA} = \text{Sign}_{SK_A} (PK_C || SIG_P)$$

where $PK_c$ is the child vetting authority’s public verifying key used to identify the child vetting authority and $SIG_P$ is the parent vetting authority’s signature chain including the signature on VA’s public key $PK_{VA}$. If applicable, a tool certification $C$ will include the vetting authority’s $SIG_{VA}$.

### 4.2 CDI Reports

CDI collects verifiable provenance information about a microservice by generating a CDI report at each software supply chain tool. Each report captures metadata about operation the specific tool performed on its input artifacts to create the output artifacts.

Specifically, after each tool $t$ performs its operation, the tool signs its output, as well as operation-specific metadata, using their report signing key $SK_t$. Specifically, a CDI report $R$ consists of:

$$R = \text{Sign}_{SK_t} (C || SIG_{VA} || M || H(output) || HR_m)$$

where $C$ is a vetting authority certification of the tool and $SIG_{VA}$ is tool’s vetting authority signature chain. $M$ is additional metadata on the operation, which may include configuration information (e.g., compiler flags used), cryptographic algorithms in use, etc. Since the tool output may be very large (e.g., entire compiled binary), a CDI report includes the cryptographic hash of the output, which also provides an additional layer of integrity for the output.

If available, $R$ also includes the hash of each CDI report $R_m$ attached to each input artifact generated by “upstream” tools creating a hash tree that forms a linked provenance chain for the entire software supply chain DAG. This hash tree allows policy engines to validate the end-to-end integrity of the software supply chain, as well as obtain a commitment that the microservice bundle produced at the end of the software supply chain corresponds to the artifact that entered the first operation of the supply chain (e.g., C++ source code).

In practice, validating the full supply chain hash tree may become too costly for cloud providers or orchestrators; we envision allowing application principals to customize provenance validation on a per-operation basis at the orchestrator, or providing a blockchain-based solution to facilitate the retrieval of the provenance chain.

### 4.3 Supply Chain Integrity

The emergence of TEE technologies offer an opportunity to strengthen the integrity of the software supply chain and vetting authorities. Though our approach in CDI is general, we describe a design based on Intel SGX [20, 25]. Intel SGX is designed to protect the confidentiality and validate the integrity of application code and data, even in the face of an untrusted or compromised host by providing a hardware enclave, an encrypted memory region within the address space of a userspace process. To enable integrity checking of enclave code, Intel SGX computes a digitally signed SHA-256 hash of the enclave memory when the enclave is initialized. This signed hash also allows remote parties to authenticate the enclave code via the Intel SGX attestation protocol [23].

By running individual supply chain tools or components and vetting authorities in an Intel SGX enclave, CDI can gain three benefits. First, we can preserve the confidentiality of privacy-sensitive data such as proprietary source code at build time or vetting authority cryptographic keys. Second, vetting authorities can use Intel SGX remote attestation to ensure they are certifying the expected tool, while policy engines may remotely authenticate trusted vetting authorities. Third, Intel SGX can help CDI extend and enforce provenance in hardware as tools and vetting authorities may derive their signing keys within an enclave, binding tool certifications and CDI reports to the specific platform that generated the keys.

### 5 Proof of Concept

We have implemented a prototype of CDI for the WebAssembly build toolchain for the Private Data Objects (PDO) [1] framework for confidential off-chain smart contracts. To preserve data confidentiality, execution integrity and enforce data
access policies defined in the contract, PDO executes smart contracts inside Intel SGX-based contract enclaves.

5.1 Background

Smart contracts are programs that are used to automatically execute an agreement or protocol between multiple parties relying on a decentralized blockchain infrastructure rather than trusted intermediaries for compliance with the agreement [19]. Though used for different purposes, smart contracts architecturally share many similarities with microservices: they typically implement a subset of functionality within a larger application, they are deployed on-demand when an application participant requests a result, and they may only be invoked through a small pre-defined API.

Private Data Objects (PDO) are designed for formalizing data access and update policies through smart contracts. Developers can implement PDO contracts in any programming language that can be compiled into WebAssembly. At runtime, the PDO contract enclave dynamically loads and executes the deployed contract code into the WebAssembly runtime running inside the enclave.

WebAssembly (or Wasm) is a binary format whose programming model mandates built-in code sandboxing. Since Wasm was initially designed for portable execution of code in browsers, being able to isolate different mutually distrusting modules running in the same runtime is a necessary security feature. Thus, the Wasm binary format requires that memory bounds checks to be inserted around modules to prevent cross-module access.

The Wasm runtime used in PDO is based on the WebAssembly Micro Runtime (WAMR) [22], which supports executing both Wasm bytecode as well as ahead-of-time compiled binary code built by a WAMR-specific AoT compiler. Due to the performance gains achieved by running AoT compiled Wasm binaries compared to running interpreted Wasm bytecode, our prototype adds support for loading AoT compiled smart contracts into a PDO contract enclave.

5.2 Validating our Approach

PDO provides an ideal experimental platform for CDI for two reasons. First, the PDO contract enclave represents an example of a lightweight isolated execution environment used in emerging microservice-based deployments today. Second, Wasm’s mandated memory bounds checks allow us to enforce the type of security properties that are expected by the cloud provider to be preserved by the software supply chain, while enabling us to express coarse-grained developer-side security policies. Thus, we believe our CDI prototype demonstrates the feasibility of enabling deployment-time trust establishment and security-oriented deployment through code provenance in a practical scenario.

Experimental platform. To enable the WAMR AoT compiler to generate CDI reports about the compilation of Wasm bytecode into Wasm binary, we built a wrapper around the compiler that computes the SHA-256 hashes of the bytecode input and binary output, records any compiler flags used, and captures these metadata in an ECDSA-signed CDI report. For simplicity, we implemented a simple root vetting authority as a PDO contract that generates an ECDSA signature on another ECDSA key allowing us to take advantage of PDO’s confidentiality and integrity properties to protect the vetting authority’s signing key. Figure 2 describes the architecture of our prototype. We discuss challenges and practical approaches to run our enhanced Wasm AoT compiler as well as other types of software supply chain tools inside an Intel SGX enclave in §6.

In a preliminary performance evaluation, we found that the additional security checks introduced by CDI do not have a significant performance impact on vanilla PDO. That is, the run time improvements we gain by running AoT-compiled smart contracts in PDO compared to running interpreted Wasm contracts remain significant even with CDI enabled.

Security Policy Specification. Our prototype assumes the cloud provider hosting PDO contract enclaves seek to enforce a single security policy: that AoT-compiled Wasm contracts originate from a Wasm build toolchain that preserves Wasm code sandboxing. Thus, for simplicity our prototype accepts two types of host security policies: a default accept-all policy, which essentially acts as a no-op, and a default-deny policy which requires that the provenance of all contracts must be validated before deployment. To avoid requiring a cloud provider to have a priori knowledge of every possible Wasm build toolchain, a default-deny policy must include a set of trusted CDI vetting authorities.

Since PDO runs smart contracts inside of Intel SGX enclaves, we assume an implicit developer policy that requires contracts to be run in a TEE. To enable developers to verify that their contract is deployed using Intel SGX, our prototype relies on the validation mechanism PDO provides.
Policy Enforcement. At contract enclave startup, an integrated CDI policy engine is initialized with the host-specified security policy. Our prototype enables a PDO contract enclave to make a security-oriented deployment decision by validating the provenance of a smart contract bundle. That is, the policy engine intercepts each incoming bundle, and validates three properties using the attached CDI report: 1) That it can establish a chain of trust between the vetting authority that certified the Wasm toolchain (in our case the WAMR AoT compiler) and a trusted root vetting authority. 2) That the CDI report contained in the contract bundle was generated by this certified Wasm toolchain. 3) That the contract binary to be deployed matches the binary indicated in the CDI report. Only if these three properties hold can the contract enclave gain trust that the contract binary contains the required Wasm sandboxing properties in order to safely deploy the contract.

6 Discussion & Future Work

Our proof-of-concept for CDI leaves many open challenges that must be addressed to make our approach practical for emerging distributed applications.

Creating a high-integrity supply chain with TEEs. Porting supply chain tools such as compilers to TEEs often introduces additional adoption complexities. For example, since Intel SGX provides a restricted interface to standard OS features, running a tool such as the enhanced Wasm AoT compiler in our prototype would require significant refactoring efforts. One approach to address this issue is to use a TEE-aware LibraryOS (e.g., [6, 7]) which supports running unmodified applications in the TEE. Nevertheless, given the growing number of TEE technologies (e.g., [2, 21]), important future work includes evaluating a larger set of supply chain tools in TEEs, ensuring interoperability, and providing consistent provenance properties.

Detecting inconsistencies. For application principals with stricter security requirements, validating a single version of the full provenance chain may not be sufficient to establish trust in a microservice bundle. We envision addressing this issue with a protocol extension that allows principals to specify a threshold number of signatures by trusted vetting authorities on specific supply chain operations to increase their confidence in the trustworthiness of a tool’s output. For example, a cloud provider may require that 3 out of 5 of its trusted vetting authorities sign a Wasm compiler’s report certifying that it preserves Wasm sandboxing.

Making policy specification practical. CDI must ultimately enable data owners and developers to express concrete yet platform-agnostic policies and to map these to fine-grained cloud provider requirements. We have been exploring human-readable security tags such as CODE_SANDBOXING or CONFIDENTIAL_EXECUTION, which can be mapped to security properties like Wasm memory bounds checks in code or specific TEE hardware. However, since this approach would require identifying an exhaustive list of enforceable security requirements, which is likely intractable, a more flexible and expressive policy specification process is needed.

Preserving security requirements in scheduling. Security-oriented orchestration ultimately requires the orchestrator to make scheduling decisions based on the performance and security tradeoffs between different combinations of available hardware security features (e.g., VM vs. TEE) and target execution environments (e.g., container vs. lightweight runtime). In addition, the performance impact that certain higher-level security requirements may have on resource utilization (e.g., single-tenancy for a workload) must be captured as part of the node selection decision. Identifying techniques to address this major challenge is a crucial next step.

7 Summary

We have introduced the concept of security-oriented orchestration, which ensures that microservice deployments meet multi-principal security requirements. To enable such orchestration, we have presented CDI (Code Deployment Integrity) a security policy framework that captures provenance metadata about the software supply chain that created a microservice. By validating and establishing trust in the provenance of a microservice, CDI provides an orchestrator with assurances about the security properties of the code, allowing it to enforce security policies prior to deployment.

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