Infrastructure as Code for Dynamic Deployments

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ABSTRACT

Modern DevOps organizations require a high degree of automation to achieve software stability at frequent changes. Further, there is a need for flexible, timely reconfiguration of the infrastructure, e.g., based on application load to use pay-per-use infrastructure efficiently. Infrastructure as Code (IaC) is the DevOps tool to automate infrastructure. However, modern *static IaC* solutions only support infrastructures that are deployed and do not change afterward. To implement infrastructures that *dynamically* change over time, static IaC programs have to be (updated and) re-run, e.g., in a CI/CD pipeline, or configure an external orchestrator that implements the dynamic behavior, e.g., an autoscaler or Kubernetes operator. Both do not capture the dynamic behavior in the IaC program, preventing analysis and testing of the infrastructure configuration that also accounts for its dynamic behavior.

To fill this gap, we envision *dynamic IaC*, which augments static IaC with the ability to define dynamic behavior within the IaC program. In contrast to static IaC programs, dynamic IaC programs run continuously, notice when external signals change, then re-evaluate the parts of the program depending on the signal, and automatically adjust the infrastructure accordingly. We implement $\mathsf{D}_{\mathsf{IaC}}$ as the first dynamic IaC solution and demonstrate it in two realistic use cases of broader relevance. With dynamic IaC, becoming convinced that the program is correct is even harder to achieve but, at the same time, more important than for static IaC because programs may define many target configurations in contrast to only a few. To improve this situation, we propose automated, specialized property-based testing for IaC programs and implement it in ProTI.

CCS CONCEPTS

• **Software and its engineering → Orchestration languages**; *Cloud computing*; Architecture description languages.

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1 INTRODUCTION

DevOps organizations unite development and operations in cross-functional teams to improve their *Software Delivery and Operational* (SDO) performance [12]. They aim at producing stable software (Dev) with reliable operations (Ops), requiring automation along the whole software delivery pipeline. In these efforts, the tool to automate infrastructure management is *Infrastructure as Code* (IaC) [22].

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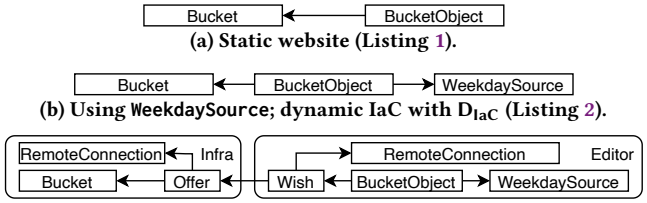
Early IaC solutions, e.g., Ansible [4] and Chef [7] used imperative scripts. Later, in *declarative* solutions, e.g., Puppet [28], developers only describe the desired infrastructure state and the tool automatically derives the required actions to achieve it. Declarative IaC is often preferred because it promises better adaptability and robustness. More recent IaC solutions focus on declarative provisioning of virtualized cloud infrastructure. In AWS CloudFormation [3], ARM [21], and Terraform [15] developers describe the infrastructure in JSON, YAML, or similar tool-specific DSLs, e.g., HCL and Bicep. The AWS Cloud Development Kit (AWS CDK) [34] and CDK for Terraform (CDKTF) [14] allow to generate AWS CloudFormation and Terraform programs from IaC programs written in a general-purpose programming language. Thus, they are limited to the abilities of the underlying tools' JSON, YAML, or HCL DSLs. In contrast, Pulumi [26] performs the operations itself, enabling intertwined IaC program execution and deployment operations. This approach allows, e.g., arbitrary computations based on a resource's post-deployment configuration to configure other resources, providing a more integrated user experience. In this project, we focus on the most recent generation of IaC solutions, leveraging (imperative) general-purpose programming languages like Go, Python, or TypeScript to declaratively define the desired infrastructure state.

The core abstraction in all common declarative IaC solutions is the typed, directed, acyclic resource graph [44] (examples in Figure 1). Nodes are resources, i.e., deployable units like servers, files, or policies. Arcs are dependencies, typically describing *depends-on* or *contained-in* relationships. The arcs constrain the order in which resources have to be (un)deployed, i.e., a resource may only be deployed after all resources it depends on are available and must be undeployed before any of them. E.g., a server must exist before a file on it, and the file must be deleted before the server.

Today's IaC solutions implement *static IaC*, where the resource graph is static, i.e., the IaC program runs once, terminates, and the infrastructure remains unchanged until the next execution. To achieve dynamic infrastructure behavior, developers have to fall back on external tools like CI/CD pipelines or dynamic infrastructure resources like Kubernetes operators. They either re-run the IaC program with changed configuration or statically configure a dynamic orchestrator. This prevents central, holistic analysis and testing of the infrastructure configuration and its dynamic changes.

To solve this issue, we envision *dynamic IaC*, allowing to describe dynamic infrastructure behavior in the IaC program, i.e., expressing dynamically changing resource graphs. For instance, to efficiently use pay-per-use infrastructure, developers could define that the infrastructure is different based on the load (i.e., an external signal), implementing automatic reconfiguration in the dynamic IaC program. In our previous work on automating the coordination of deployments, a topic that is motivated by our survey with 134 IT professionals [38], we already proposed an early, specialized



(a) Static website (Listing 1).

(b) Using `WeekdaySource`; dynamic IaC with D_{IaC} (Listing 2).

(c) Decentralized and coordinated through dynamic IaC (Listing 3).

Figure 1: Resource graphs of the website IaC programs.

dynamic IaC solution [36]. In our work on how to update components in modern distributed systems such that no distributed transaction breaks [37], we discussed another inherently dynamic infrastructure topic. Building upon these works, we develop the general dynamic IaC solution D_{IaC} (Section 4). We discuss D_{IaC} in both use cases that we studied in depth (Section 5), and evaluate its performance, comparing to Pulumi and AWS CDK (Section 7).

Dynamic IaC amplifies the need for easy and thorough testing because developers have to be confident that all infrastructure configurations their dynamic IaC program may result in are correct—in contrast to static IaC programs, targeting only a single or few infrastructure configurations. Current testing of modern IaC programs is limited to standard unit testing (before deployment), property testing (during deployment), and integration test (after deployment) [27]. Property and integration testing is potentially costly and slow. Unit testing is typically example driven and effortful because developers have to mock all resources manually.

To close this gap, we propose ProTI (Section 6), a specialized, automated tool for property-based testing [11] (a technique pioneerd by QuickCheck [8]) of static and dynamic IaC programs. ProTI automatically runs IaC programs in many different configurations before deployment, allowing out-of-the-box quick but thorough termination testing. Further, ProTI is an easy way to thoroughly check application-specific properties in IaC programs. We plan to evaluate ProTI on all publicy available Pulumi TypeScript programs on GitHub, and all IaC programs used in this project (Section 7).

2 RELATED WORK

Infrastructure as Code. Rahman et al. [29] provide a systematic overview on IaC research. Guerriero et al. [13] found out through interviews that pracitioners need better support and tooling for IaC program maintenance and evolution. Various works studied problems, code smells, evolution, and proposed linters for Ansible, Chef, and Puppet [24, 25, 30, 31, 33, 35]. Previous IaC research clearly focused on CaC solutions. This work focuses on modern declarative IaC for virtualized cloud infrastructure, including provisioning.

Resource Orchestration. Weerasiri et al. [43] give an overview on cloud resource orchestration techniques, Ranjan et al. [32] on the programming of resource orchestration operations, and COPE [20] is a distributed policy enforcement engine for resource orchestrators. Plenty of industrial grade cloud resource orchestrators exist, e.g., Kubernetes and Mesos. Resource orchestration is about achieving infrastructure setup and changes. In contrast, IaC is about how developers configure the infrastructure. IaC solution runtimes are or use resource orchestrators when running IaC programs.

Listing 1: Static website showing the weekday in Pulumi.[1]

```
1.1 const bucket = new aws.s3.Bucket("website", {
1.2     website: { indexDocument: "index.html" } });
1.3 const today = getWeekday(new Date());
1.4 new aws.s3.BucketObject("index", {
1.5     bucket: bucket, key: "index.html",
1.6     contentType: "text/html; charset=utf-8",
1.7     content:     `<!DOCTYPE html>${today}` });
```

Modelling Languages. Wurster et al. [44] proposed EDMM as least denominator metamodel for IaC solutions, and mapped it to a subset of TOSCA [45]. TOSCA [23] is an OASIS standard for cloud modeling, Bellendorf and Mann [6] provide an overview on related research and tools. TOSCA separates static, declarative topology (i.e., resource graph) descriptions from imperatively described dynamic infrastructure behavior, e.g., in BPMN workflows. In contrast, dynamic IaC with D_{IaC} allows to define the dynamic behavior declaratively united with the resource graph description.

Architecture Description Languages (ADLs). ADLs on various levels have been proposed, e.g., ArchJava [2] on software component level and ORS [19] on the service level. Other work allows to constrain such definitions [39]. ADLs allow to describe and verify architecture. However, in contrast to IaC, they are not executable specifications and typically do not cover dynamic behavior.

3 STATIC INFRASTRUCTURE AS CODE

To illustrate the difference between static IaC and dynamic IaC, we discuss a website deployment: A static HTML page that shows the weekday, hosted in an AWS S3 bucket. Listing 1 is the website's IaC program in Pulumi TypeScript, constructing the resource graph in Subfigure 1a. Lines 1.1 and 1.2 define the S3 bucket hosting the website. Line 1.3 assigns the current workday as string to the constant `today`, which is used in the content of the `index.html` page that is an object within the bucket (Lines 1.4 to 1.7).

After executing this IaC program, the website displays the correct workday. However, the webpage will be wrong the next day because Pulumi is static IaC, i.e., the IaC program executes once, terminates, and the infrastructure does not change afterward. With static IaC, users have two options to ensure that the website displays the correct weekday every day.

First, implementing the dynamic behavior externally, e.g., a CI/CD pipeline re-runs the IaC program every day. This separation of static and dynamic concerns may be wanted in some use cases. Nevertheless, in many use cases a holistic view and possibility to analyze and test jointly is beneficial (cf. Sections 4 and 6).

Second, implementing the dynamic behavior in infrastructure that is configured statically. E.g., AWS could offer a specialized bucket object resource that replaces every occurrence of the string `$$WEEKDAY$$` in the content with the current weekdy whenever the object is accessed. Such a resource would enable the static configuration of the website, e.g., removing Line 1.3 and replacing the content value in Line 1.7 with `"<!DOCTYPE html>$$WEEKDAY$$"`. However, the infrastructure provider has to support the desired dynamic behavior. Unsupported dynamic behavior cannot be implemented.

[1] For brevity, imports, export, and the bucket policy to allow public access are omitted.

4 DYNAMIC INFRASTRUCTURE AS CODE

Listing 2 is an alternative IaC program for the weekday website. In contrast to Listing 1, Line 2.2 defines a `WeekdaySource` resource, providing the current weekday in its `today` property. Given an implementation of `WeekdaySource`, Listing 2 is a valid Pulumi program and configures the static infrastructure in Subfigure 1b, achieving the same result as Listing 1. The `apply` method on resource outputs provides access to their values, which are only available after the resource is deployed. E.g., apply in Line 2.3 provides the weekday value in the inline function (Lines 2.3 to 2.6). Listing 2 does not generate the dynamically changing value, but retrieves it from a resource. That resource is long-living and knows when the weekday changes. Unfortunately, with Pulumi we can only retrieve the value after deployment and then the IaC program terminates, preventing to react on an update from the `WeekdaySource` to update `index.html`.

To solve this issue, we propose D_{IaC}, an extension of Pulumi TypeScript for dynamic IaC. In D_{IaC}, resource outputs are not limited to values that are resolved once. Instead, they are streams, i.e., values that can change in time. Practically, this means that dynamic IaC programs in D_{IaC} are continuously running—in contrast to static IaC programs in Pulumi that run once and terminate. On the code level, D_{IaC} evaluates and deploys the whole program once, like Pulumi. However, in contrast to Pulumi, D_{IaC} continues watching for updates of resource outputs. Whenever a resource output changes, D_{IaC} re-evaluates the parts of the IaC program that depend on the updated output. If such re-evaluation results in a changed resource graph, D_{IaC} changes the infrastructure accordingly.

This design yields that Listing 2 is already a valid dynamic IaC program for D_{IaC}. Yet, `weekdays.today` is now a stream of weekday strings, not a future-like string that is only resolved once. D_{IaC} executes all code registered to the stream—here, the inline function Lines 2.3 to 2.6—whenever a new value is available. This is first directly after the start of the IaC program and then every midnight when the `WeekdaySource` provides a new weekday value.

At first sight, the solution for dynamic IaC is similar to the opposed workarounds for static IaC (cf. Section 3). Yet, as shown in the example, the dynamic behavior is not externalized, e.g., to the `WeekdaySource`. The external resource is only used as signal to (a) trigger partial re-evaluation and (b) provide new data, i.e., the current weekday. The dynamic behavior—re-configuring *another* resource based on the changed weekday—is encoded in the IaC program, making it a central source for holistic reasoning about the infrastructure, including its dynamic behavior.

5 EXAMPLE USE CASES FOR DYNAMIC IAC

We now present two practical use cases of broader relevance.

Automated Decentralized Deployment Coordination. In modern DevOps organizations, cross-functional teams aim to operate their application(s) as independently as possible. Still, in practice, applications depend on one another, and these dependencies carry on to the applications' (un)deployment. For example, lets consider the "infra" team is responsible for the bucket of the weekday website and the "editor" team for `index.html`. They have to coordinate to ensure that (a) infra always deploys the bucket before editor deploys `index.html`, (b) editor always undeploys `index.html` before infra undeploys the bucket, and (c) editor updates `index.html` when infra changes the bucket. This coordination can be automated with dynamic IaC in D_{IaC}, ensuring the operational independence of the teams. For instance, Listing 3 and Subfigure 1c show both teams' dynamic IaC programs and the resource graphs. They explicitly define their connection to the other deployment (Lines 3a.1 and 3b.1). The infra team *offers* in Line 3a.3 the bucket to the editor team, which explicitly wishes for it (Line 3b.2). The offer is deployed when the wish signals its use and undeployed once the wish confirmed that it is not used anymore. This achieves that `index.html` (Lines 3b.5 to 3b.7) is only deployed when the offer is available, always updated with new weekday values, and undeployed when `wish.offer` indicates the infra team signals it withdraws its offer.

Listing 2: Weekday website using `WeekdaySource` resource.[1]

```
2.1 const bucket = new aws.s3.Bucket("website", { /* ... */ });
2.2 const weekdays = new WeekdaySource("weekdays")
2.3 const weekdays.today.apply((today) => {
2.4     new aws.s3.BucketObject("index", { /* ... */
2.5         content: `<!DOCTYPE html>${today}` });
2.6 });
```

Listing 3: Weekday website decentralized across two independent teams with automated (un)deployment coordination.[1]

(a) The infra team's dynamic IaC program.

```
3a.1 const editor = new RemoteConnection("editor", /* ... */);
3a.2 const bucket = new aws.s3.Bucket("website", /* ... */);
3a.3 new Offer(editor, "bucket", bucket);
```

(b) The editor team's dynamic IaC program.

```
3b.1 const infra = new RemoteConnection("infra", { /* ... */ });
3b.2 const wish  = new Wish<aws.s3.Bucket>(infra, "bucket");
3b.3 const wdays = new WeekdaySource("weekdays");
3b.4 join(wish.offer, wdays.today).apply((bucket, today) => {
3b.5     new aws.s3.BucketObject("index", { /* ... */
3b.6         bucket:  infraBucket,
3b.7         content: `<!DOCTYPE html>${today}` });
3b.8 });
```

Safe Dynamic Software Updating (Safe DSU). Updating software is important, e.g., to fix vulnerabilities or introduce features. However, updating a component in a distributed system may break running distributed transactions. If these transactions are rare and short, they can be repeated. However, if they are frequent or take long, perhaps even days, breaking and repeating them is infeasible. Safe DSU is about identifying *when* a component can be updated such that no transaction breaks, i.e., they do not have to be repeated and interruption is minimal. The safety criterion is *version consistency*: in each transaction a component participates in at most one version.

Safe DSU requires for each component update that sequentially (1) a safe update interval is enforced, then (2) the update is performed, and, after completion, (3) the safe update interval is released. In static IaC programs this protocol cannot be implemented. In contrast, dynamic IaC with D_{IaC} can implement this protocol by (re-)configuring the component's inbound proxies and the component itself based on the comparison of the current and desired component version and the transaction monitoring insights of the component's inbound proxies.

6 TESTING DYNAMIC IAC PROGRAMS

Ensuring IaC programs work correctly is important and dynamic IaC amplifies the need for easy and thorough testing (cf. Section 1). To solve this issue, we propose ProTI, a specialized, automated tool for property-based testing of static and dynamic IaC programs.

ProTI randomly executes the IaC program many times with different values, trying to systemtically find errors. Every resource is replaced with an auto-generated mock. The mocks check that occurring resource input values satisfy their type. Resource outputs are so called *arbitraries*, random generators for concrete values of the outputs' specified types, guided by the testing framework. To replace other non-resource objects with mocks, ProTI provides an annotation. This suffices to randomly execute the IaC program thousands of times with different values, providing out-of-the-box high confidence that the IaC program always terminates. Additionally, users can narrow down expected resource inputs and outputs using annotations providing *application-specific* specifications that ProTI checks against and uses for more precise arbitrary value generation. A first version of ProTI targets static Pulumi TypeScript and dynamic D_{IaC} programs. ProTI's annotations are TypeScript decorators and fast-check [10] implements property-based testing.

For instance, testing the editor team's IaC program (Sublisting 3b) with ProTI runs the program many times. ProTI checks that resource input values comply with their specified type, e.g., only string values are assigned to `content` in Line 3b.7. Arbitrary values are generated for all resource outputs, respecting their type. E.g., `wish.offer` generates different buckets and `undefined`, signaling the offer is unavailable, and `wdays.today` generates random string values. These executions convince us that the program does generally not crash, i.e., it always terminates. Further, we can add application-specific specifications, e.g., by annotating the `content` input in Line 3b.7 with `@inNarrow([/* 7 weekdays */].map((d) => ` <!DOCTYPE html>${d}`))`, narrowing down its accepted values from any string to seven concrete strings. Now the ProTI tests fail, because inference from the type yields that `wdays.today` may provide any string value. To make the tests pass again, `WeekdaySource` in Line 3b.3 must be annotated with `@outNarrow({ today: [/* 7 weekdays */] })`, narrowing down the values of its `today` output.

7 EVALUATION

To evaluate D_{IaC} we first synthesize typical static IaC programs and compare their deployment with D_{IaC}, Pulumi, and AWS CDK, showing that D_{IaC} does not introduce significant overhead. To evaluate D_{IaC}'s dynamic IaC capabilities, we thorougly demonstrate its applicability in the two presented use cases of broader relevance:

To motivate automated coordination of decentralized deployments, we organize a cross-sectional online survey with IT professionals from industry, complying with common standards, including the ACM SIGSOFT guidelines [1, 16, 17]. The survey assesses the state of application dependencies in practice, whether they constrain deployment orders, and how these are coordinated. We then demonstrate in depth on the TeaStore microservices application [42] how dynamic IaC can be leveraged for such deployment coordination. Further, we assess the scaling behavior of the coordination through dynamic IaC using synthetic decentralized deployment benchmarks. To confirm general applicability, we automatically convert all public Pulumi TypeScript projects using stack references to D_{IaC} with automated deployment coordination. Stack references are the only mean in Pulumi to depend on another deployment; however, they do suffice for automated coordination.

For safe DSU, we show how state of the art approaches [5, 18, 37, 40] can be applied to modern workflow applications. First we evaluate this application through discrete-event simulation of updates in all 106 realistic collaborative BPMN workflows from RePROSitory [9]. We then generate dynamic IaC programs in D_{IaC} for these workflows and repeat the experiments using the D_{IaC} dynamic IaC programs, continuous-time simulation for the workflow engines, and Kubernetes for the execution of the workflow tasks. These experiments demonstrate the capabilities of D_{IaC} for safe DSU and its applicability to many realistic applications.

To evaluate ProTI, we apply it to all publicly available Pulumi TypeScript programs on GitHub, showing that it is easy to apply, and that we effectively find termination issues. Additonally, we apply it to the dynamic IaC programs used in our evaluation for D_{IaC}. In contrast to out-of-the-box termination testing, the deeper insight into these case studies allows us to evaluate the applicability of D_{IaC} for checking application-specific properties.

8 CONTRIBUTION AND ACHIEVED RESULTS

By now, research on IaC in the SE community either discussed CaC or modeling. We extend the community's discussion to modern IaC solutions for infrastructure provisioning and configuration, especially solutions leveraging general-purpose programming languages. We further contribute novel ideas in this domain, i.e., for dynamic IaC, testing, deployment coordination, and safe updating.

We organized the *Dependencies in DevOps Survey 2021* [38], answered by 134 IT professionals. The survey revealed that (1) applications often depend on another, (2) these dependencies often constrain the order of (un)deployment operations, and (3) such coordination is typically performed manually, even though (4) automation promises better SDO performance.

We implemented and evaluated μIS ([mju:z] *"muse"*) [36], a dynamic IaC extension of Pulumi [26] using Hareactive [41] for automated deployment coordination. μIS' performance is better than AWS CDK and similar to Pulumi. The scaling behavior is as expected. Existing decentralized Pulumi deployments using stack reference could be converted to it. μIS is the basis for D_{IaC}.

We motivated safe DSU, applied previous approaches to asynchronous workflows, and suggested Essential Safety [37]. The evaluation simulates 106 realistic BPMN workflows from RePROSitory [9], confirming the applicability to workflows on distributed systems. This work is the basis for the proposed evaluation work using Kubernetes and dynamic IaC with D_{IaC}.

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