InsomniHack 2024

Standing on the Shoulders of Giant(Dog)s

A Kubernetes Attack Graph Model

DATADOG

KUBEHOUND

by DATADOG

$ whoami

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$cat /etc/group

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Agenda

01 Introduction

02 The Problem Space

03 The Solution

04 KubeHound In Action

05 Under the hood in a nutshell

06 Development Process Retro

07 Future Vision

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Introduction

Kubernetes, graphs and their combined power

Kubernetes 101

Kubernetes

Open-source container orchestration platform

- Automates the deployment, scaling, and management of **containerized applications**
- High availability and auto-scaling

Container

Lightweight, standalone, and executable software packages

- Encapsulate an application and its dependencies
- **Sandboxed** execution

Pod

Smallest **deployable unit** in Kubernetes

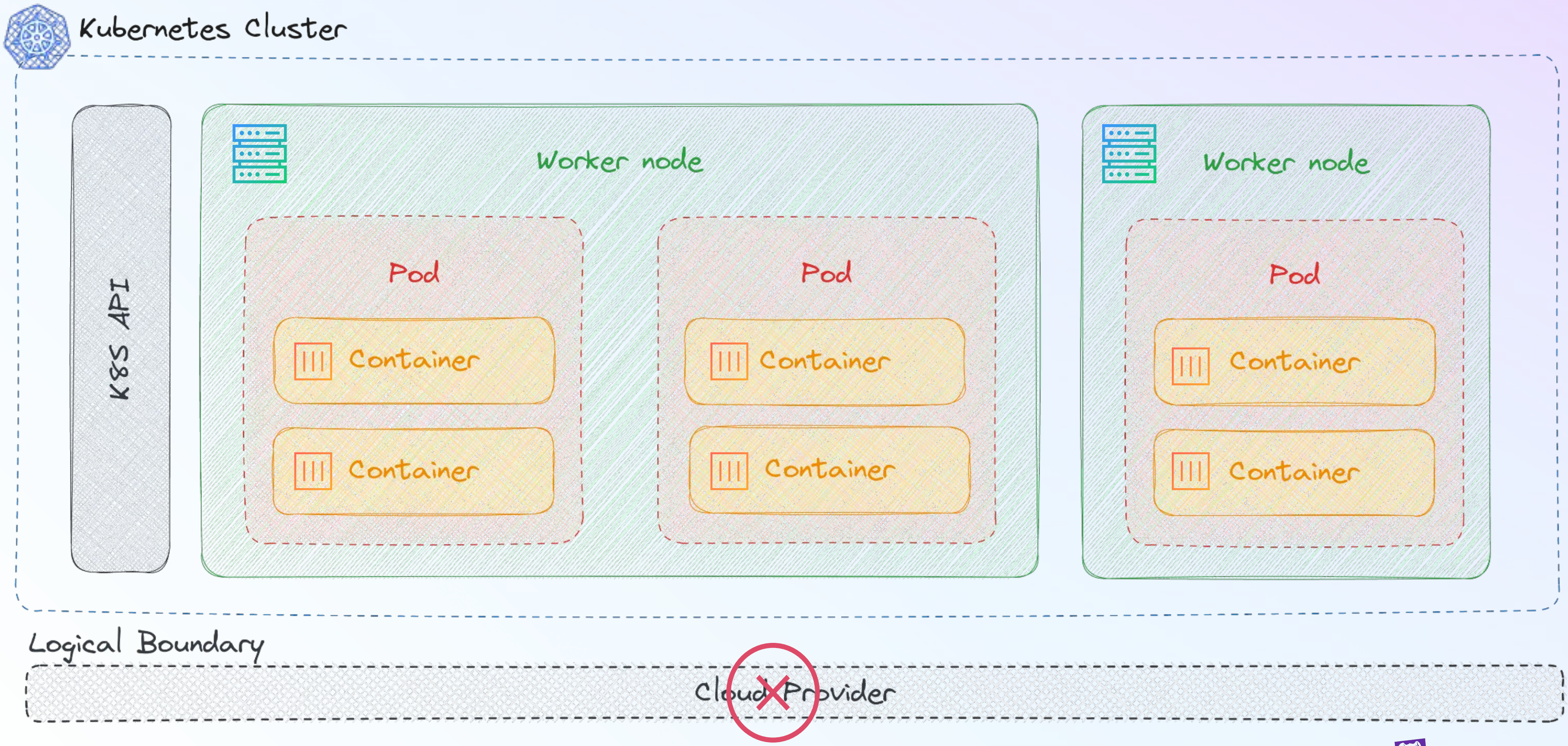
- Contain one or more containers that share the same network namespace and storage volumes
- Designed to run a single instance of an application and are scheduled to *nodes*

Node

Worker **machines** within a Kubernetes cluster

- Host *pods* and provide the necessary resources (CPU, memory, storage) for running containers
- Grouped together in a **cluster**

Kubernetes 101



Kubernetes Security 101

Container escape

Exploit a container misconfiguration to gain node access

- Multiple avenues
- Very **powerful** - grants access to all node resources

Kubernetes Identity

Define **service accounts** (robot), users (humans) and groups (both)

- Service accounts linked to pods

Kubernetes Roles

Set of permissions granted to an identity on specific resources

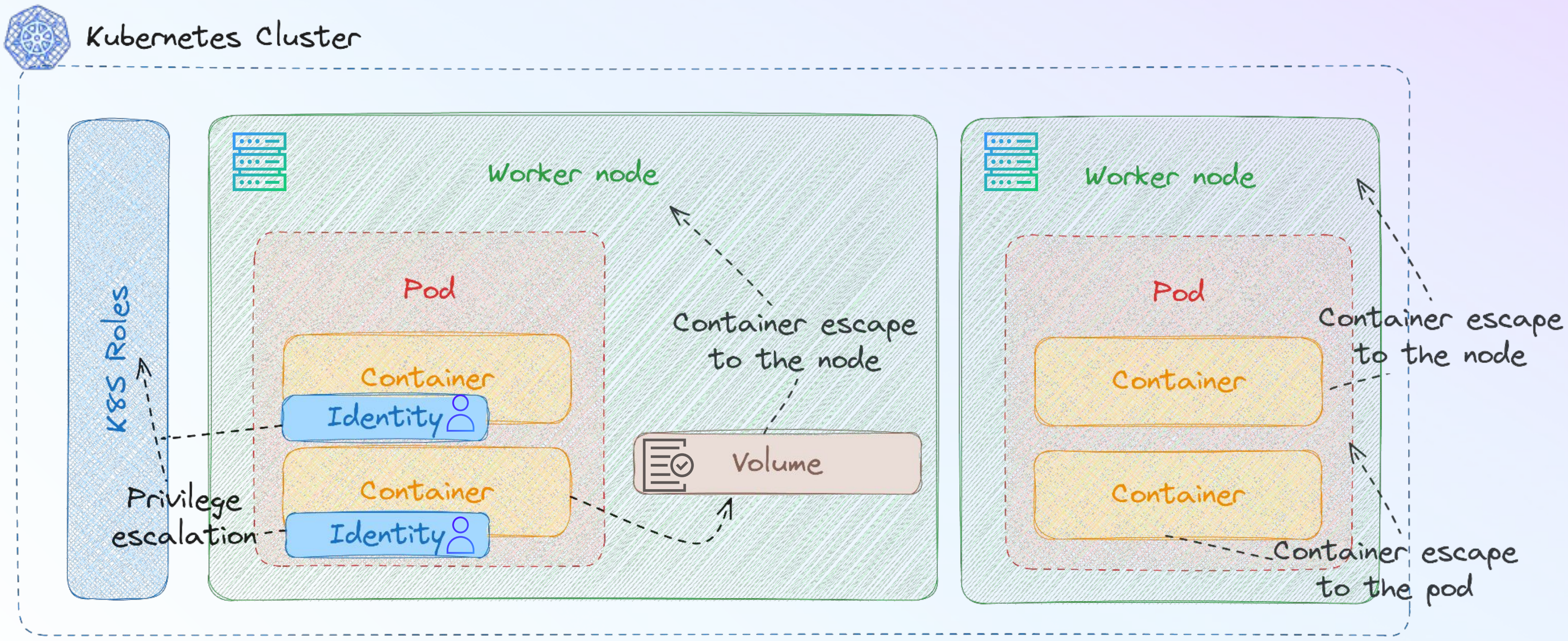
- Addition only (**no deny**)
- Certain permissions are very **powerful** - *secrets/list, pods/exec, etc.*

Mounted Volumes

Node or “projected” directories can be mounted into the container

- Mounting the wrong directory = **container escape**
- Projected directories contain service account **tokens**

Kubernetes Security 101



Of course **there are a lot more attacks path** but we will not have time to cover all of them …

The Problem Space

Scale, complexity and quantifying security

Vulnerability Context

Manual processing takes time

FINDING: Container escape

Web application exposed to the internet running inside a container with `privileged: true`

- Internet facing
- Privilege is not necessary
- Limited auditing

FINDING: Container escape

Control plane DNS container running with `CAP_SYS_MODULE` enabled

- Internal service
- Restricted, audited access
- Privilege is necessary

Can you do it at scale ?

Let’s play a game …

Let’s assume we have a cluster with …

14 **container escapes** are present in my kubernetes cluster.

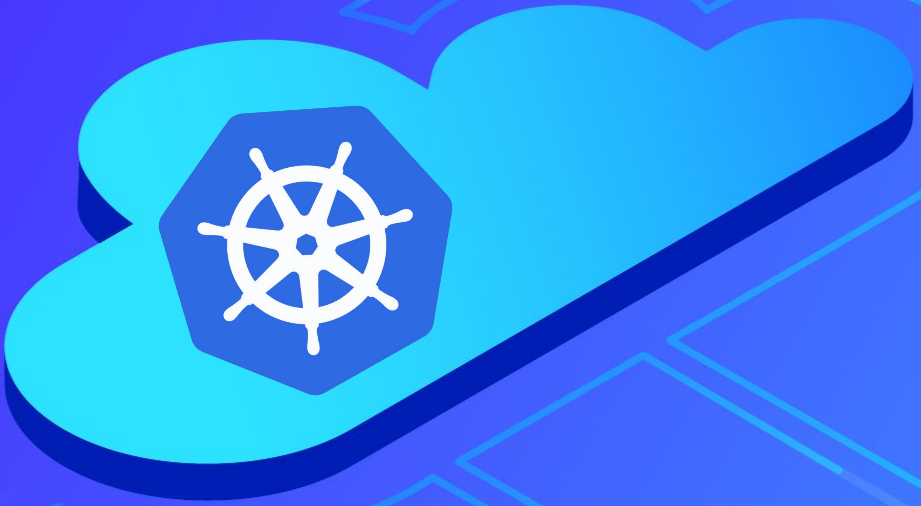
32 **privilege escalations** through RBAC issues.

34 **escape to host** through weak vulnerables volumes configurations.

72 **lateral movement** between containers (Share Process Namespace for instance)

? 🤷 ?

How secure is this cluster ?
(on scale 1 to 10)



April 26, 2015

John Lambert

Corporate Vice President, Security Fellow, Microsoft Security Research

> “**Defenders think in lists, attackers think in graphs**; as long as this is true, **attackers win**.”

Need to Quantify a Security Posture

The old way

List approach

How many vulnerabilities ?

How many misconfiguration ?

How many outdated/CVE ?

The new way

Graph approach

Public facing ?

Can have the most significant impact on my cluster security ?

Lead to a critical attack path ?

Quantifying Security Posture

If you cannot measure it, you cannot improve it

Current state

What is the **shortest exploitable path** between an internet facing service and cluster admin?

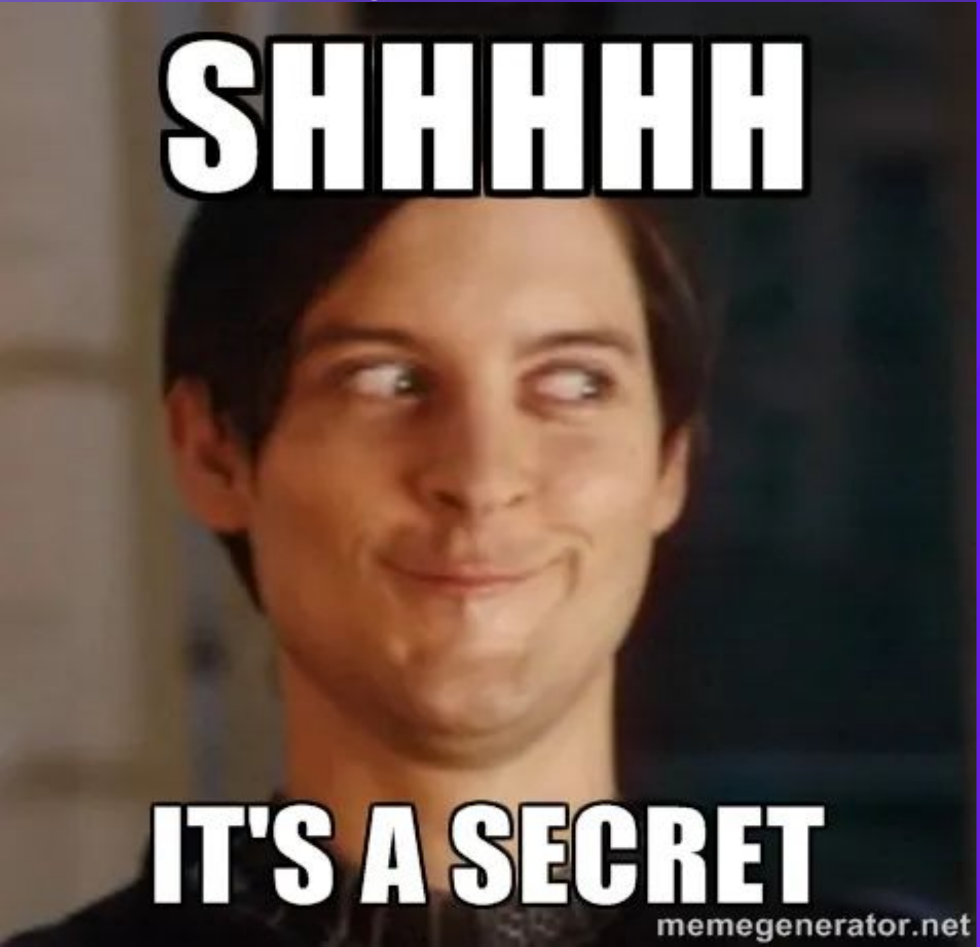
What **percentage of internet-facing services have an exploitable path** to cluster admin?

Measuring Change

What **type of control would cut off the largest number of attack paths** in your cluster?

By what percentage did the introduction of a security control reduce the attack surface in your environment?

Quantifying at scale at Datadog …



Datadog environment is **vast**:

- **“tens of thousands of nodes"**
- **"hundreds of thousands of pods"**
- **“multi-cloud”**

Traditional **penetration testing does not scale** to this level.

Demo

Security metrics calculation

LET'S PRAY
TO THE DEMO GODS
imgflip.com

Quantitative Analysis of Security Posture

Demo time

Can we use KubeHound to answer the question of “how secure is my cluster” and track that metric over time?

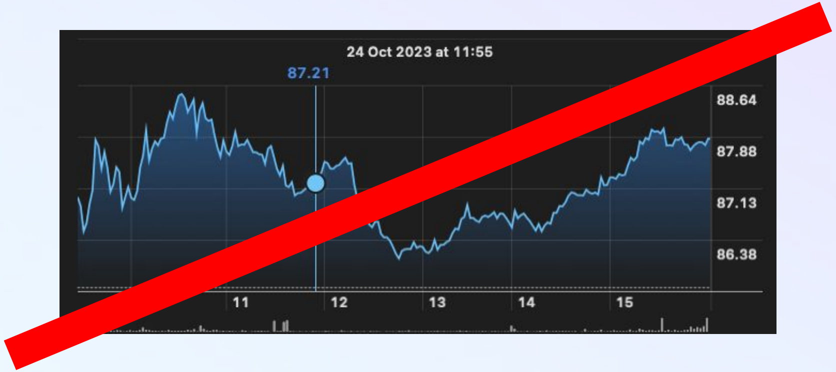
- ✅ Quantifying security posture
- ✅ Democratising offense (reducing from days to instant findings)
- ✅ Exhaustiveness at scale (finding all of the attack paths)

The Solution

Graph theory + **Off**ensive **Sec**urity = KubeHound

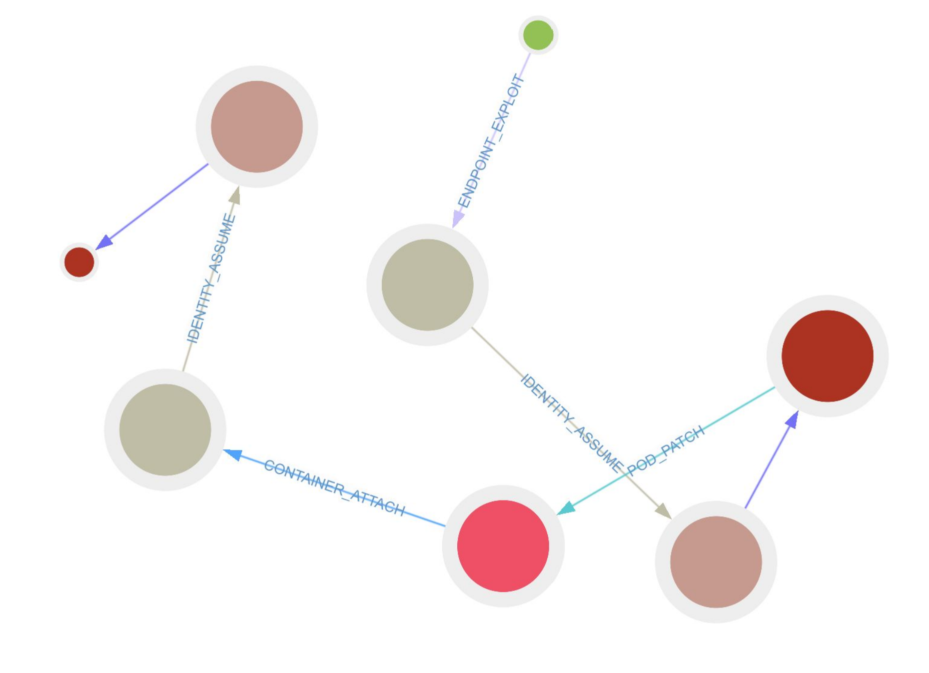
Graph Theory I

Sorry about that …



Graph Theory I

Bla bla bla



> “The study of graphs, mathematical structures used to model pairwise relations between objects.”

Wikipedia

Graph Theory 101

Taxonomy is always important

Graph

A data type to represent complex, relationships between objects.

- In KubeHound: a Kubernetes cluster at a specific time

Vertex

The fundamental unit of which graphs are formed (also known as "node").

- In KubeHound: containers, pods, endpoints, nodes, permissionsets, identity and volumes

Edge

A connection between vertices (also known as "relationship").

- Automates In KubeHound: a container escape (e.g CE_MODULE_LOAD) connects a container and a node

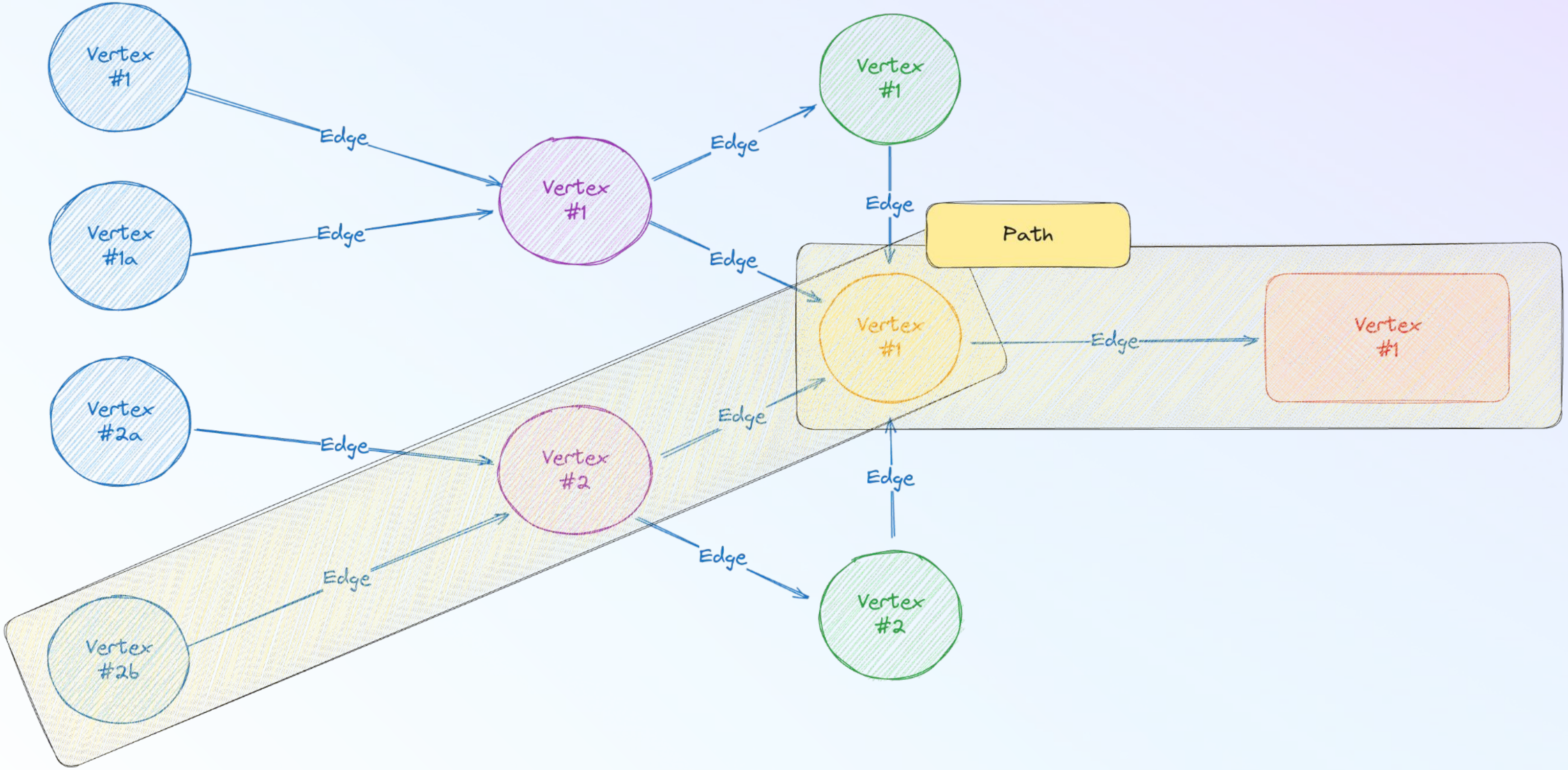
Path

A sequence of edges which joins a sequence of vertices.

- In KubeHound: a sequence of attacks from a service endpoint to a cluster admin token

Graph Theory 101

Sample graph



Why/What is KubeHound ?

Yet another tool …

What is the goal of KubeHound ?

The aim of KubeHound is to identify security gaps and real attack vectors using a **graph** to visualize **attack paths** presents in a Kubernetes cluster.

Why create KubeHound ?

Current Kubernetes auditing tools output security information from clusters in a “list”. There are no links between findings. They cannot produce an attack path like **BloodHound**, which **changed the game of Windows Domain security**.

KubeHound 101

Taxonomy is always important

Entity

An abstract representation of a Kubernetes component that form the vertices of the graph.

- For instance: PermissionSet is an abstract of Role and RoleBinding.

Critical Asset

An entity in KubeHound whose compromise would result in cluster admin (or equivalent) level access

- For now it only covers a subset of roles which are not namespaced (like `cluster-admin` or `kubeadm:get-nodes`).

Critical Path

A set of connected vertices in the graph that terminates at a critical asset.

- This is the treasure map for an attacker to compromise a Kubernetes cluster.

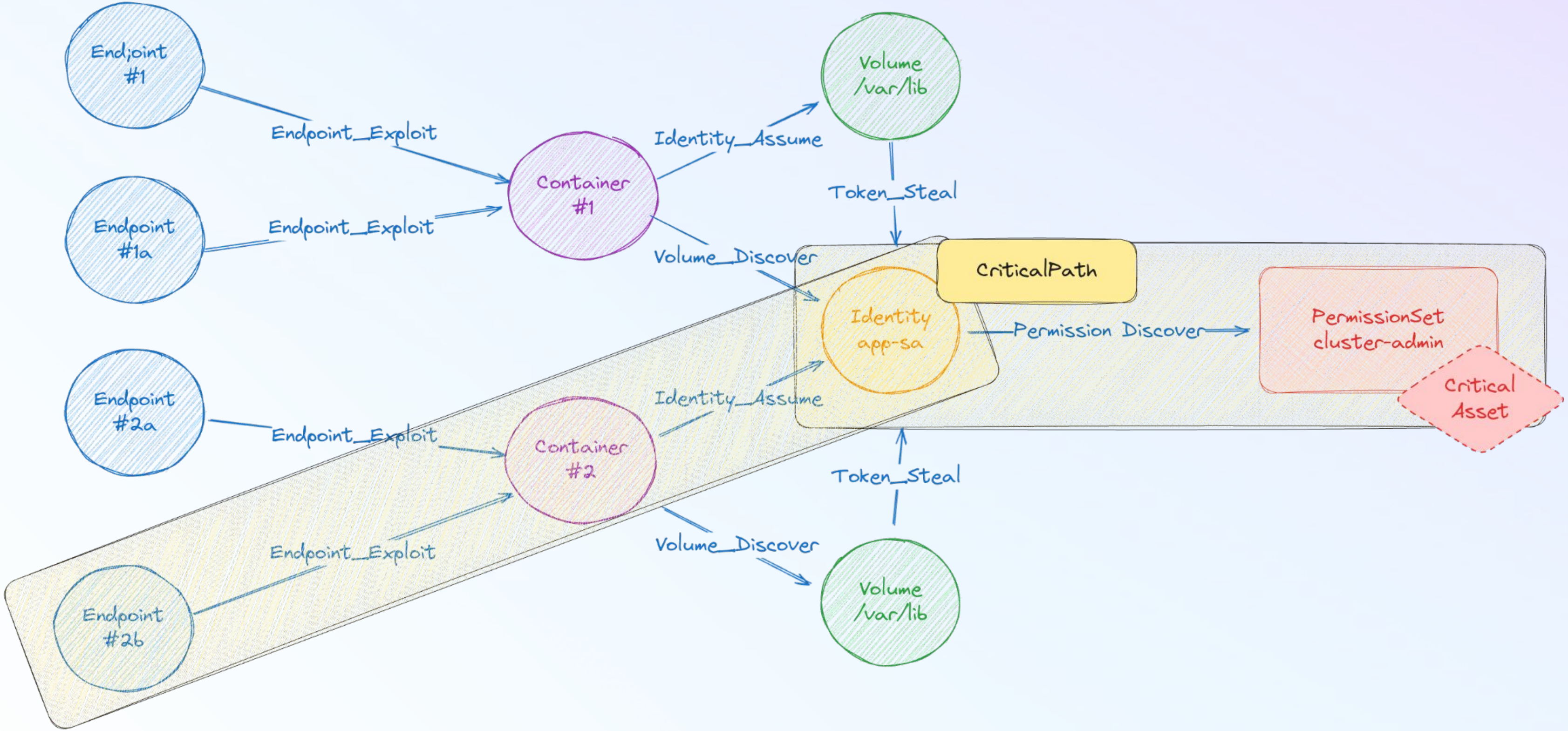
Attacks

All edges in the KubeHound graph represent attacks with a net "improvement" in an attacker's position or a lateral movement opportunity.

- For instance, an assume role is considered as an attack.

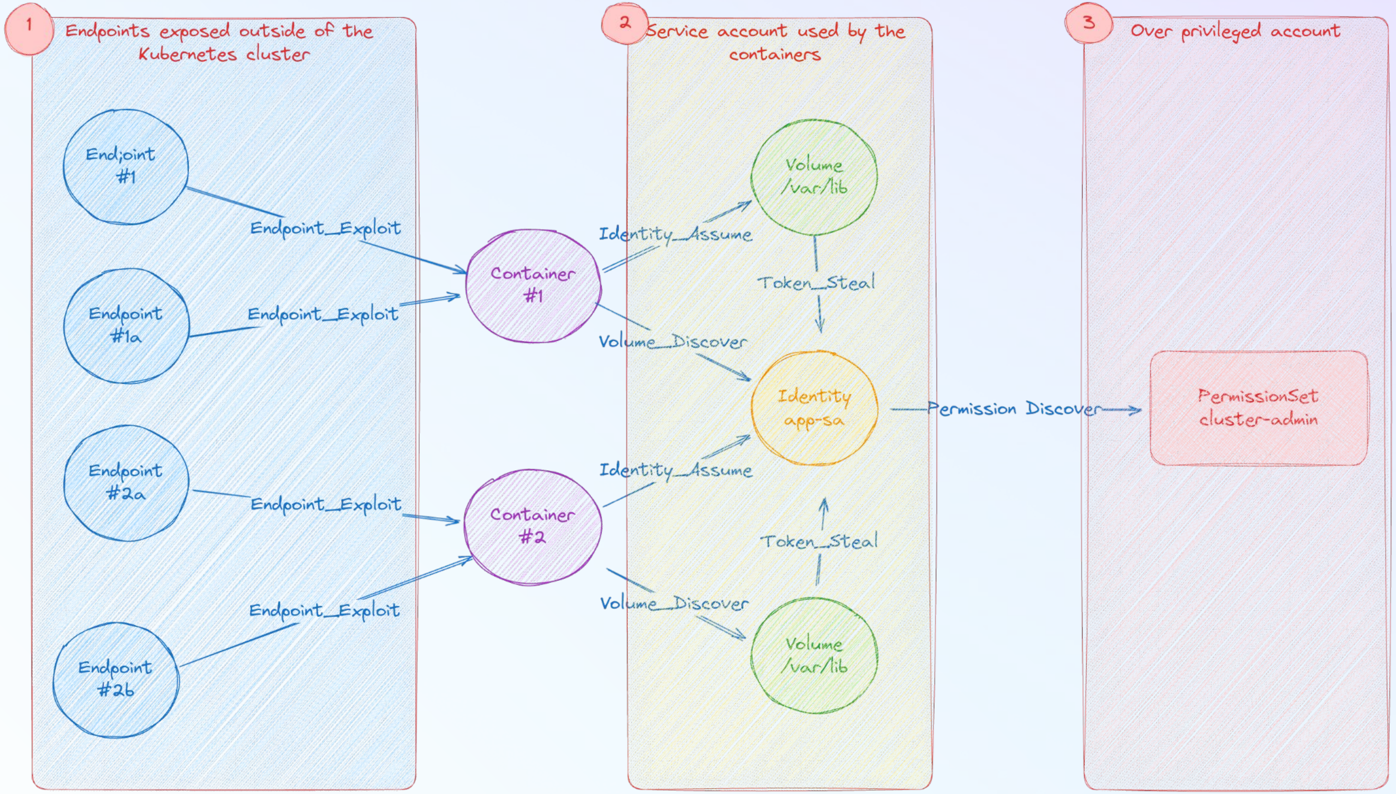
Attack Graphs

Sample graph



Attack Graphs

Sample graph



KubeHound in a nutshell

The best defense is a good offense

Attack Graph

KubeHound creates a graph of attack paths in a Kubernetes cluster, allowing you to identify direct and multi-hop routes an attacker is able to take, visually or through graph queries.

Runtime Calculation

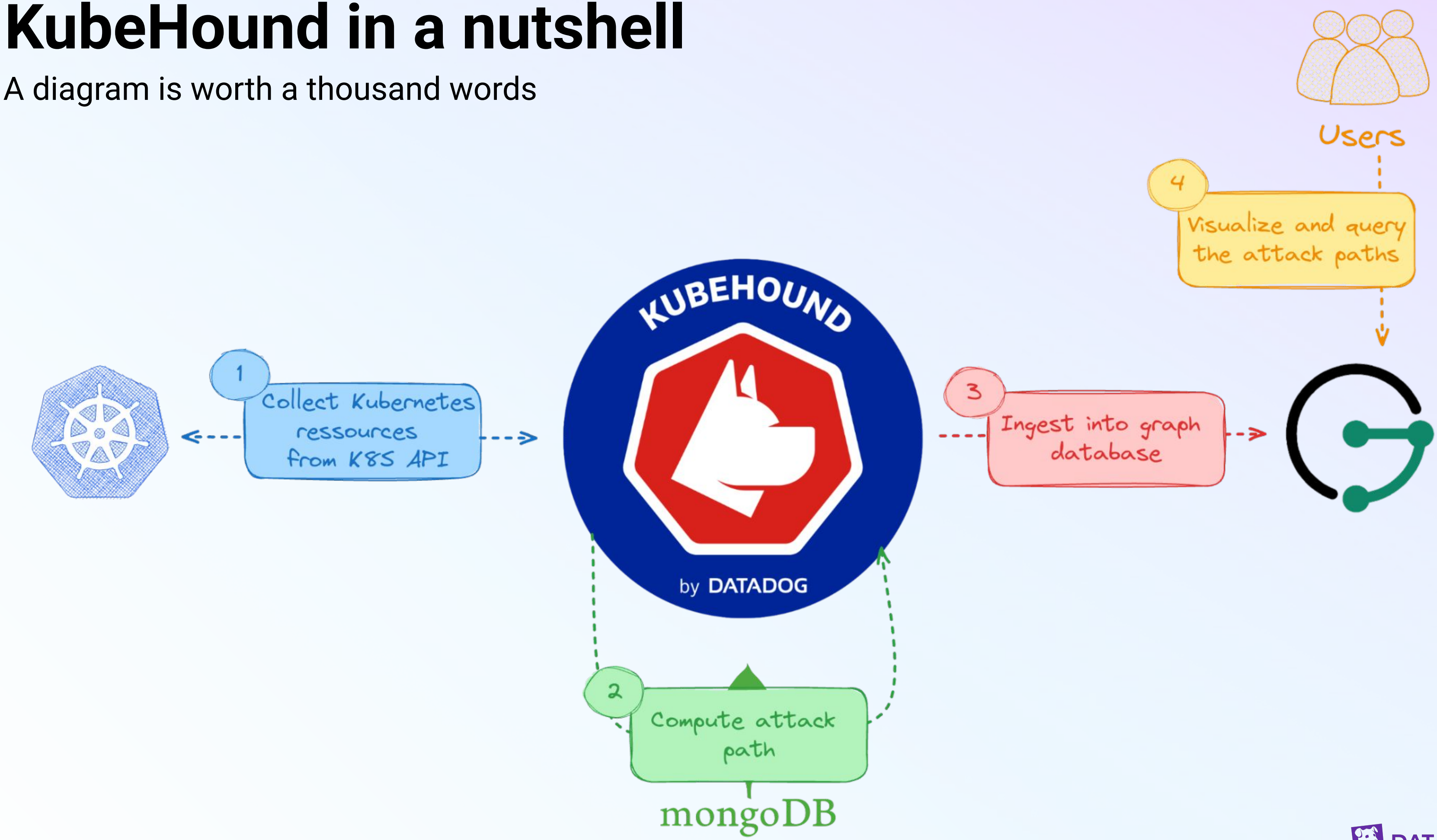
If any entity is connected to a critical asset in our attack graph - a compromise results in complete control of the cluster.

Snapshot

KubeHound analyze a snapshot of your Kubernetes cluster. It dumps all the assets needed to create an “image” of it.

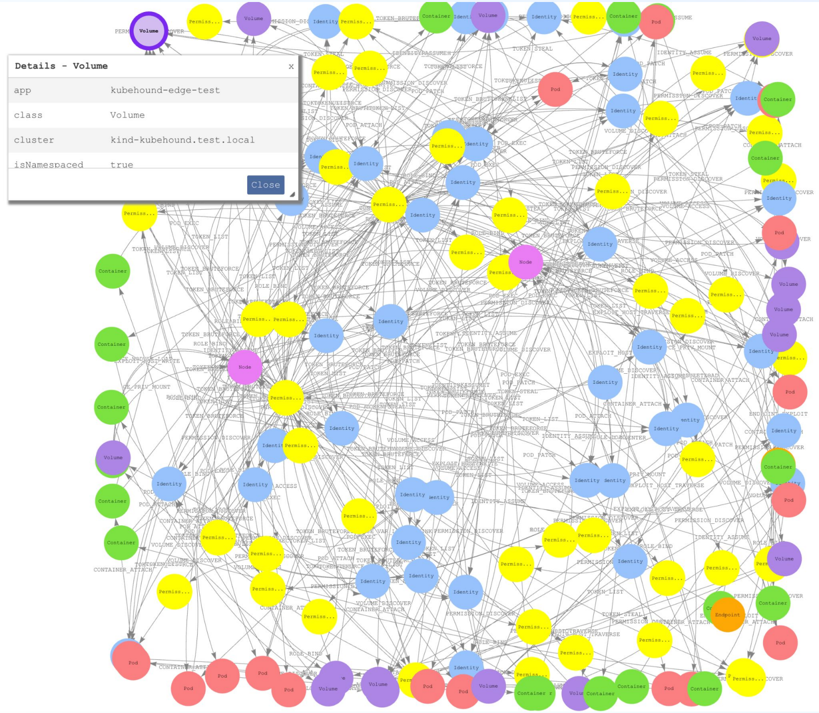
KubeHound in a nutshell

A diagram is worth a thousand words


Users
4
Visualize and query the attack paths
1
Collect Kubernetes ressources from K8S API
KUBEHOUND
by DATADOG
3
Ingest into graph database
2
Compute attack path
mongoDB

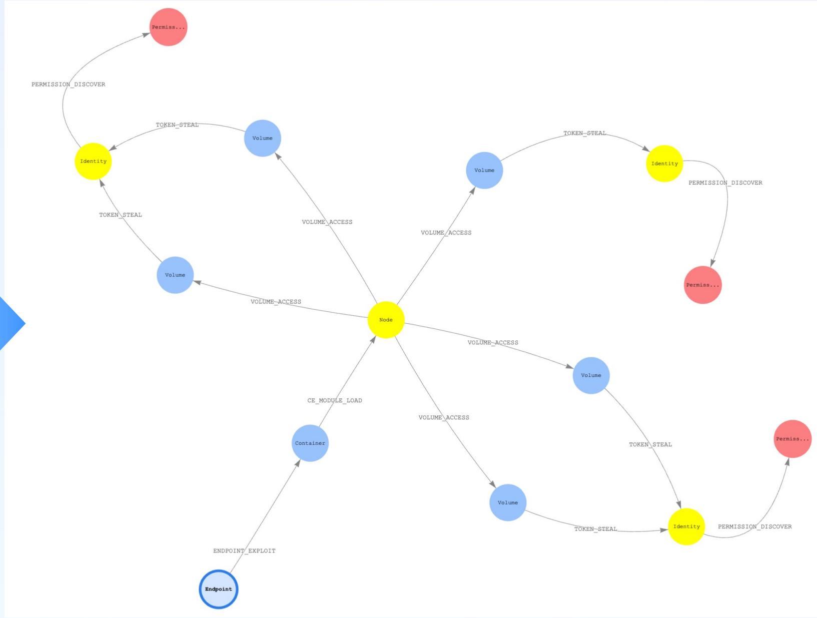
KubeHound in a nutshell

Pinpoint where the security failures are.



Details - Volume ×

app	kubehound-edge-test
class	Volume
cluster	kind-kubehound.test.local
isNamespaced	true



KubeHound in Action

Capability showcase

User Experience (UX)

Gremlin a tough query language

A really powerful language …

All k8s data is being ingested into Janusgraph which is powered by Gremlin a powerful query language.

```
g.V().hasLabel("Pod").dedup().by("name")
```

… but really hard to master

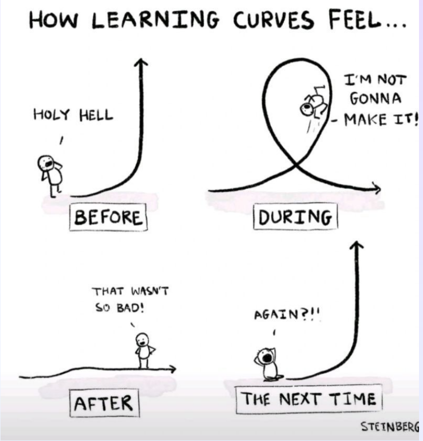
```
g.V().hasLabel("Pod").dedup().by("name")
.repeat(outE().inV().simplePath()).until(
hasLabel("Container").or().loops().is(10).or().
has("critical", true)
).hasLabel("Container").path().tail(local,1).va
lues("name").dedup()
```

KubeHound DSL

UX above all

In order to improve the User Experice (UX) we **developed a custom** Domain **S**pecific **L**anguage (**DSL**) on top of the Gremlin language.

The DSL has more than **20 custom wrappers** that allow a user to generate attack paths really easily.



Raw Gremlin request

```
g.V().hasLabel("Pod").dedup().by("name")
.repeat(outE().inV().simplePath()).until(
loops().is(10).or().has("critical", true)
)has("critical",true).path()
.by(elementMap()).limit(100)
```

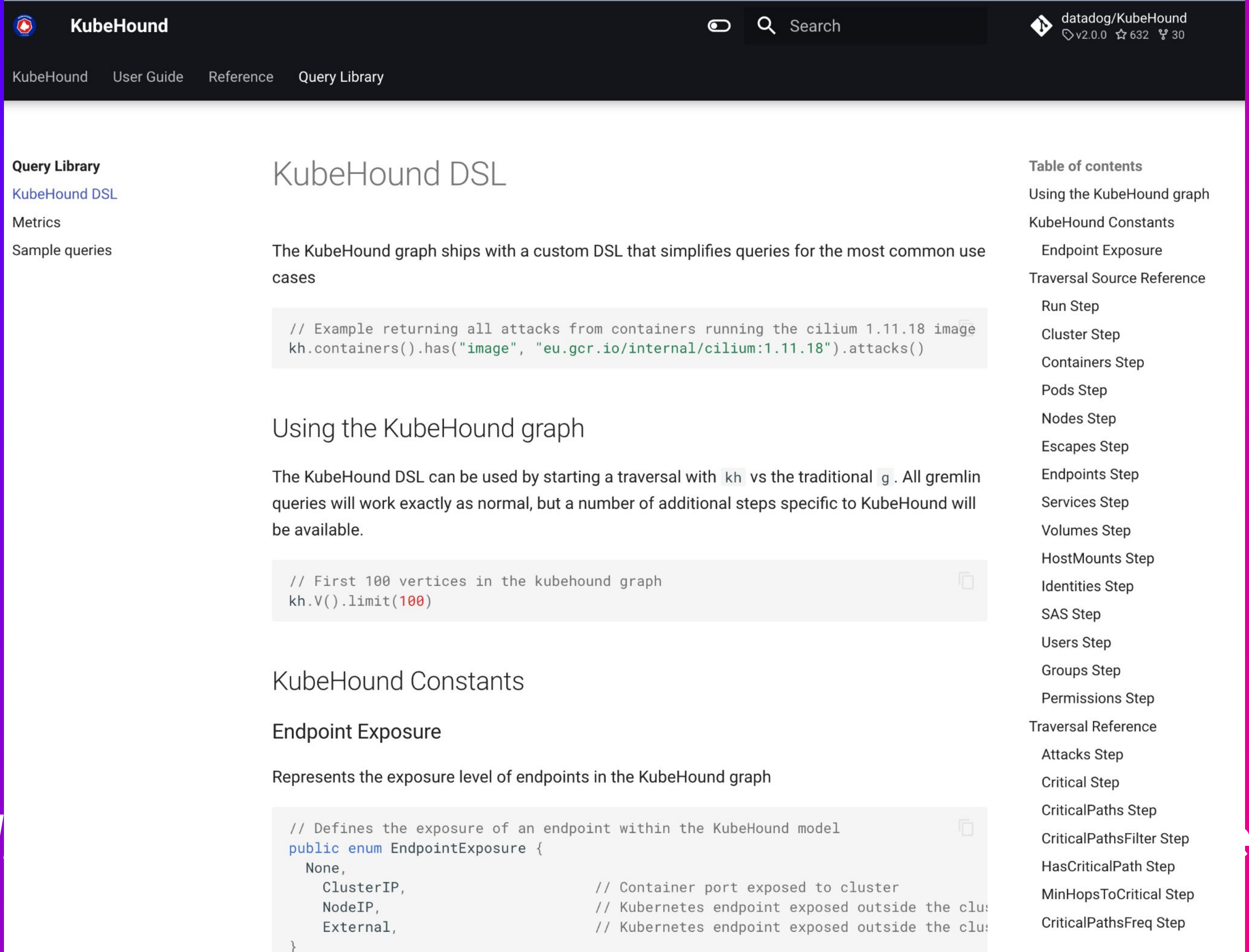
KubeHound DSL equivalent

```
kh.pods().criticalPath().limit(100)
```

Full doc

https://kubehound.io/queries/dsl/

All DSL queries are described with proper examples.



KubeHound DSL

The KubeHound graph ships with a custom DSL that simplifies queries for the most common use cases

```
// Example returning all attacks from containers running the cilium 1.11.18 image
kh.containers().has("image", "eu.gcr.io/internal/cilium:1.11.18").attacks()
```

Using the KubeHound graph

The KubeHound DSL can be used by starting a traversal with `kh` vs the traditional `g`. All gremlin queries will work exactly as normal, but a number of additional steps specific to KubeHound will be available.

```
// First 100 vertices in the kubehound graph
kh.V().limit(100)
```

KubeHound Constants

Endpoint Exposure

Represents the exposure level of endpoints in the KubeHound graph

```
// Defines the exposure of an endpoint within the KubeHound model
public enum EndpointExposure {
  None,
    ClusterIP,                    // Container port exposed to cluster
    NodeIP,                       // Kubernetes endpoint exposed outside the clus
    External,                     // Kubernetes endpoint exposed outside the clus
}
```

Table of contents

Al

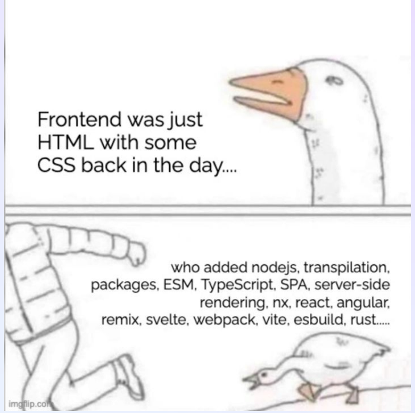
s.

KubeHound UI

Why did frontend development become so complicated?

We tried to avoid creating a fancy/Minority report style UI. **Focus most of our energy on backend and performance**, because we are not frontend developers.

Frontend development is hard, really hard …


Frontend was just HTML with some CSS back in the day....
who added nodejs, transpilation, packages, ESM, TypeScript, SPA, server-side rendering, nx, react, angular, remix, svelte, webpack, vite, esbuild, rust.....
imgflip.com

KubeHound v1.0

Cons:

- Not free anymore
- Lack of prebuilt queries
- Developers oriented
- Not available as a Service (rich client only)

KubeHound v2.0

Pros:

- Share results
- As a Service frontend
- Highly customizable
- Prebuilt queries through notebooks

Demo

From can of worms to critical vulnerability

Fr

lity

From can of worms to critical findings

Demo time

Can we use KubeHound to pinpoint where are the most critical vulnerability and therefore help the remediation team as much as the attacker ?

- ✅ Vulnerability context
- ✅ Democratising offense (reducing from days to instant findings)
- ✅ Exhaustiveness at scale (finding all of the attack paths)

Under the hood

How does this magick happen ?

Simple architecture

Taxonomy is always important

Collector

Collect all Kubernetes objects needed to create the attack path

- There is no filtering (collecting raw elements)
- Multiple input support:
  - k8s API collector
  - File collector
  - etcd collector (not implemented yet)

Ingestor

Pull the data from the collector and ingest them in the database (mongodb for now)

- Parallelized ingestion if no explicit dependencies

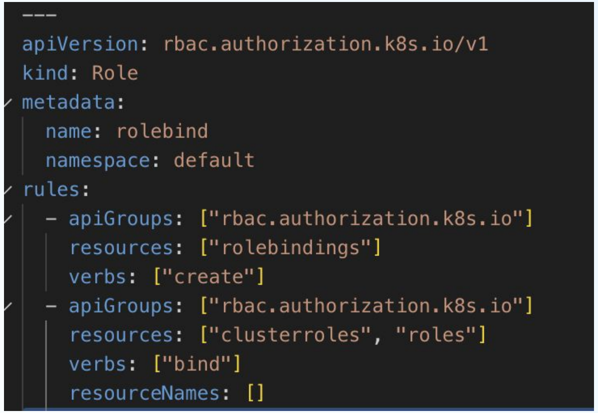
Builder

Query the database to build the graph

- Build the vertices, the “node” representing the elements of the cluster (pod, role, …)
- Build the edges, the relation representing the attacks
  - CE_NSENTER
  - POD_CREATE
  - …

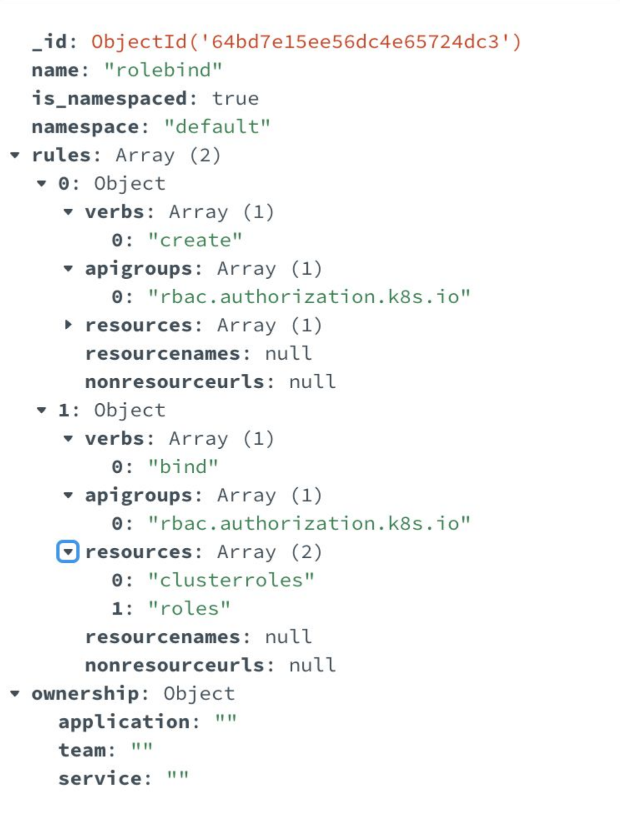
Example:

How the data is being processed



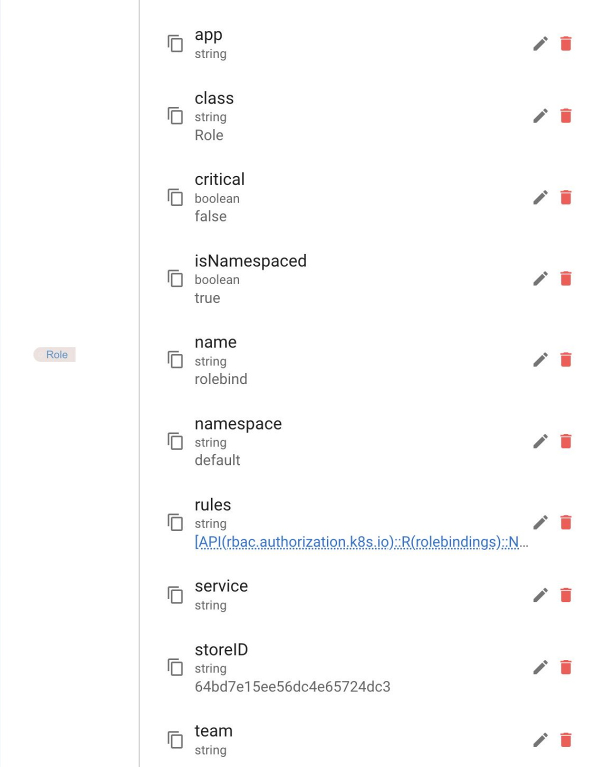
```yaml
---
apiVersion: rbac.authorization.k8s.io/v1
kind: Role
metadata:
  name: rolebind
  namespace: default
rules:
  - apiGroups: ["rbac.authorization.k8s.io"]
    resources: ["rolebindings"]
    verbs: ["create"]
  - apiGroups: ["rbac.authorization.k8s.io"]
    resources: ["clusterroles", "roles"]
    verbs: ["bind"]
    resourceNames: []
```

yaml k8s config file



```
_id: ObjectId('64bd7e15ee56dc4e65724dc3')
name: "rolebind"
is_namespaced: true
namespace: "default"
▾ rules: Array (2)
  ▾ 0: Object
    ▾ verbs: Array (1)
        0: "create"
    ▾ apigroups: Array (1)
        0: "rbac.authorization.k8s.io"
    ▸ resources: Array (1)
      resourcenames: null
      nonresourceurls: null
  ▾ 1: Object
    ▾ verbs: Array (1)
        0: "bind"
    ▾ apigroups: Array (1)
        0: "rbac.authorization.k8s.io"
    ▾ resources: Array (2)
        0: "clusterroles"
        1: "roles"
      resourcenames: null
      nonresourceurls: null
▾ ownership: Object
    application: ""
    team: ""
    service: ""
```

mongodb

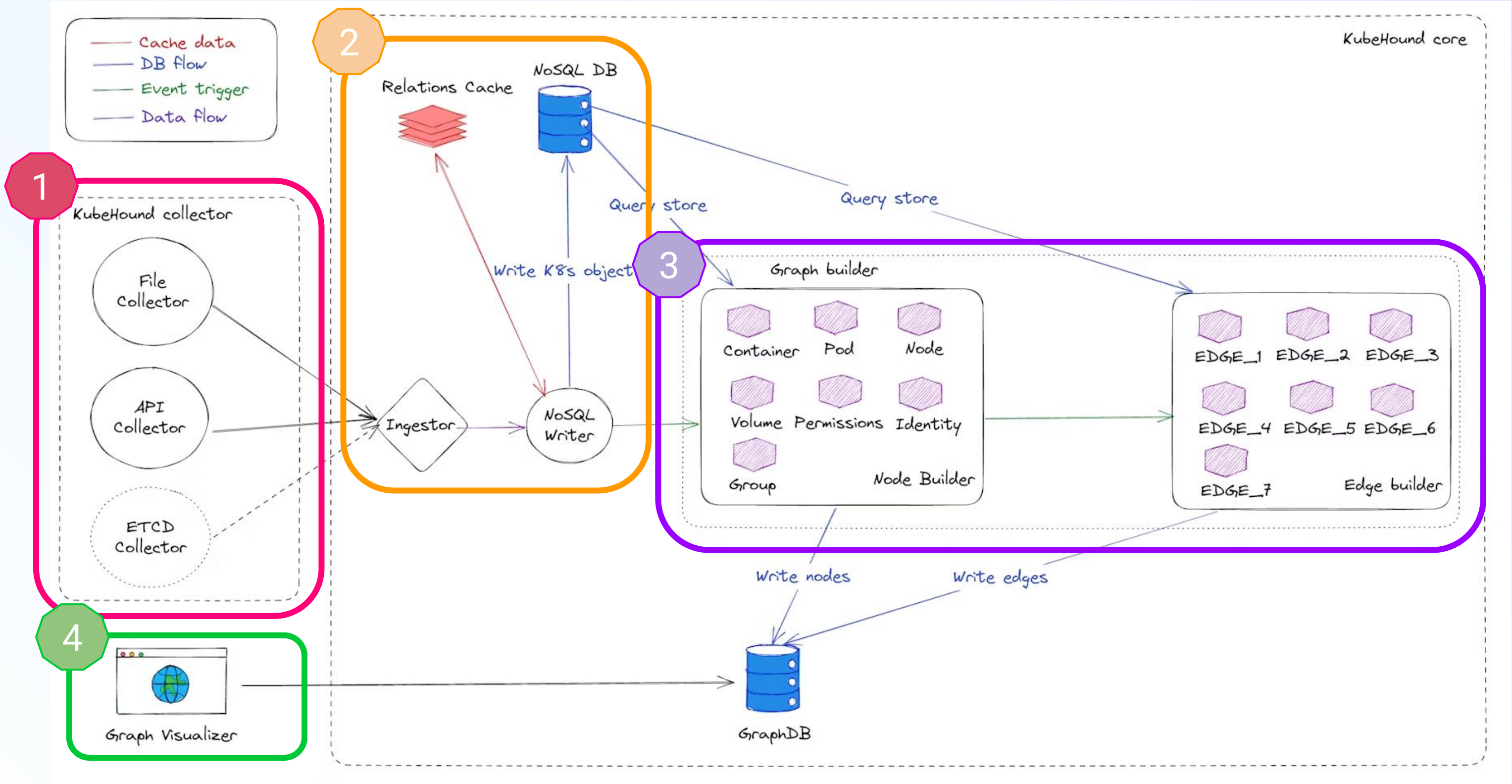


```
app
string

class
string
Role

critical
boolean
false

isNamespaced
boolean
true

name
string
rolebind

namespace
string
default

rules
string
[API(rbac.authorization.k8s.io)::R(rolebindings)::N...

service
string

storeID
string
64bd7e15ee56dc4e65724dc3

team
string
```

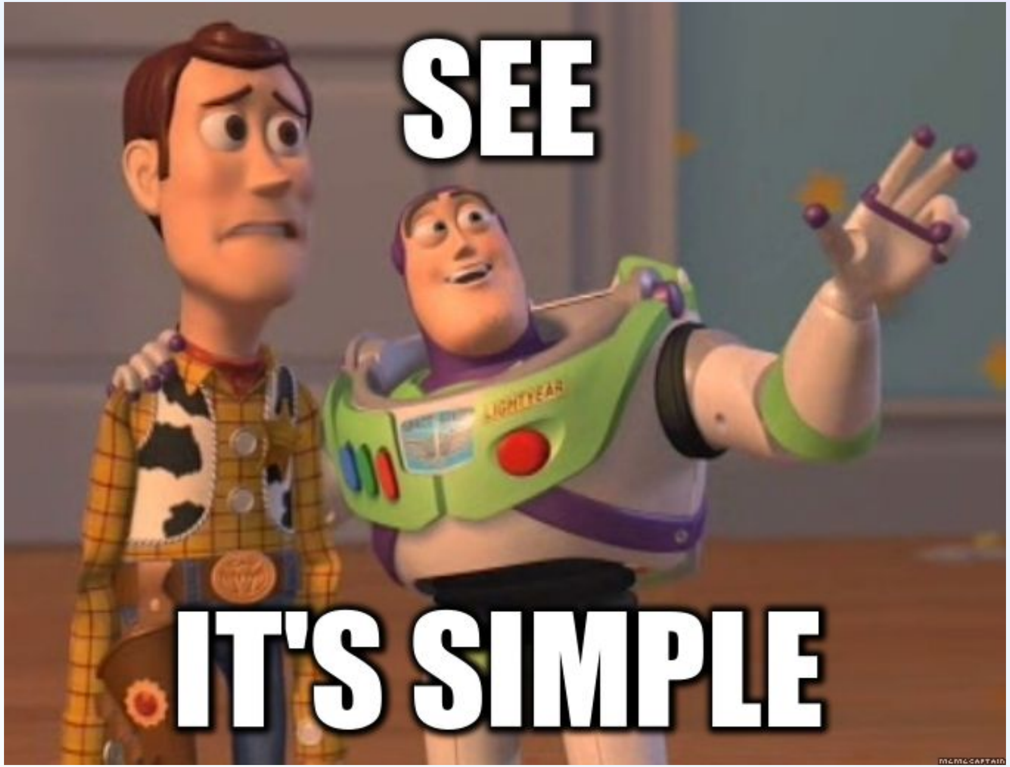
janusgraph

Full architecture

Almost everything

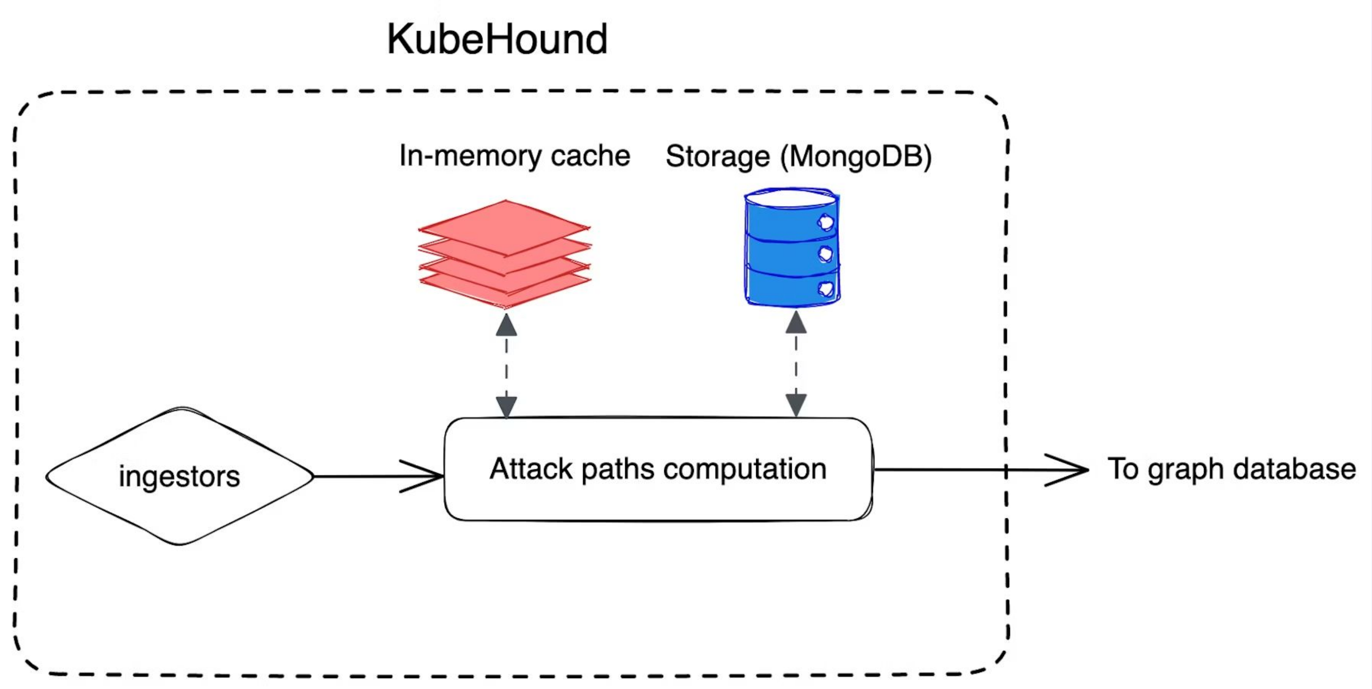


Full architecture



Summarized architecture

Less is better



K8s api collector - Safe to use :)

API rate limit (100 req/sec)

Buffer page size limited (10mb)

Number of element per page limited (500)

Development Process

Research, design, implement, iterate

Why am I talking about this?

Powerful approach

The approach I will outline can be applied to create attack graphs of any systems (AWS, Hashicorp Vault, …)

Step #1: **Research**

Collate, ingest and categorize all the Kubernetes security research.

Step #2: **Design**

Sketch attack components (vertice needed ? properties ?)

Step #3: **Implementation**

Port to graph database

i.e. RBAC

> “Compromising Kubernetes Cluster by Exploiting RBAC Permissions”
>
> CyberArk @ RSAC 2020

23 blog articles

12 Hours of Youtube

12 PoC

RESULTS

With the study of RBAC attacks, we added 11 attacks in KubeHound’s model.

Research

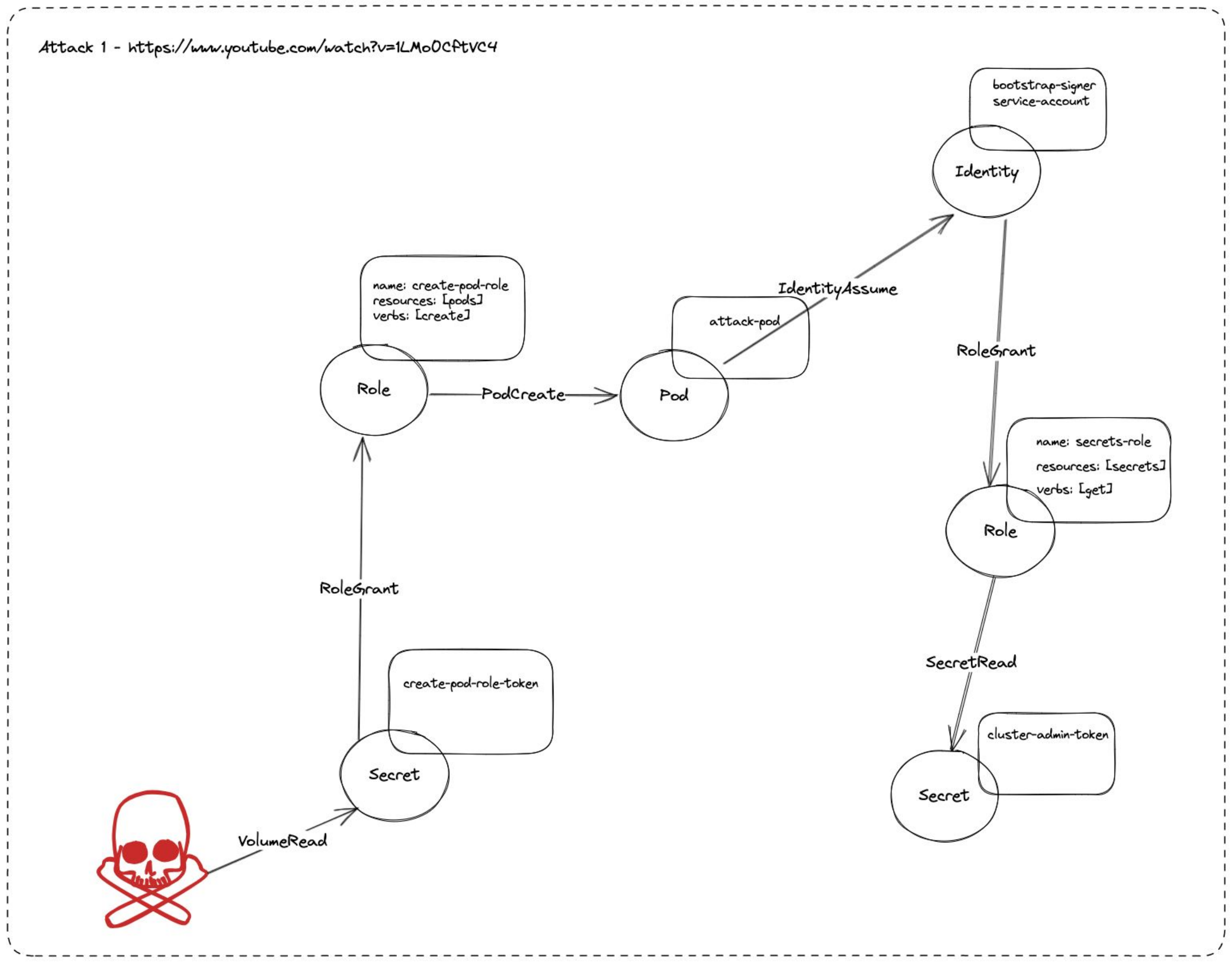
Reading a lot the official Kubernetes documentation and PoCing locally to test our assumptions.

Design

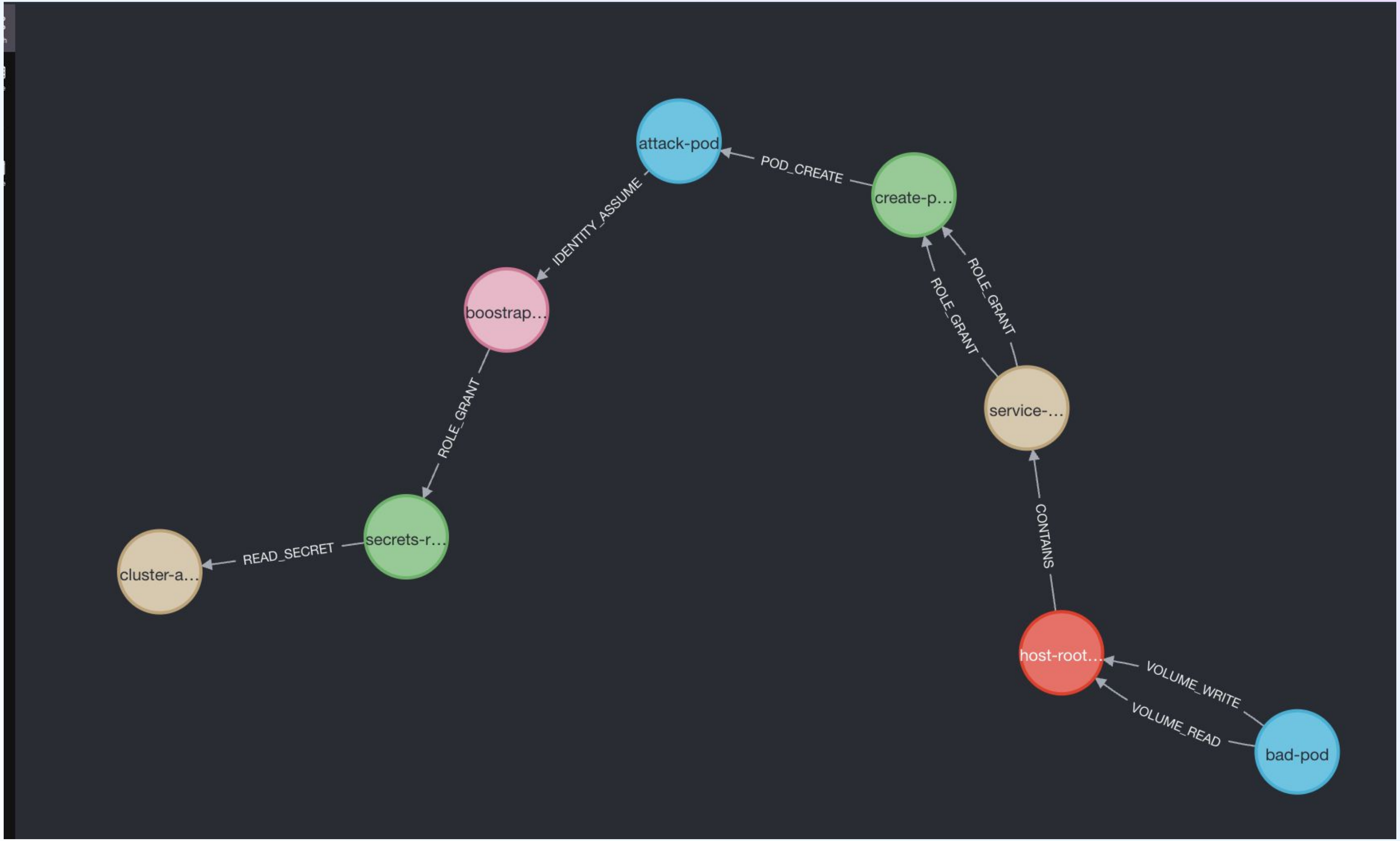
Create a specific abstraction to describe role and rolebinding: PermissionSet

Implement

Port to graph database

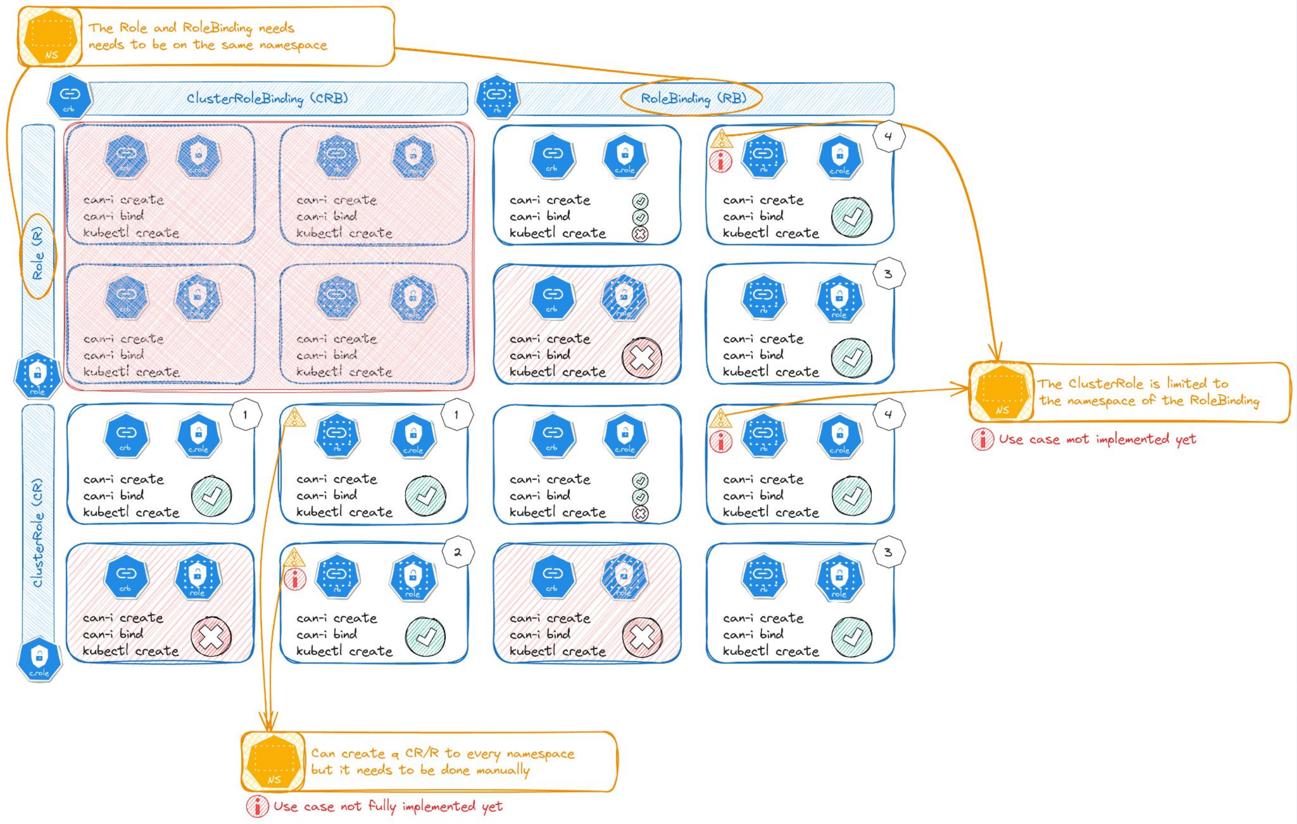


Attack 1 - https://www.youtube.com/watch?v=1LMoOCftVC4


attack-pod
POD_CREATE
create-p…
IDENTITY_ASSUME
boostrap…
ROLE_GRANT
ROLE_GRANT
ROLE_GRANT
service-…
secrets-r…
READ_SECRET
cluster-a…
CONTAINS
host-root…
VOLUME_WRITE
VOLUME_READ
bad-pod

Role bind attacks

Who does love RBAC stuff ?



The Role and RoleBinding needs needs to be on the same namespace

The ClusterRole is limited to the namespace of the RoleBinding

Use case mot implemented yet

Can create a CR/R to every namespace but it needs to be done manually

Use case not fully implemented yet

How to simulate those attacks ?

Kind cluster to the rescue

Easy to setup and lightweight

Kind cluster is an easy and lightweight cluster to deploy locally that runs into Docker. Can replicate a full Kubernetes with multiple nodes on your laptop.

End-to-end testing for each attacks.

For each attack studied an associated vulnerable pod/container/roles/endpoints/… was created. Even fake users were provisioned to test the attack from end-to-end.

… but some limitations

Even if kind cluster is not an exact replica of a Kubernetes cluster (some edge cases or limitation can be faced on some attacks that involve the kernel like CE_UMH_CORE_PATTERN), it is **sufficient for most of our needs**.

kubehound.io

The reference table for all Kubernetes Attacks implemented in KubeHound

Prerequisites

Usually it is a k8s description (for instance pods helm shart). What is needed from a configuration point of view.

- SHARE_PS_NAMESPACE: `shareProcessNamespace: true`

Exploitation

Full description step by step to exploit the attacks. The content should be sufficient for red or blue team.

- SHARE_PS_NAMESPACE: `/proc/$pid/root`

Checks

How can I do a live check when I am on a vulnerable container, pod or user ?

- SHARE_PS_NAMESPACE: `ps ax` to find a root process.

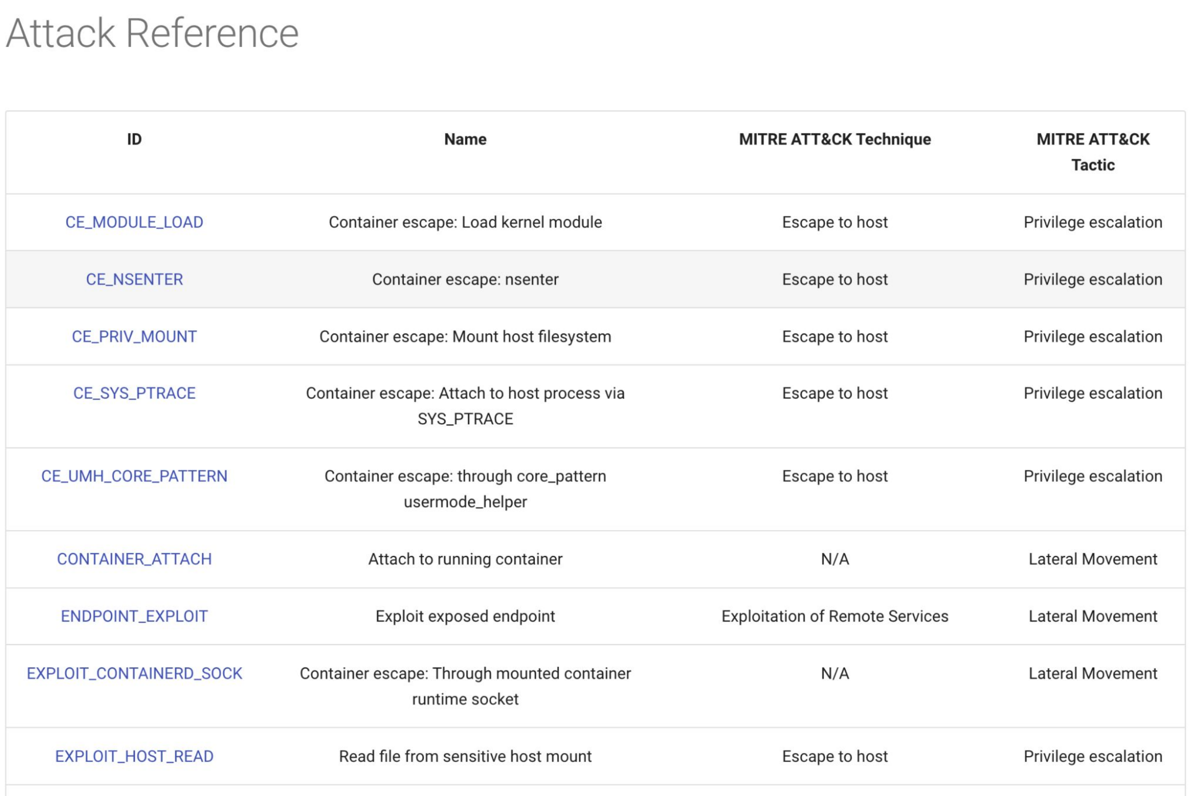
Defences

Lead to mitigate or detect the attacks. Example for least privileges or security policies are also listed.

- SHARE_PS_NAMESPACE: Prevent the use of shared namespaces in pods.

kubehound.io

26 attacks listed so far, more in the pipe



Attack Reference

ID	Name	MITRE ATT&CK Technique	MITRE ATT&CK Tactic
CE_MODULE_LOAD	Container escape: Load kernel module	Escape to host	Privilege escalation
CE_NSENTER	Container escape: nsenter	Escape to host	Privilege escalation
CE_PRIV_MOUNT	Container escape: Mount host filesystem	Escape to host	Privilege escalation
CE_SYS_PTRACE	Container escape: Attach to host process via SYS_PTRACE	Escape to host	Privilege escalation
CE_UMH_CORE_PATTERN	Container escape: through core_pattern usermode_helper	Escape to host	Privilege escalation
CONTAINER_ATTACH	Attach to running container	N/A	Lateral Movement
ENDPOINT_EXPLOIT	Exploit exposed endpoint	Exploitation of Remote Services	Lateral Movement
EXPLOIT_CONTAINERD_SOCK	Container escape: Through mounted container runtime socket	N/A	Lateral Movement
EXPLOIT_HOST_READ	Read file from sensitive host mount	Escape to host	Privilege escalation

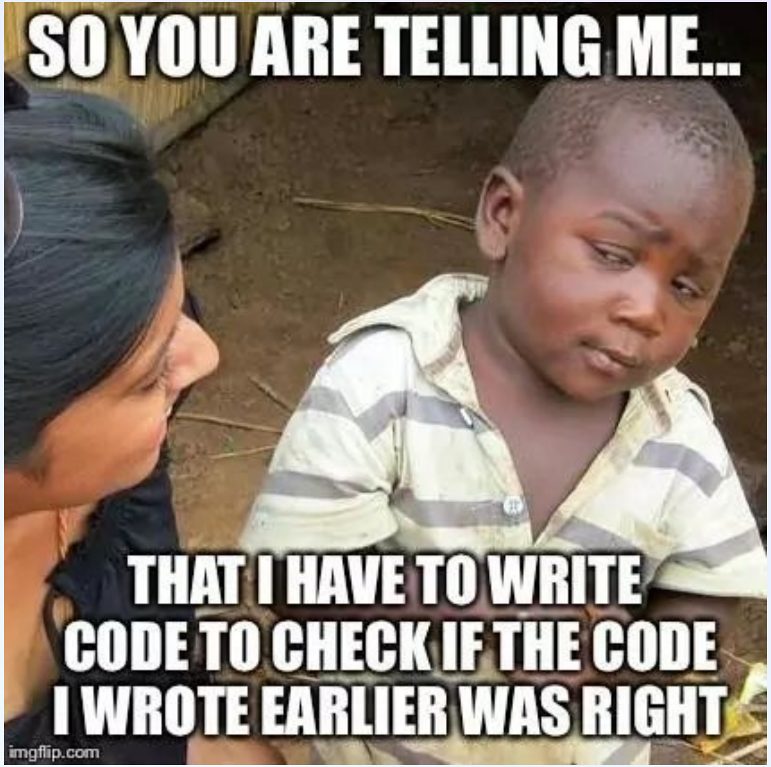
How can we prevent any regression in our model ?

Unit tests for the win

Something rare ~~in offsec world~~

46%

Coverage in KubeHound core


SO YOU ARE TELLING ME...
THAT I HAVE TO WRITE CODE TO CHECK IF THE CODE I WROTE EARLIER WAS RIGHT
imgflip.com

Systems tests for the win

The reference table for all Kubernetes Attacks implemented in KubeHound

Vulnerable kind cluster

Luckily, we can spawn a vulnerable kind cluster with all our attacks listed in KubeHound.io reference table.

- **In Github action generated in every PR**.
- Locally for some automated tests.

Generated code

From the vulnerable kind cluster configuration helm configuration files, we convert them into Golang resources to have **an exhaustive list** of pods, roles, endpoints, …

Automated ingestion

Ingest the vulnerable kind cluster like a regular cluster. Building a real graph referencing all k8s objects and associated attack paths.

End-to-end tests

Run KubeHound/Gremlin queries to check if we have the expected results:

- Vertice: How many attack paths CE_NSENTER ?
- Edges: Do we have all the expected volumes ?
- DSL: Testing our custom queries.

Fun Fact

When your CTO join the party

PoC

v0.1

Neo4J based

10 hours to ingest 25k pods

1 hour to dump all objects using a bash script

Ultimate goal set by the team

v1.0

Full OSS stack

1 hour to ingest 25k pods

10 minutes to dump all k8s objects using only API endpoints

Set a new standard :)

But …

Commenting OKR …

ALQ / Datadog CTO

> “Are we sure about the orders of magnitude? Let's say you have 1,000 nodes in a cluster, each connected to every other node, thus O(10^6) edges. An iPhone runs 6 cores at 2GHz, getting data to and from memory takes O(100) cycles so we should get O(10^7) edges processed by second. There are gross oversimplifications in all this, but the napkin math says that it should be measured in seconds, not hours or days.”

Performance improvements

There is always a but …

use in memory graph backend

+

tune graph to better optimize for writes

+

optimize queries used to generate edges

+

optimize K8s API querying

30 sec building graph (from 35 min)

Take away

Some insights gleaned on **the power of automated attack graphs** through developing and using KubeHound:

- Provide the ability to quantify security posture and risk
- Scale horizontally to handle any environment
- Act as a force multiplier by sharing the mindset of the best offensive practitioners with defenders

TLDR: **Attack graphs change the game and will be the natural evolution of security tooling**

Future Vision

KubeHound v3.0

Customization

Fine tune the model

Enable tailoring KubeHound to your own environment

- Custom rules to define critical assets

- Custom inputs to exploitable conditions e.g EXPLOIT_HOST_READ file path

- Custom filters to discard extra data

Refining the Graph

Compare the different attack paths

Embed extra information within edges using a weight which defines

- How easy is the attack to execute?

- How easy is the attack to detect?

- Does the attack require time to execute? (bruteforcing for instance)

Refining the Graph

Leadership loves KPI

Enable automated reporting of key metrics and risks

- Calculate security posture metrics

- Heatmap of critical attack paths

- Consolidate processing errors

We have a dream

KubeHound roadmap

- Create a proper UI to navigate across the results
- Generate readable report based on automated query
- Enable tailoring KubeHound to your own environment easily
- Diff checker to identify progress between 2 snapshots

KubeHound as a Service
KHaaS

Coming soon …

(will also be Open Source of course :blob_happy:)

Q&A

We are recruiting for the team :)

Senior Security Engineer - Adversary Simulation Engineering

Engineering

Paris, France