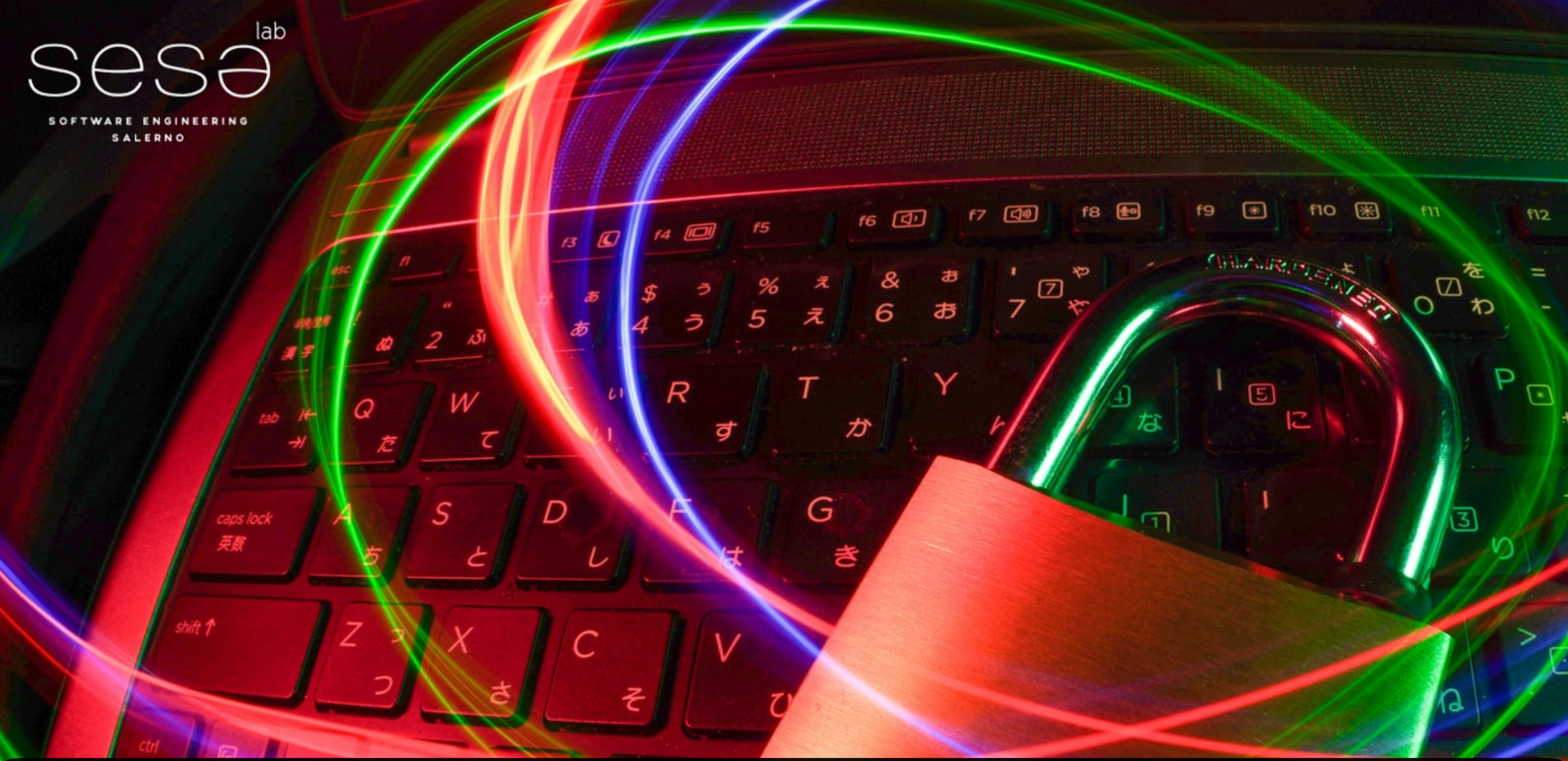

sesa lab
SOFTWARE ENGINEERING
SALERNO

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

Emanuele Iannone
Ph.D. Student
Software Engineering (SeSa) Lab
University of Salerno

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Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

Next on this lecture

Fabio Palomba

Fundamentals of Mining Software Repositories for Vulnerability Prediction: The Methodological Perspective

(1) How does a general predictive task work?

(2) How can MSR support vulnerability prediction?

(3) Which data processing activities are required for predictive tasks?

(4) What are the pitfalls when developing a vulnerability prediction model?

(5) What are the current limitations and challenges you are called to face?

Emanuele Iannone

Fundamentals of Mining Software Repositories for Vulnerability Prediction: The Practical Perspective

(1) What kind of data do we have to collect?

(2) How do we query the data sources?

(3) How can we make mining smart and efficient?

(4) How do we process the collected data?

(5) How do we prepare the data for the prediction models?

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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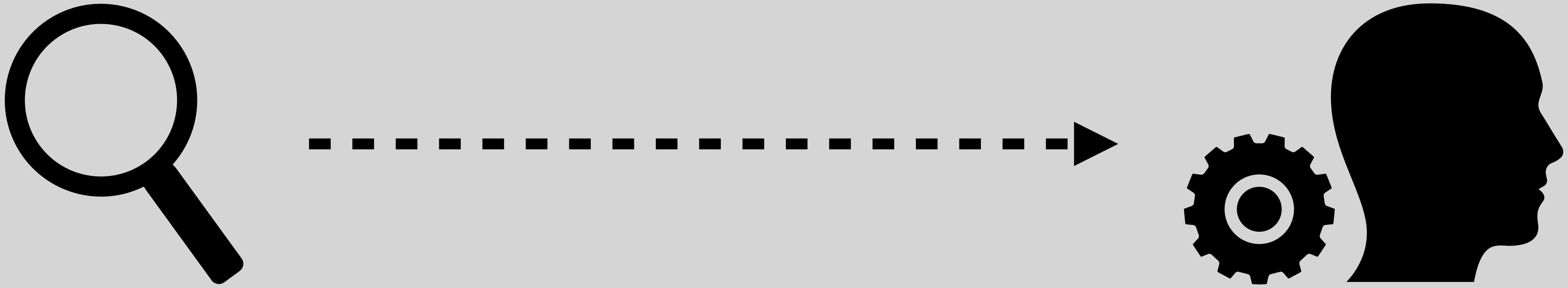

Predicting vulnerabilities needs…
machine learning

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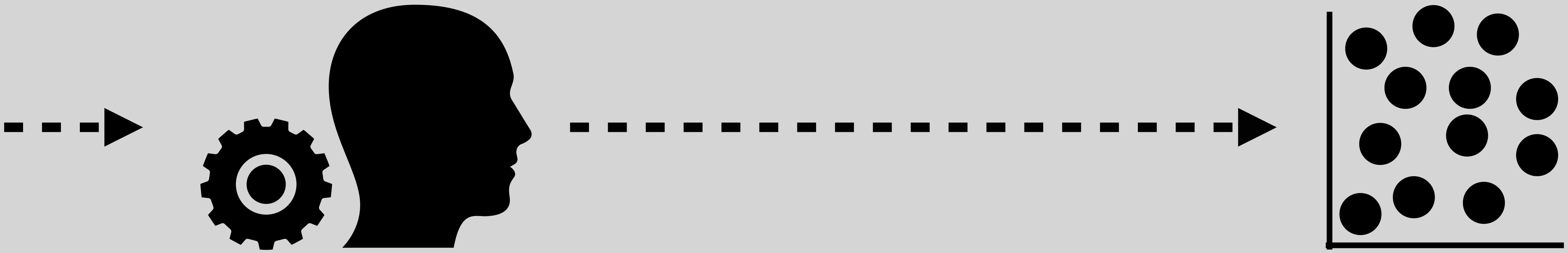

But machine learning needs…

lots of data…

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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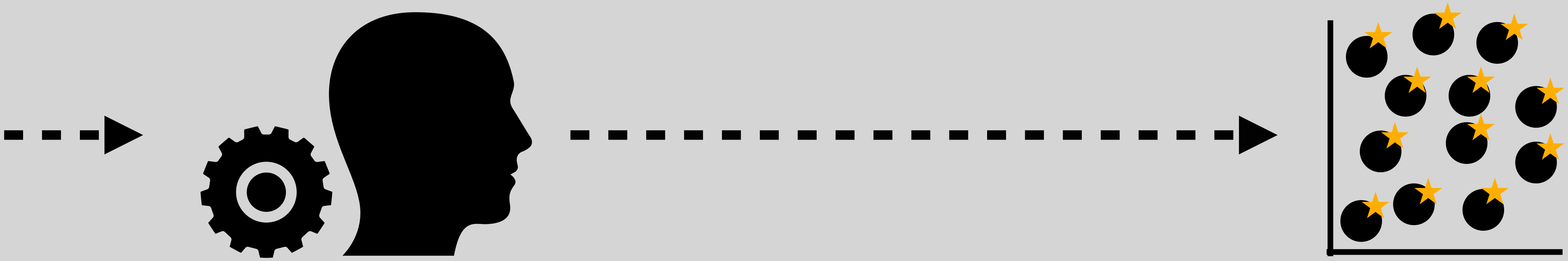

But machine learning needs…

lots of data…

possibly of high quality

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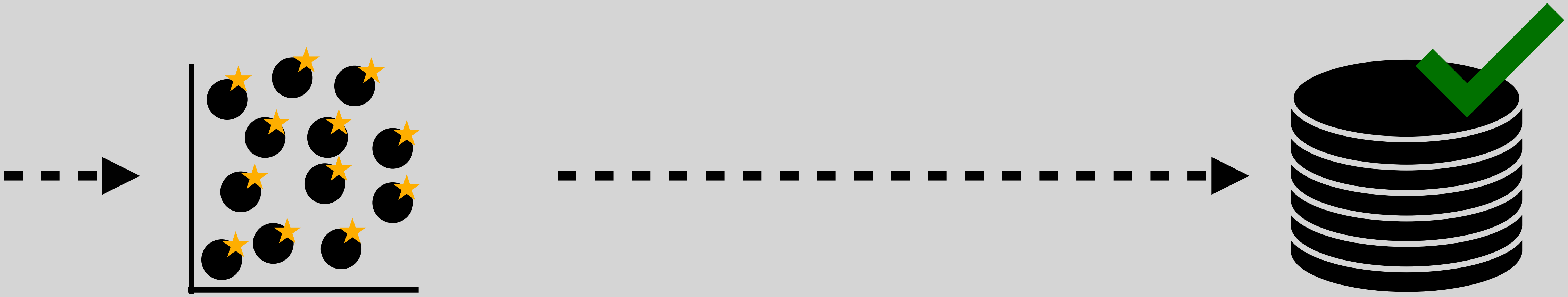

But high quality data needs…

reliable data sources…

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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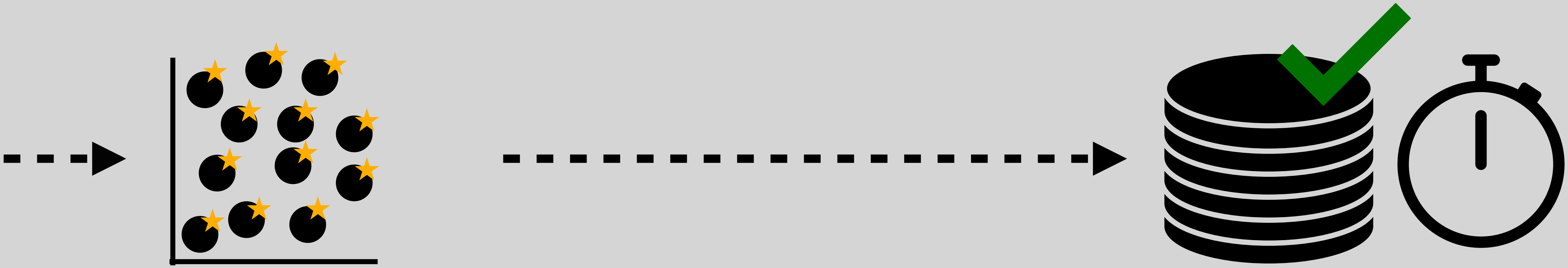

But high quality data needs…
reliable data sources…
and **time!**

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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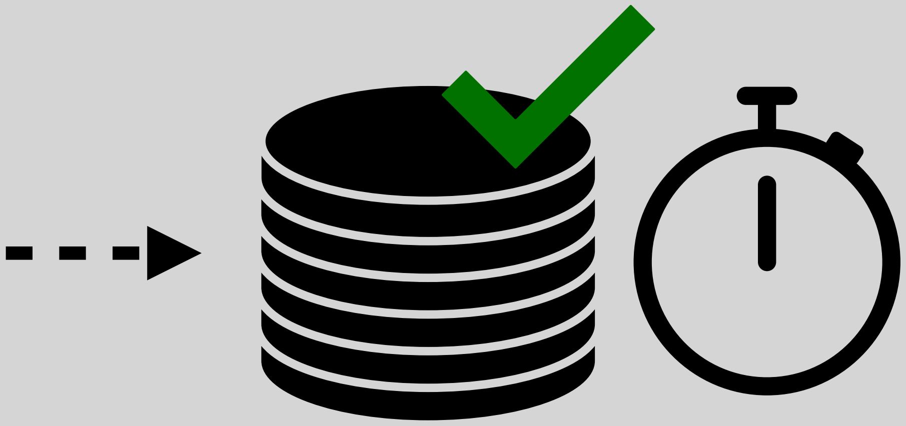


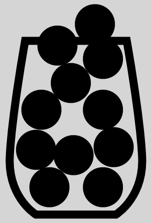
Mining data **IS** time-consuming! We must be smart and efficient to **minimize the times we go back to our steps** and re-do everything.

To minimize such a risk, it is good to ask ourselves:

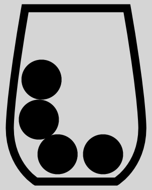
?

What kind of predictions do I want to make?
What do I want to achieve?
How do I plan to use the collected data?

Answering these questions helps to avoid collecting:



Too much data
(pointless workload)



Too few data
(no good models)

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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Fundamentals of Mining Software Repositories for Vulnerability Prediction: The Practical Perspective

Let’s be a bit more practical with an example…

Build a VPM that determines whether a C file in a specific project is vulnerable.

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

Next on this lecture *Fundamentals of Mining Software Repositories for Vulnerability Prediction: The Practical Perspective*

Let’s be a bit more practical with an example…

Build a VPM that determines whether **a C file** in a specific project is vulnerable.

The object of the classification is files written in C: the ML models will train on a set of C files and make their predictions on C files. We have to mine data associated with C files; the more, the better.

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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Let’s be a bit more practical with an example…

Build a VPM that determines whether a C file **in a specific project** is vulnerable.

We can collect historical data regarding that specific project, go for synthetic C files (transfer learning), or even a mixture. This is a **methodological decision** that must be taken seriously.

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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Let’s be a bit more practical with an example…

Build a VPM that determines whether a C file in a specific project **is vulnerable.**

We need information that helps a classifier **recognize the differences** between a vulnerable C file and a “safe” C file. In other words, we need the data that will be used to **encode/extract the features**.

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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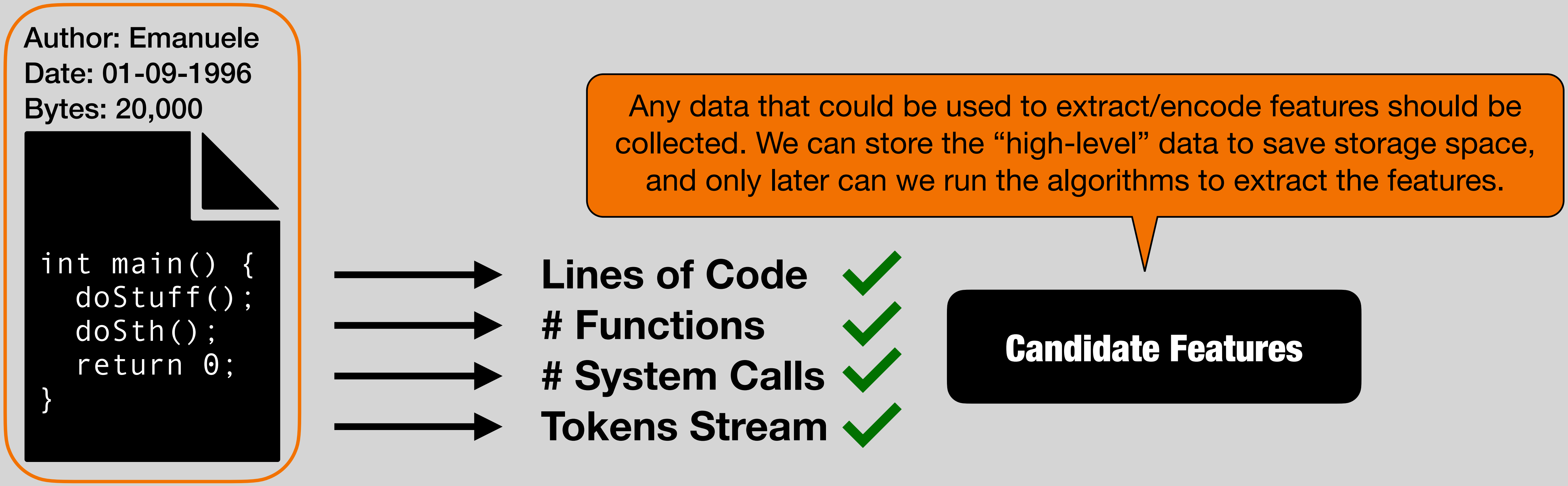
Let's assume we find a dataset with records of past vulnerable C files observed in a project.



Author: Emanuele
Date: 01-09-1996
Bytes: 20,000

```
int main() {
  doStuff();
  doSth();
  return 0;
}
```

Lines of Code ✓
# Functions ✓
# System Calls ✓
Tokens Stream ✓

Any data that could be used to extract/encode features should be collected. We can store the "high-level" data to save storage space, and only later can we run the algorithms to extract the features.

Candidate Features

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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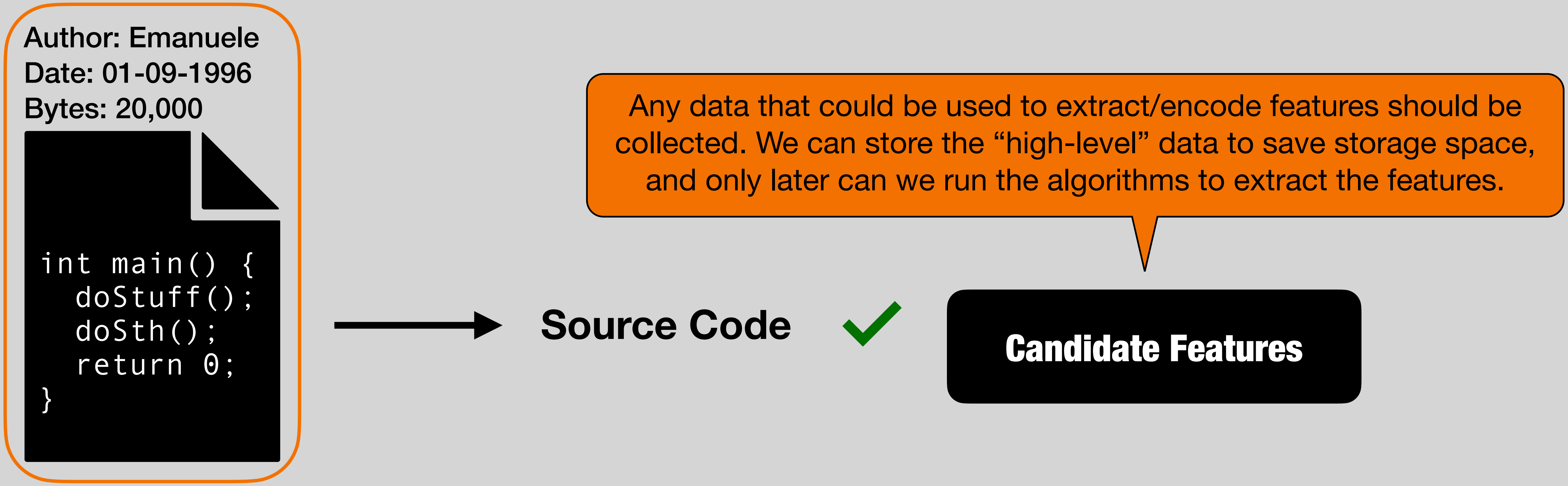

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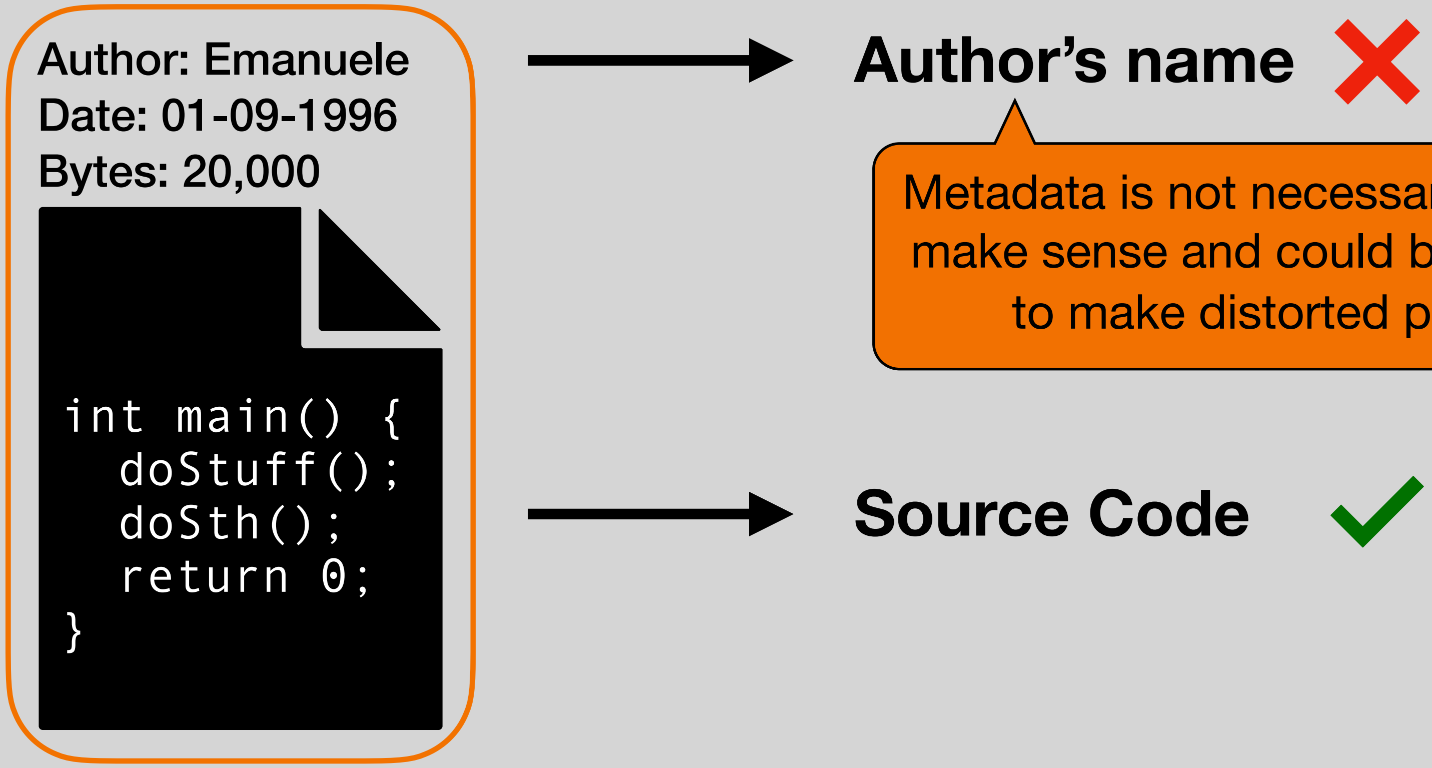

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Author’s name ✗

Metadata is not necessarily useful as features. The author's name does not make sense and could be harmful: it might give the classifiers a “shortcut” to make distorted predictions (exploiting **spurious correlations**).

Source Code ✓

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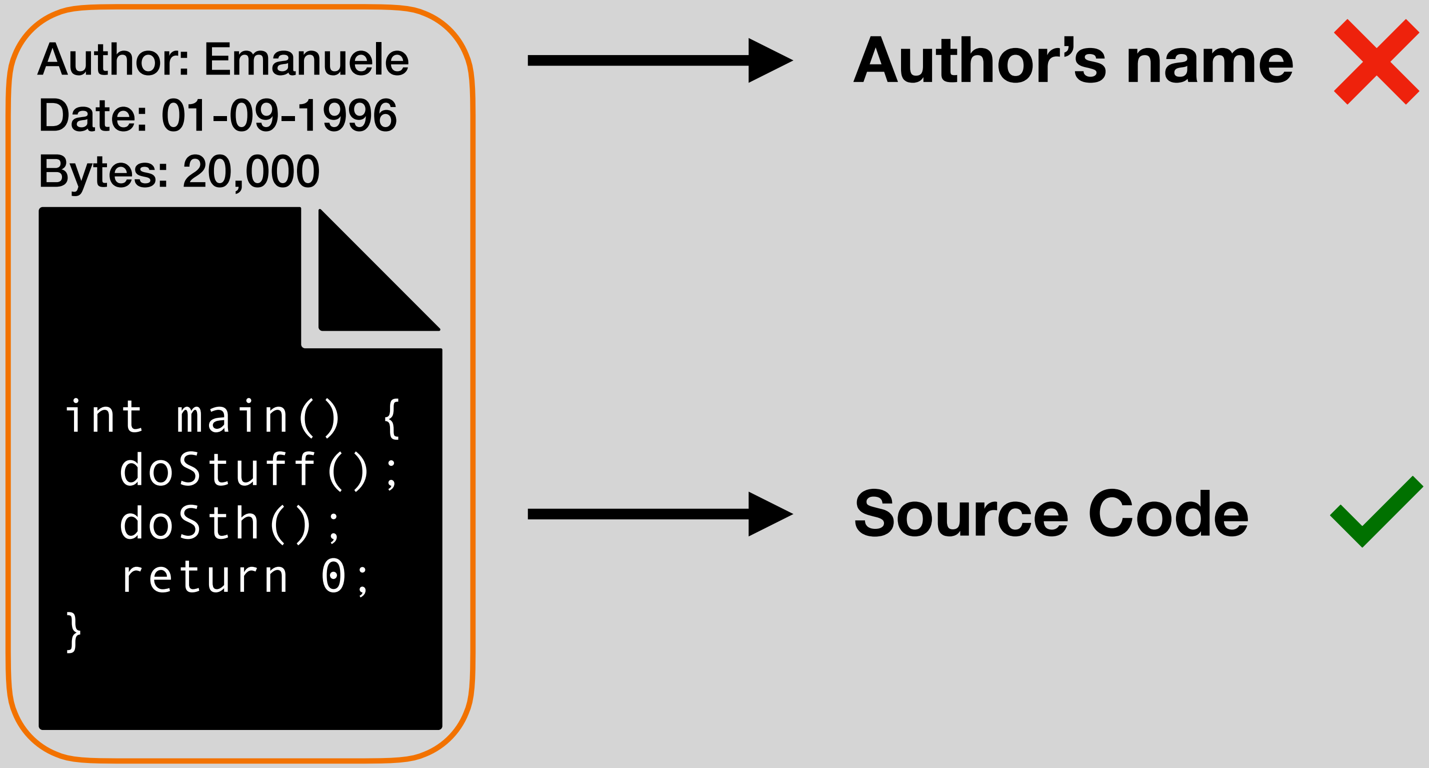

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Author’s name ✗

Source Code ✓

Features are not the only reason why we mine data. There are **other purposes** for which we can use the mined data.

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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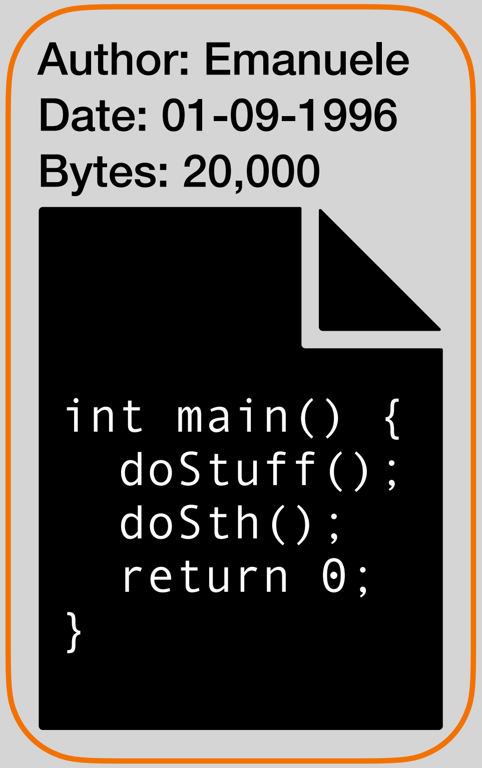

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```
int main() {
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```

Creation Date. It can be used to filter out specific files. For instance, we could drop **outdated files**, as we think they are not reliable enough for today’s predictions. ✓

It’s not rare that we re-use the same “high-level” data for multiple purposes, i.e., data selection and features.

Source code (again). It can be used to filter out additional files. For instance, we could drop **empty files**, **not parsable** files, or files with **no functions**. ✓

Data Selection

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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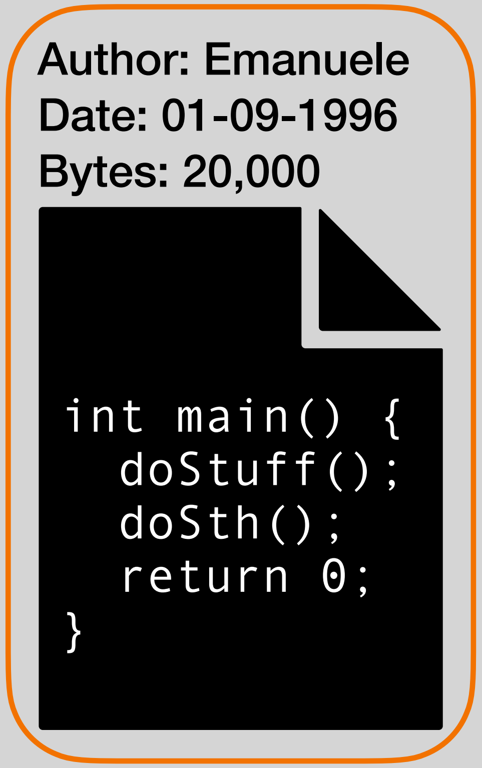

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```
int main() {
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}
```

But wait, there is more!

Source code (again). It can be inspected with a static vulnerability analyzer to obtain the *Nr. warnings*. This metric can be used to **set our ground truth.** ✓

Label Assignment

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

Next on this lecture

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To sum up, we mine data for three main reasons:

Candidate Features

Data intended to **be used for extracting features**, either manually or automatically.

LOC, #Functions, #System Calls, Token Stream, Past Faults, Nr. maintainers

Data Selection

Data intended to **support the selection of valid instances**, i.e., those that will be seen by the models.

Creation Date, Size, Vulnerability Type/CWE

Label Assignment

Data intended to **support the process of determining the labels** to assign to each instance.

Analysis tool's report, Vulnerability Insertion Date, Vulnerability Type/CWE

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To sum up, we mine data for three main reasons:

Candidate Features

Data Selection

Label Assignment

In this respect, I want to introduce the first of my personal *10 commandments*, i.e., 10 lessons I learned while working on mining data for vulnerability prediction.

1

Thou shalt not be too eager to terminate the mining

There will **always** be some data that you forgot to collect, and you'll regret it. Take your time, and think!

When in doubt, **collect all data available** if it does not cost you too much. If you have no time, do it later… think incrementally!

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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Fabio showed us many possible data sources: NVD, CVE, GitHub, etc. Depending on many factors, we might have to **query multiple sources.**

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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Fabio showed us many possible data sources: NVD, CVE, GitHub, etc. Depending on many factors, we might have to **query multiple sources.**

Let's assume we opt for NVD and want to collect **ALL existing CVEs**! The real deal now is to **find an "entry point"**: an *interface* allowing the retrieval of the stored data.

↓

Reliable data sources often come with **public web APIs**, allowing the retrieval of data—in JSON format—with simple HTTP requests. Whenever they exist, it's a good sign.

☞ Let's go check the dedicated page on the NVD website: https://nvd.nist.gov/vuln/data-feeds

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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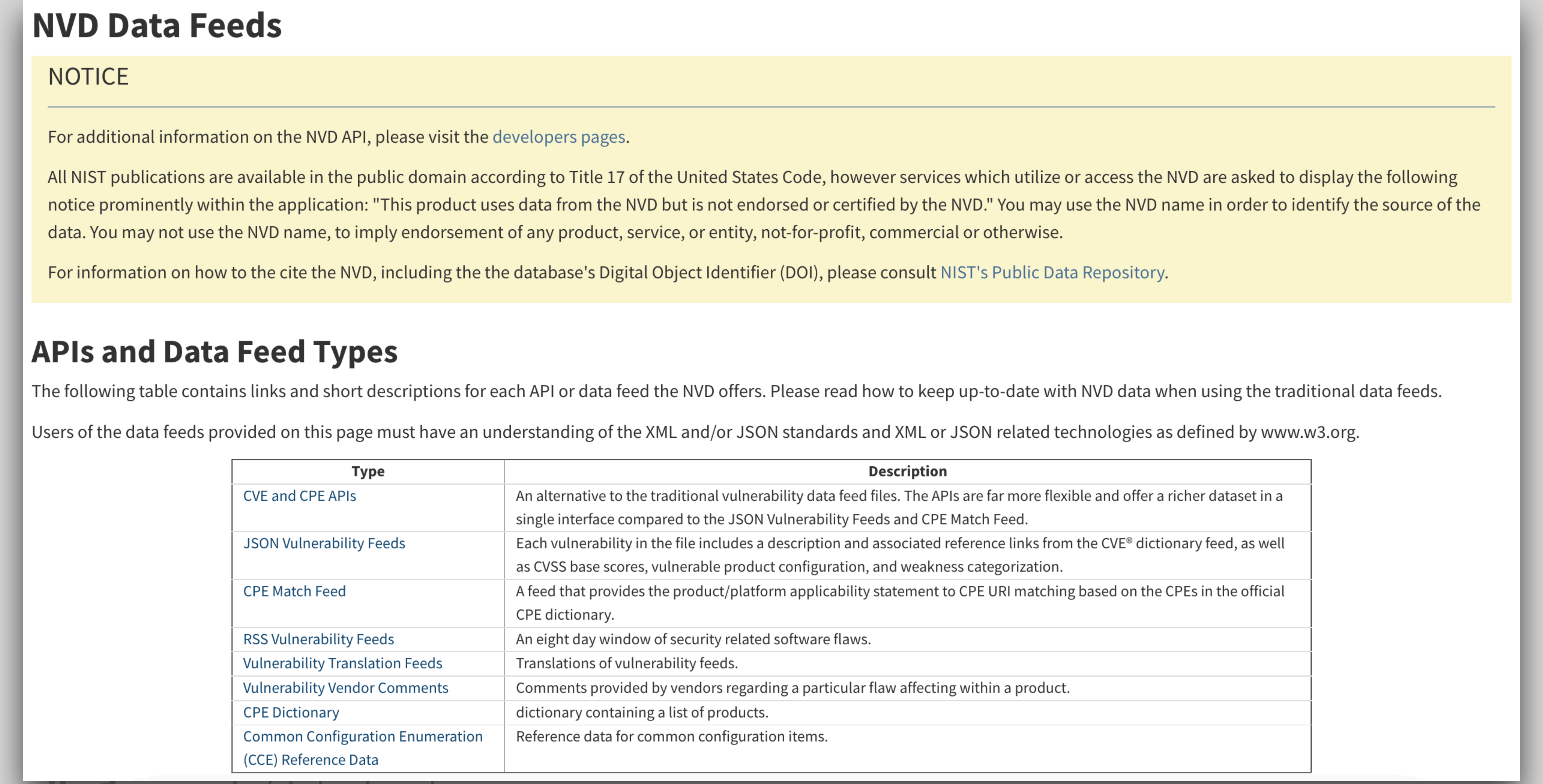

NVD Data Feeds

NOTICE

For additional information on the NVD API, please visit the developers pages.

All NIST publications are available in the public domain according to Title 17 of the United States Code, however services which utilize or access the NVD are asked to display the following notice prominently within the application: "This product uses data from the NVD but is not endorsed or certified by the NVD." You may use the NVD name in order to identify the source of the data. You may not use the NVD name, to imply endorsement of any product, service, or entity, not-for-profit, commercial or otherwise.

For information on how to the cite the NVD, including the the database's Digital Object Identifier (DOI), please consult NIST's Public Data Repository.

APIs and Data Feed Types

The following table contains links and short descriptions for each API or data feed the NVD offers. Please read how to keep up-to-date with NVD data when using the traditional data feeds.

Users of the data feeds provided on this page must have an understanding of the XML and/or JSON standards and XML or JSON related technologies as defined by www.w3.org.

Type	Description
CVE and CPE APIs	An alternative to the traditional vulnerability data feed files. The APIs are far more flexible and offer a richer dataset in a single interface compared to the JSON Vulnerability Feeds and CPE Match Feed.
JSON Vulnerability Feeds	Each vulnerability in the file includes a description and associated reference links from the CVE® dictionary feed, as well as CVSS base scores, vulnerable product configuration, and weakness categorization.
CPE Match Feed	A feed that provides the product/platform applicability statement to CPE URI matching based on the CPEs in the official CPE dictionary.
RSS Vulnerability Feeds	An eight day window of security related software flaws.
Vulnerability Translation Feeds	Translations of vulnerability feeds.
Vulnerability Vendor Comments	Comments provided by vendors regarding a particular flaw affecting within a product.
CPE Dictionary	dictionary containing a list of products.
Common Configuration Enumeration (CCE) Reference Data	Reference data for common configuration items.

vuln/data-feeds

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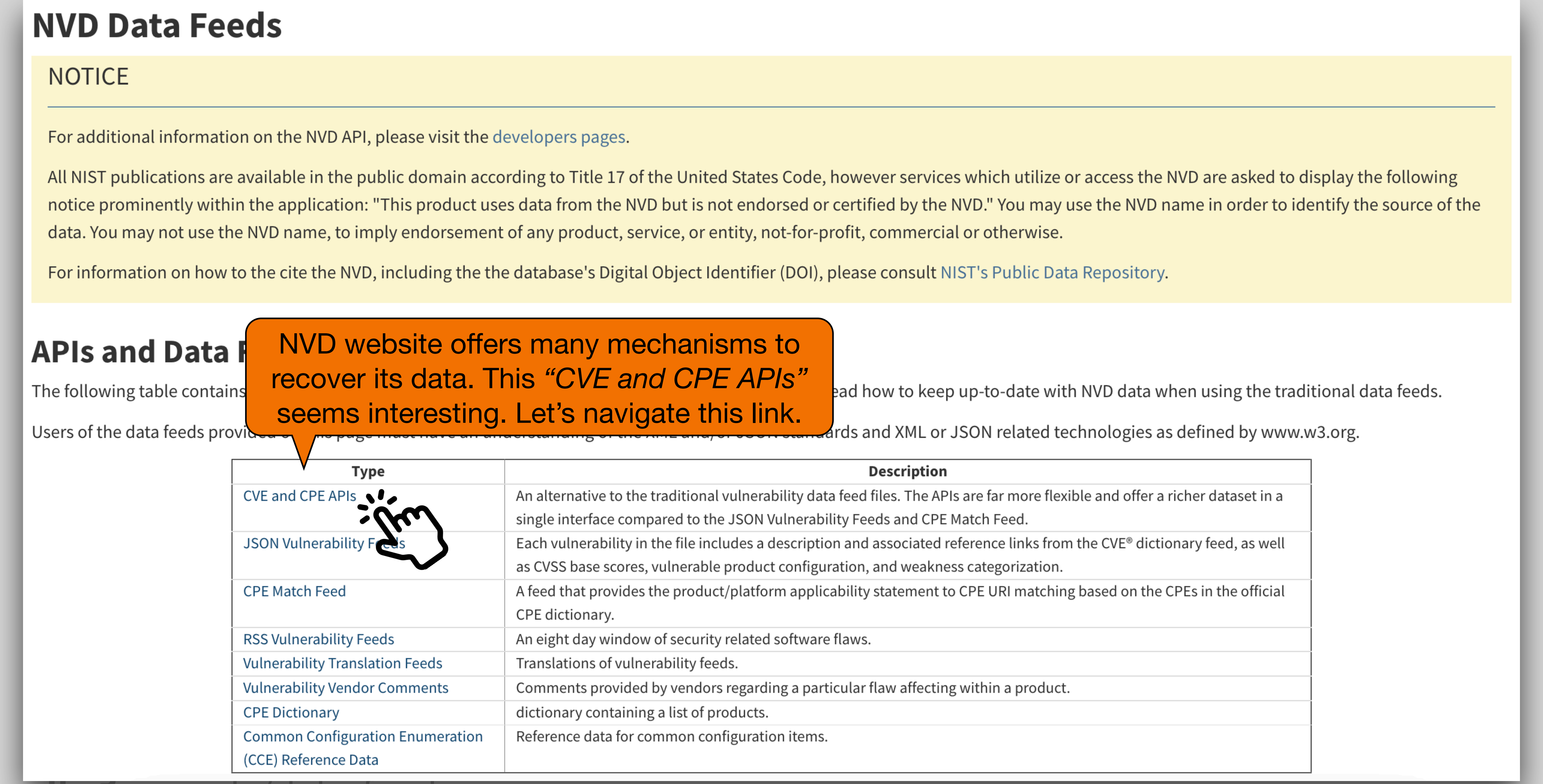

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NVD website offers many mechanisms to recover its data. This *"CVE and CPE APIs"* seems interesting. Let's navigate this link.

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vuln/data-feeds

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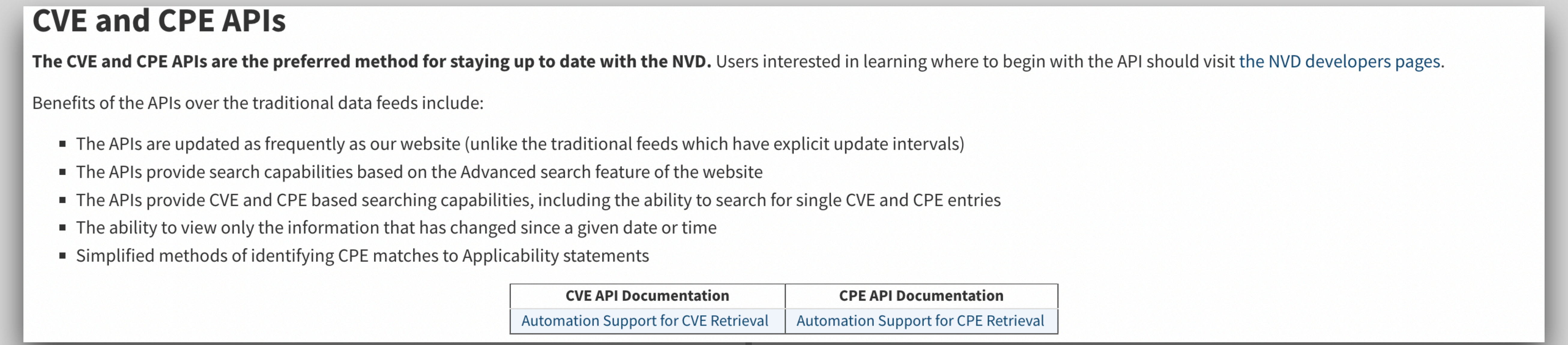

CVE and CPE APIs

The CVE and CPE APIs are the preferred method for staying up to date with the NVD. Users interested in learning where to begin with the API should visit the NVD developers pages.

Benefits of the APIs over the traditional data feeds include:

- The APIs are updated as frequently as our website (unlike the traditional feeds which have explicit update intervals)
- The APIs provide search capabilities based on the Advanced search feature of the website
- The APIs provide CVE and CPE based searching capabilities, including the ability to search for single CVE and CPE entries
- The ability to view only the information that has changed since a given date or time
- Simplified methods of identifying CPE matches to Applicability statements

CVE API Documentation	CPE API Documentation
Automation Support for CVE Retrieval	Automation Support for CPE Retrieval

Reliable data sources often come with **public web APIs**, allowing the retrieval of data—in JSON format—with simple HTTP requests. Whenever they exist, it's a good sign.

☞ Let's go check the dedicated page on the NVD website: https://nvd.nist.gov/vuln/data-feeds

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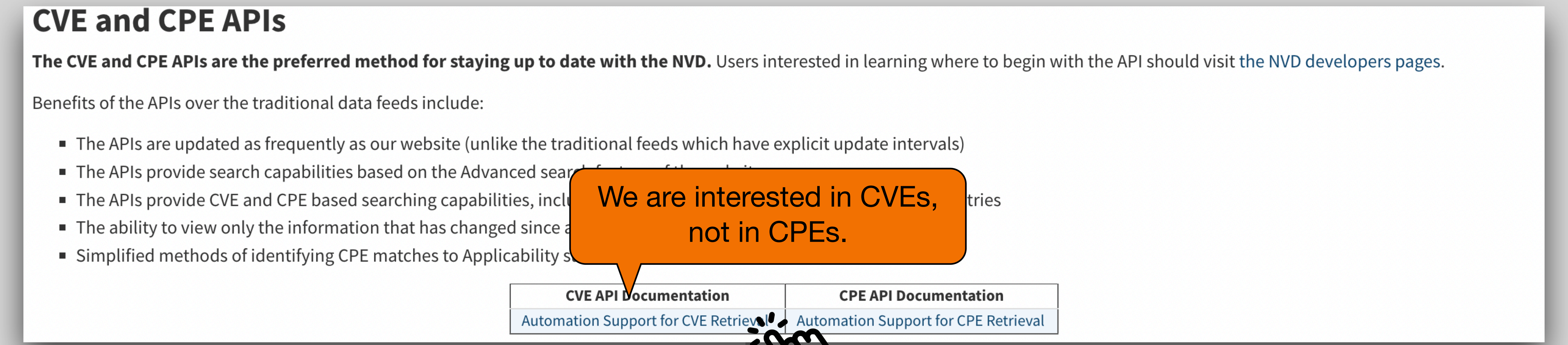

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We are interested in CVEs, not in CPEs.

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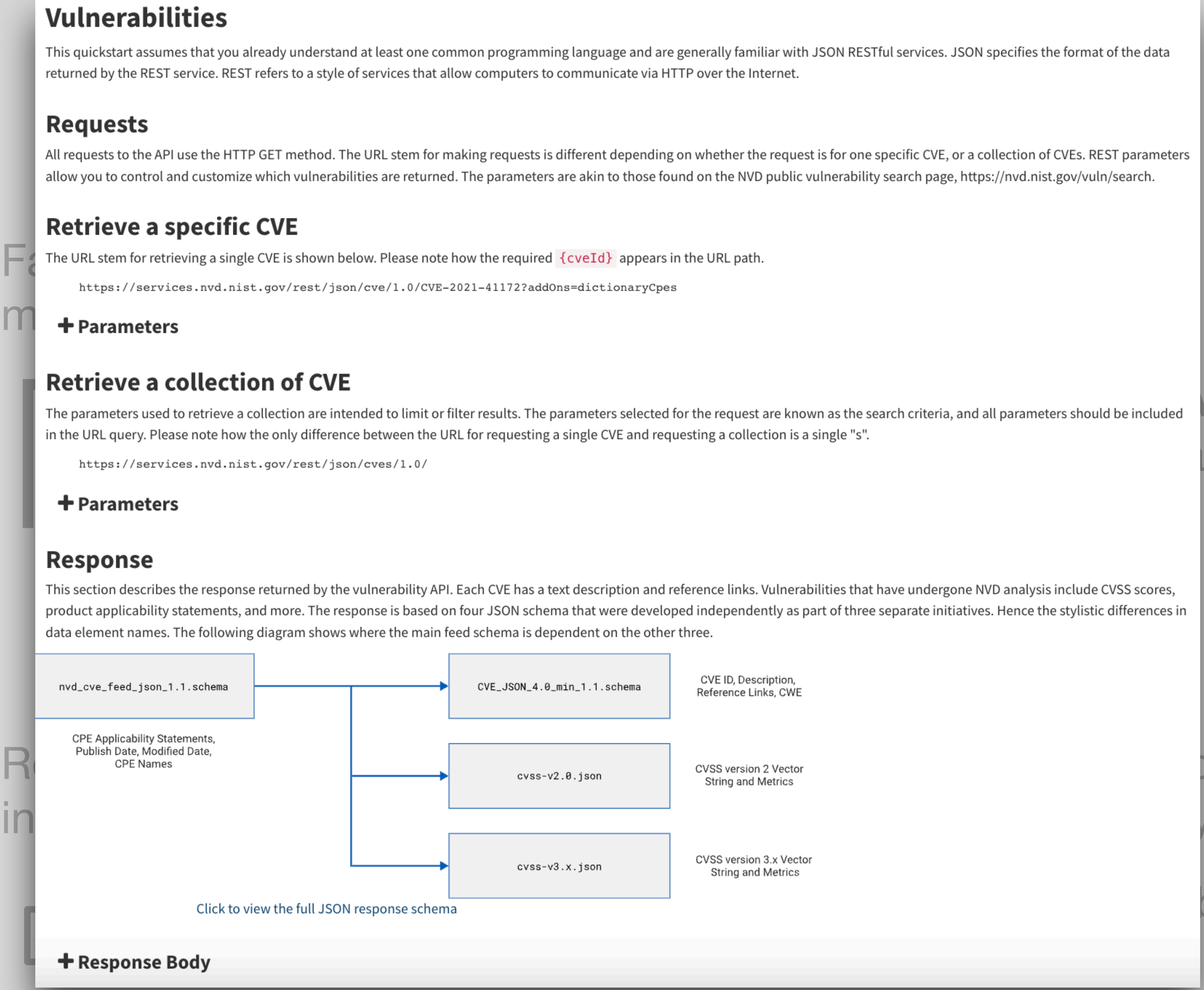

Vulnerabilities

This quickstart assumes that you already understand at least one common programming language and are generally familiar with JSON RESTful services. JSON specifies the format of the data returned by the REST service. REST refers to a style of services that allow computers to communicate via HTTP over the Internet.

Requests

All requests to the API use the HTTP GET method. The URL stem for making requests is different depending on whether the request is for one specific CVE, or a collection of CVEs. REST parameters allow you to control and customize which vulnerabilities are returned. The parameters are akin to those found on the NVD public vulnerability search page, https://nvd.nist.gov/vuln/search.

Retrieve a specific CVE

The URL stem for retrieving a single CVE is shown below. Please note how the required `{cveId}` appears in the URL path.

```
https://services.nvd.nist.gov/rest/json/cve/1.0/CVE-2021-41172?addOns=dictionaryCpes
```

+ Parameters

Retrieve a collection of CVE

The parameters used to retrieve a collection are intended to limit or filter results. The parameters selected for the request are known as the search criteria, and all parameters should be included in the URL query. Please note how the only difference between the URL for requesting a single CVE and requesting a collection is a single "s".

```
https://services.nvd.nist.gov/rest/json/cves/1.0/
```

+ Parameters

Response

This section describes the response returned by the vulnerability API. Each CVE has a text description and reference links. Vulnerabilities that have undergone NVD analysis include CVSS scores, product applicability statements, and more. The response is based on four JSON schema that were developed independently as part of three separate initiatives. Hence the stylistic differences in data element names. The following diagram shows where the main feed schema is dependent on the other three.

nvd_cve_feed_json_1.1.schema

CPE Applicability Statements, Publish Date, Modified Date, CPE Names

CVE_JSON_4.0_min_1.1.schema

CVE ID, Description, Reference Links, CWE

cvss-v2.0.json

CVSS version 2 Vector String and Metrics

cvss-v3.x.json

CVSS version 3.x Vector String and Metrics

Click to view the full JSON response schema

+ Response Body

Here we discover that with a single HTTP GET request, we can retrieve the info of **a given CVE**.

Fa … itHub, etc. Depending on
m

… **LL existing CVEs**! The real
… llowing the retrieval of the

R … wing the retrieval of data—
in … exist, it's a good sign.

… bsite: https://nvd.nist.gov/

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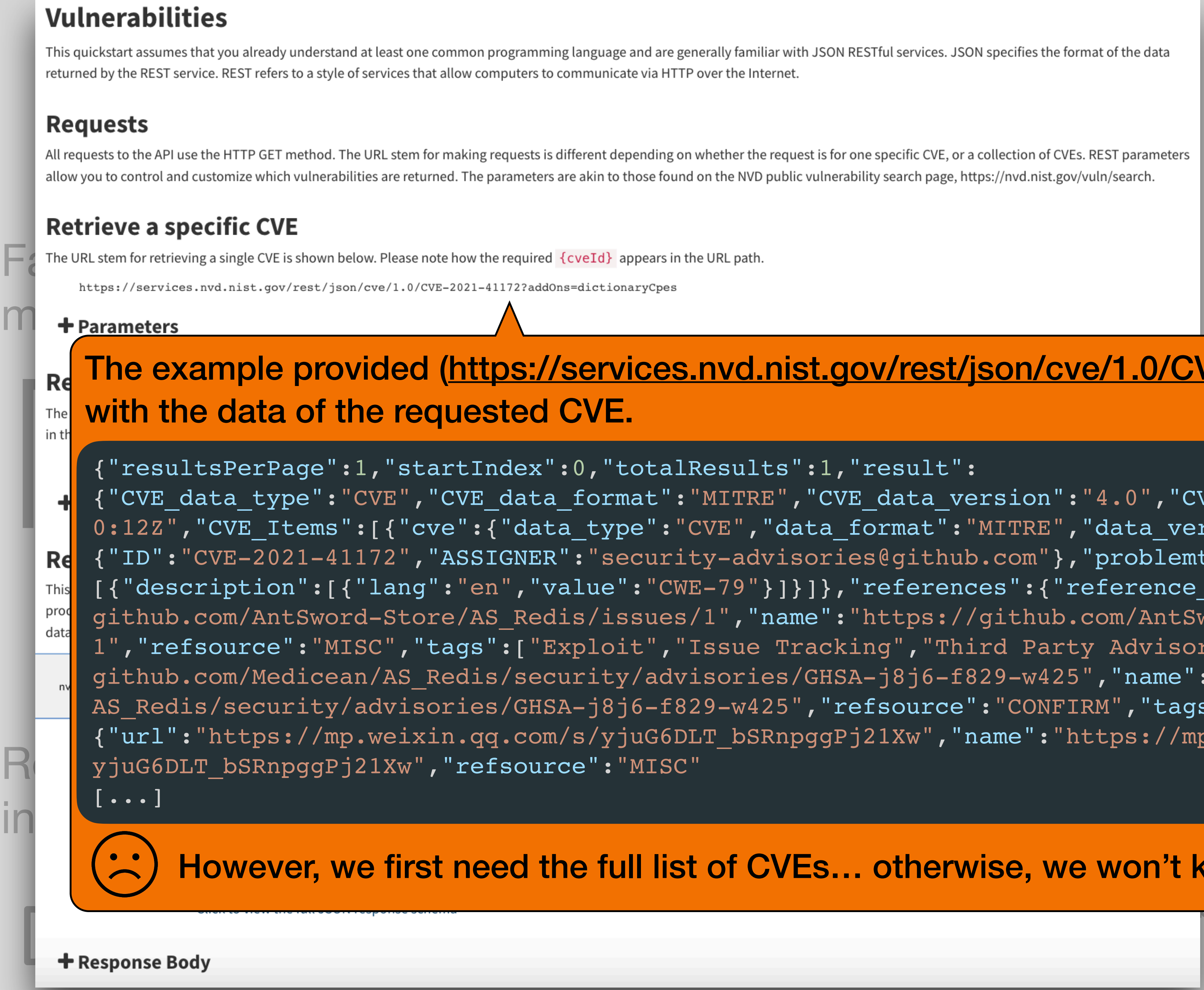

Vulnerabilities

This quickstart assumes that you already understand at least one common programming language and are generally familiar with JSON RESTful services. JSON specifies the format of the data returned by the REST service. REST refers to a style of services that allow computers to communicate via HTTP over the Internet.

Requests

All requests to the API use the HTTP GET method. The URL stem for making requests is different depending on whether the request is for one specific CVE, or a collection of CVEs. REST parameters allow you to control and customize which vulnerabilities are returned. The parameters are akin to those found on the NVD public vulnerability search page, https://nvd.nist.gov/vuln/search.

Retrieve a specific CVE

The URL stem for retrieving a single CVE is shown below. Please note how the required `{cveId}` appears in the URL path.

```
https://services.nvd.nist.gov/rest/json/cve/1.0/CVE-2021-41172?addOns=dictionaryCpes
```

+ Parameters

+ Response Body

Here we discover that with a single HTTP GET request, we can retrieve the info of **a given CVE**.

The example provided (https://services.nvd.nist.gov/rest/json/cve/1.0/CVE-2021-41172) returns a JSON with the data of the requested CVE.

```
{"resultsPerPage":1,"startIndex":0,"totalResults":1,"result":
{"CVE_data_type":"CVE","CVE_data_format":"MITRE","CVE_data_version":"4.0","CVE_data_timestamp":"2022-09-01T1
0:12Z","CVE_Items":[{"cve":{"data_type":"CVE","data_format":"MITRE","data_version":"4.0","CVE_data_meta":
{"ID":"CVE-2021-41172","ASSIGNER":"security-advisories@github.com"},"problemtype":{"problemtype_data":
[{"description":[{"lang":"en","value":"CWE-79"}]}]},"references":{"reference_data":[{"url":"https://
github.com/AntSword-Store/AS_Redis/issues/1","name":"https://github.com/AntSword-Store/AS_Redis/issues/
1","refsource":"MISC","tags":["Exploit","Issue Tracking","Third Party Advisory"]},{"url":"https://
github.com/Medicean/AS_Redis/security/advisories/GHSA-j8j6-f829-w425","name":"https://github.com/Medicean/
AS_Redis/security/advisories/GHSA-j8j6-f829-w425","refsource":"CONFIRM","tags":["Third Party Advisory”]},
{"url":"https://mp.weixin.qq.com/s/yjuG6DLT_bSRnpggPj21Xw","name":"https://mp.weixin.qq.com/s/
yjuG6DLT_bSRnpggPj21Xw","refsource":"MISC"
[...]
```

☹ **However, we first need the full list of CVEs… otherwise, we won’t know which CVE to request.**

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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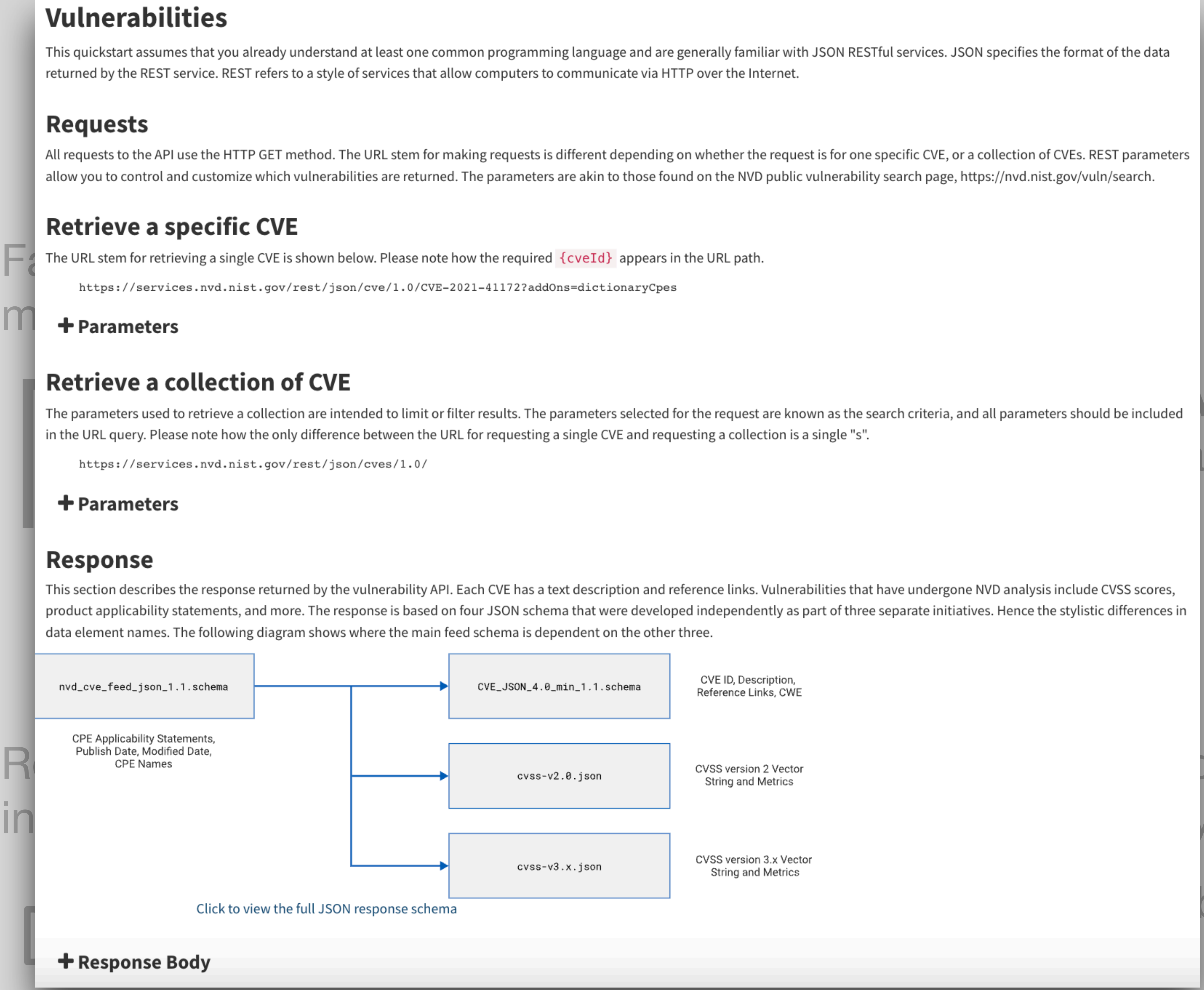

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```

+ Parameters

Retrieve a collection of CVE

The parameters used to retrieve a collection are intended to limit or filter results. The parameters selected for the request are known as the search criteria, and all parameters should be included in the URL query. Please note how the only difference between the URL for requesting a single CVE and requesting a collection is a single "s".

```
https://services.nvd.nist.gov/rest/json/cves/1.0/
```

+ Parameters

Response

This section describes the response returned by the vulnerability API. Each CVE has a text description and reference links. Vulnerabilities that have undergone NVD analysis include CVSS scores, product applicability statements, and more. The response is based on four JSON schema that were developed independently as part of three separate initiatives. Hence the stylistic differences in data element names. The following diagram shows where the main feed schema is dependent on the other three.

nvd_cve_feed_json_1.1.schema
CPE Applicability Statements, Publish Date, Modified Date, CPE Names
CVE_JSON_4.0_min_1.1.schema
CVE ID, Description, Reference Links, CWE
cvss-v2.0.json
CVSS version 2 Vector String and Metrics
cvss-v3.x.json
CVSS version 3.x Vector String and Metrics

Click to view the full JSON response schema

+ Response Body

Fa… itHub, etc. Depending on m…

ALL… allowing the retrieval of the

Fortunately, we can collect **multiple CVEs** at once… right?

R… owing the retrieval of data— in… exist, it's a good sign.

…bsite: https://nvd.nist.gov/

Next on this lecture

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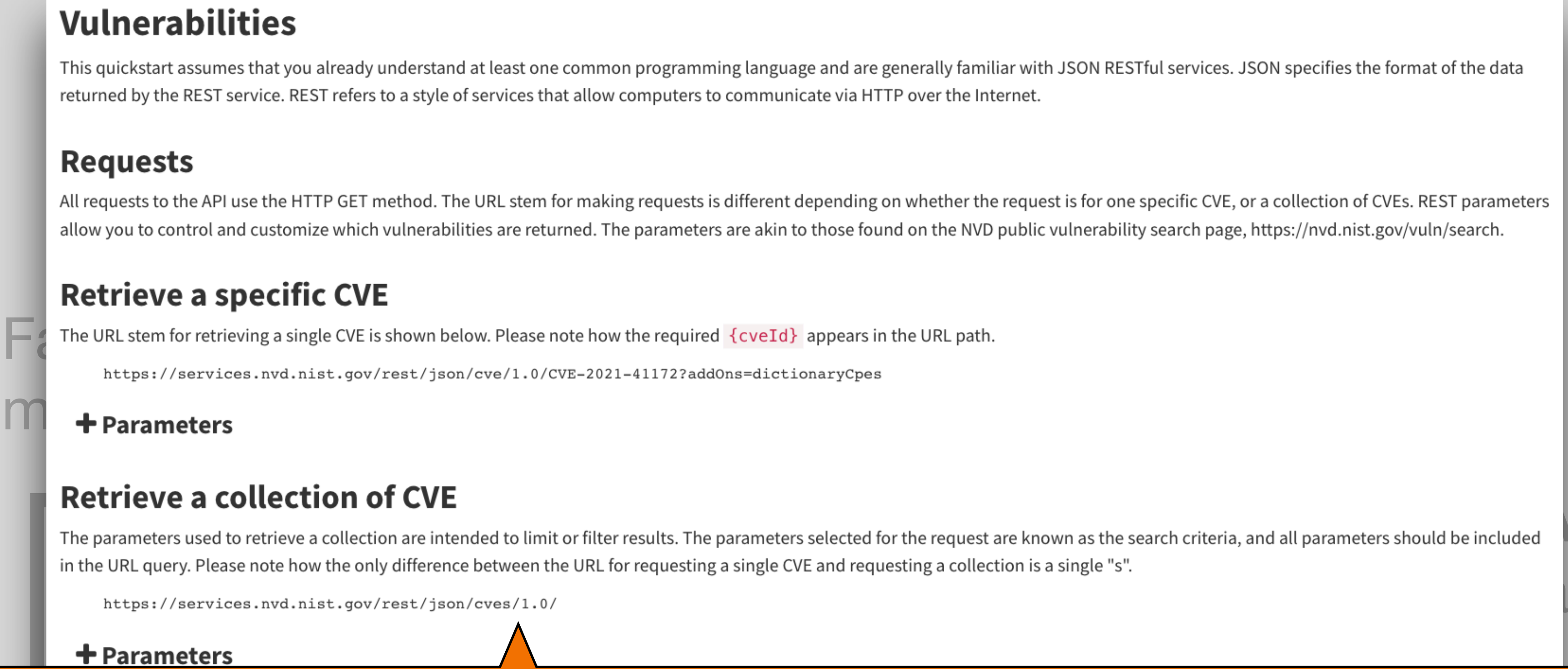

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```
https://services.nvd.nist.gov/rest/json/cves/1.0/
```

+ Parameters

Fortunately, we can collect **multiple CVEs** at once… right?

Let's try this one: https://services.nvd.nist.gov/rest/json/cves/1.0/

```
{“resultsPerPage":20,"startIndex":0,"totalResults":183571,"result":
{"CVE_data_type":"CVE","CVE_data_format":"MITRE","CVE_data_version":"4.0","CVE_data_timestamp":"2022-09-01T10:35Z
","CVE_Items":[{"cve":{"data_type":"CVE","data_format":"MITRE","data_version":"4.0","CVE_data_meta":
{"ID":"CVE-2022-3072","ASSIGNER":"security@huntr.dev"},"problemtype":{"problemtype_data":[{"description":
[{"lang":"en","value":"CWE-79"}]}]},"references":{"reference_data":[{"url":"https://huntr.dev/bounties/9755ae6a-
b08b-40a0-8089-c723b2d9ca52","name":"https://huntr.dev/bounties/9755ae6a-b08b-40a0-8089-
c723b2d9ca52","refsource":"CONFIRM","tags":[]},
[…]
```

This should be fine, but it seems we just obtained… 20 CVEs?! How is that possible? Many public APIs have two main limitations: **pagination**, which limits the amount of data per response, and **rate limits**, which prevent making too many requests in a short period, especially without an API token (to request).

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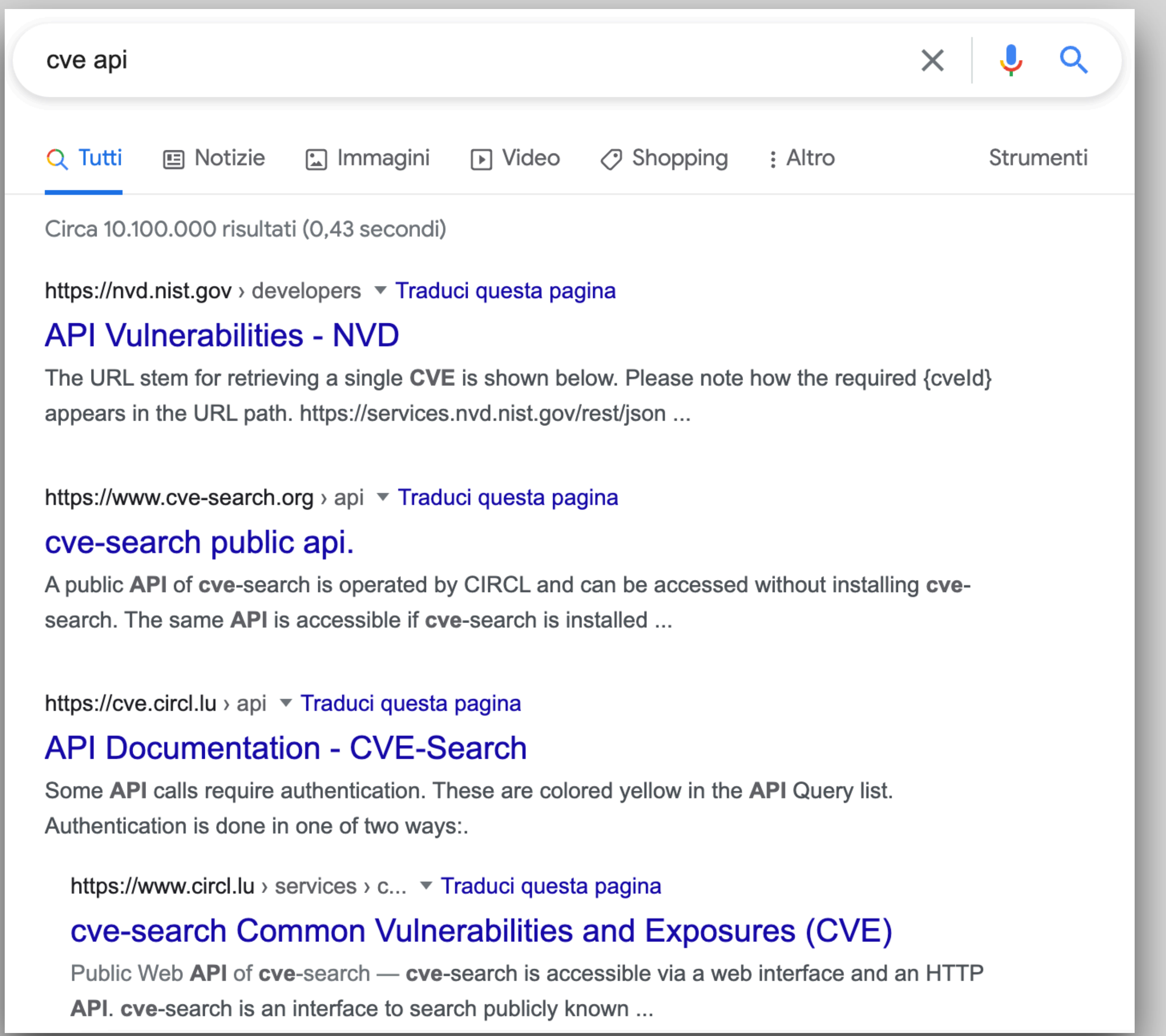
If these limitations are too tight, we must look for something different. Let’s make a quick Google search: “*cve api*”.



Circa 10.100.000 risultati (0,43 secondi)

https://nvd.nist.gov › developers ▾ Traduci questa pagina

API Vulnerabilities - NVD

The URL stem for retrieving a single **CVE** is shown below. Please note how the required {cveId} appears in the URL path. https://services.nvd.nist.gov/rest/json ...

https://www.cve-search.org › api ▾ Traduci questa pagina

cve-search public api.

A public **API** of **cve**-search is operated by CIRCL and can be accessed without installing **cve**-search. The same **API** is accessible if **cve**-search is installed ...

https://cve.circl.lu › api ▾ Traduci questa pagina

API Documentation - CVE-Search

Some **API** calls require authentication. These are colored yellow in the **API** Query list. Authentication is done in one of two ways:.

https://www.circl.lu › services › c... ▾ Traduci questa pagina

cve-search Common Vulnerabilities and Exposures (CVE)

Public Web **API** of **cve**-search — **cve**-search is accessible via a web interface and an HTTP **API**. **cve**-search is an interface to search publicly known ...

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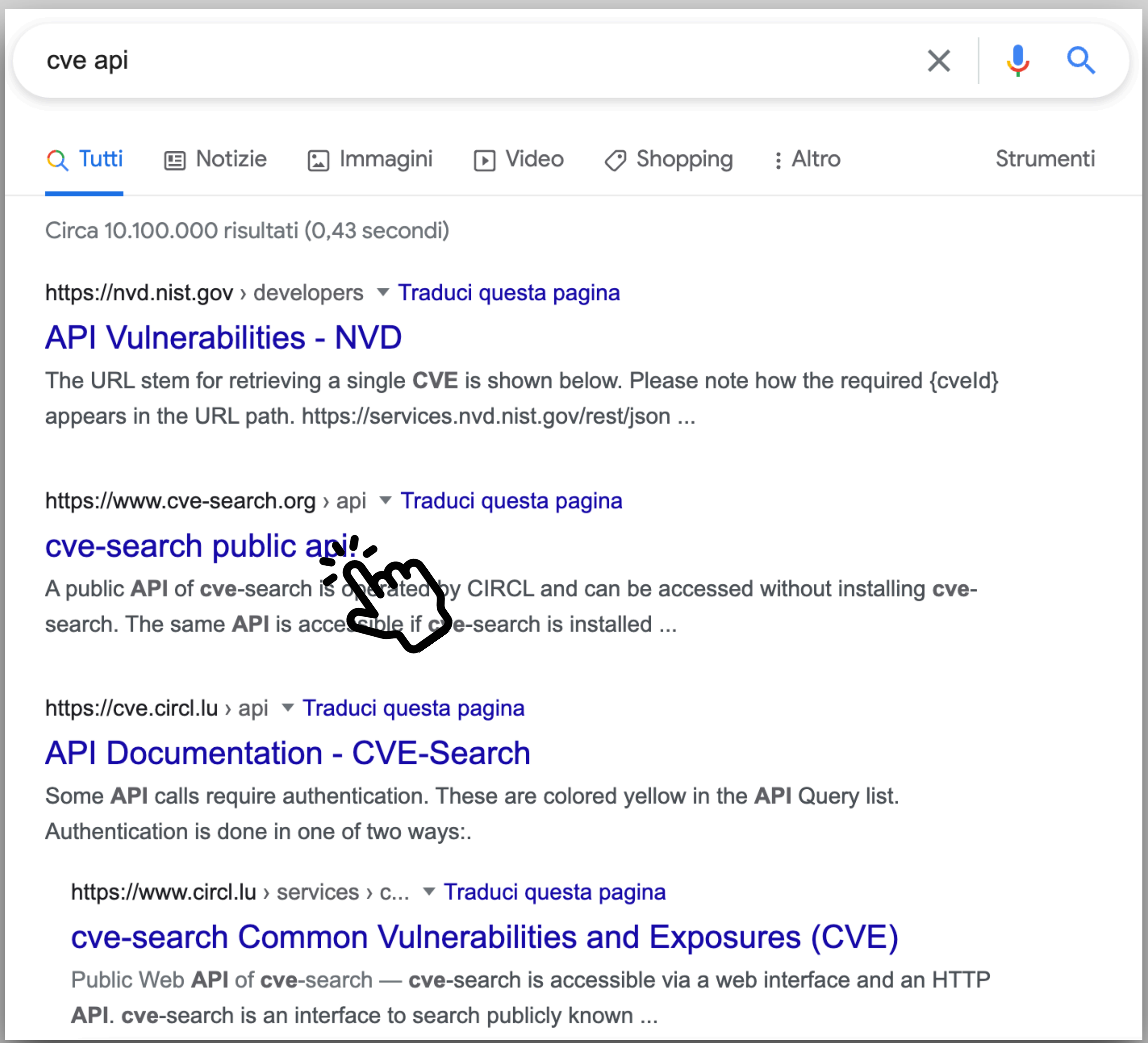

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CIRCL CVE Search

We discover **CVE Search**, a tool that automatically imports CVEs into *MongoDB*. CVE Search also exposes public web API operated by *Computer Incident Response Center Luxembourg* (CIRCL) initiative. Let's take a look.

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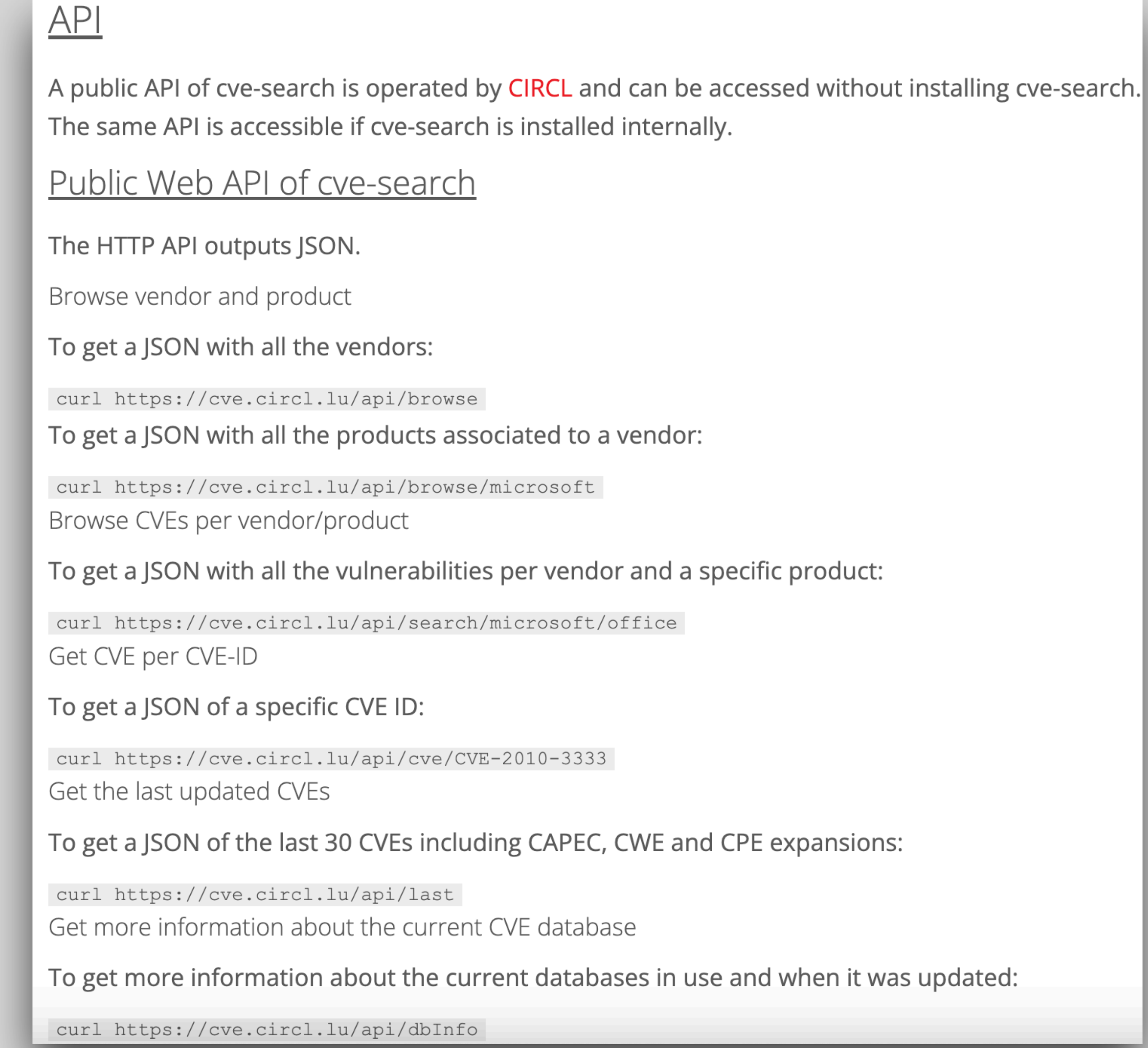

API

A public API of cve-search is operated by CIRCL and can be accessed without installing cve-search. The same API is accessible if cve-search is installed internally.

Public Web API of cve-search

The HTTP API outputs JSON.

Browse vendor and product

To get a JSON with all the vendors:

```
curl https://cve.circl.lu/api/browse
```

To get a JSON with all the products associated to a vendor:

```
curl https://cve.circl.lu/api/browse/microsoft
```

Browse CVEs per vendor/product

To get a JSON with all the vulnerabilities per vendor and a specific product:

```
curl https://cve.circl.lu/api/search/microsoft/office
```

Get CVE per CVE-ID

To get a JSON of a specific CVE ID:

```
curl https://cve.circl.lu/api/cve/CVE-2010-3333
```

Get the last updated CVEs

To get a JSON of the last 30 CVEs including CAPEC, CWE and CPE expansions:

```
curl https://cve.circl.lu/api/last
```

Get more information about the current CVE database

To get more information about the current databases in use and when it was updated:

```
curl https://cve.circl.lu/api/dbInfo
```

CIRCL CVE Search

We can get the list of all the vendors…

…the list of their products…

…and the CVEs of each product.

But even in this case, we might need several requests for the complete list of CVEs. Apparently, there are no particular limitations…

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Querying an API is not that difficult. We can opt for:

Command-line tools. For example, `wget`.

```
wget https://cve.circl.lu/api/cve/cve-2020-1234
```

Dedicated libraries. For example, Python’s `requests`.

```
def call_api(url, try_num=1, max_try=None):
  try:
    headers = {'Accept': 'application/json'}
    return requests.get(url, headers=headers).json()
  except:
    time.sleep(2**try_num + random() * 0.01)
    if max_try and try_num < max_try:
      return call_api(url, try_num=try_num+1)
    else:
      return None
```

Requests project on PyPI: https://pypi.org/project/requests

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To recap, when does public web API worth it?

When there are no limits! This is undoubtedly the best-case scenario, but it is not quite common as you would expect… or there might be a catch, e.g., poor-quality data are returned.

When we just need a sample of the full content. For instance, we are only interested in collecting the CVEs published since 2019 or those with CVSS Base Score = 10. Not suitable for large-scale mining.

When we just need to enrich a set of known data. For instance, we already own some CVEs and want to add more data using the “single CVE” endpoint.

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APIs are cool, but they are not the only entry point to data sources…

If we closely inspect both the NVD and CVE Search websites, we discover the existence of **dumps** (called *data feeds*), i.e., JSON files containing a subset of the full content of the databases.

NVD

JSON format

Extended dump
(daily, per year)

“Recent” dump
(2-hourly)

! Constantly monitor their websites as things can change through time. For example, by the end of 2023, NVD will only offer APIs.

CIRCL
CVE Search

JSON format

Extended dump
(daily, full)

Partial dumps
(daily, CVEs and references)

I tend to use this one, as it’s “just” less than 200MB. I integrate the missing data with API calls or other methods (e.g., scraping).

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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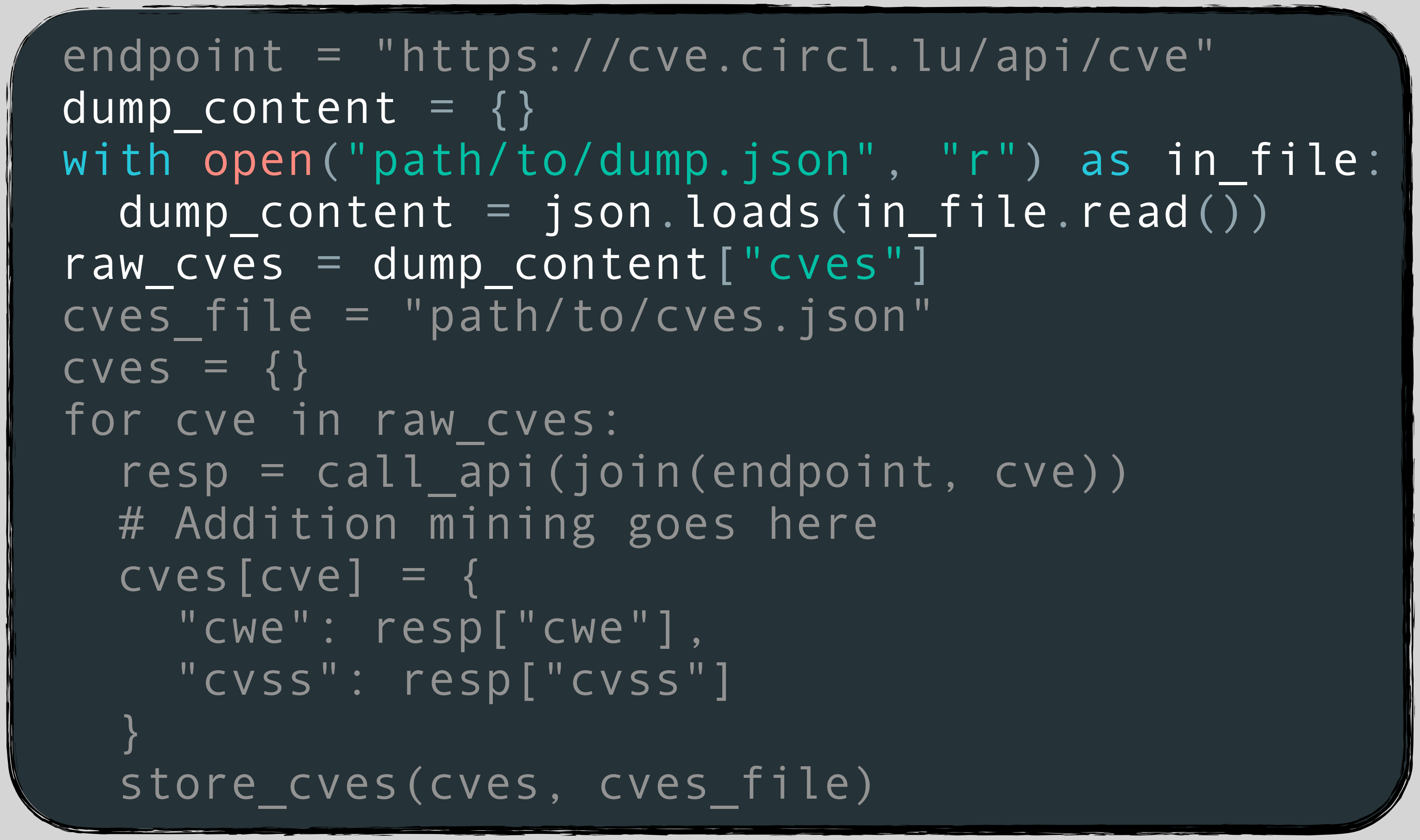
How to collect data from dumps and APIs? The first step is to load the dump into an **iterable data structure** (using any programming language), then loop through each element. During the loop, we can query missing data using the web API.



```
endpoint = "https://cve.circl.lu/api/cve"
dump_content = {}
with open("path/to/dump.json", "r") as in_file:
  dump_content = json.loads(in_file.read())
raw_cves = dump_content["cves"]
cves_file = "path/to/cves.json"
cves = {}
for cve in raw_cves:
  resp = call_api(join(endpoint, cve))
  # Addition mining goes here
  cves[cve] = {
    "cwe": resp["cwe"],
    "cvss": resp["cvss"]
  }
  store_cves(cves, cves_file)
```

We read the file and get the JSON of all CVEs, which becomes a dictionary in Python.

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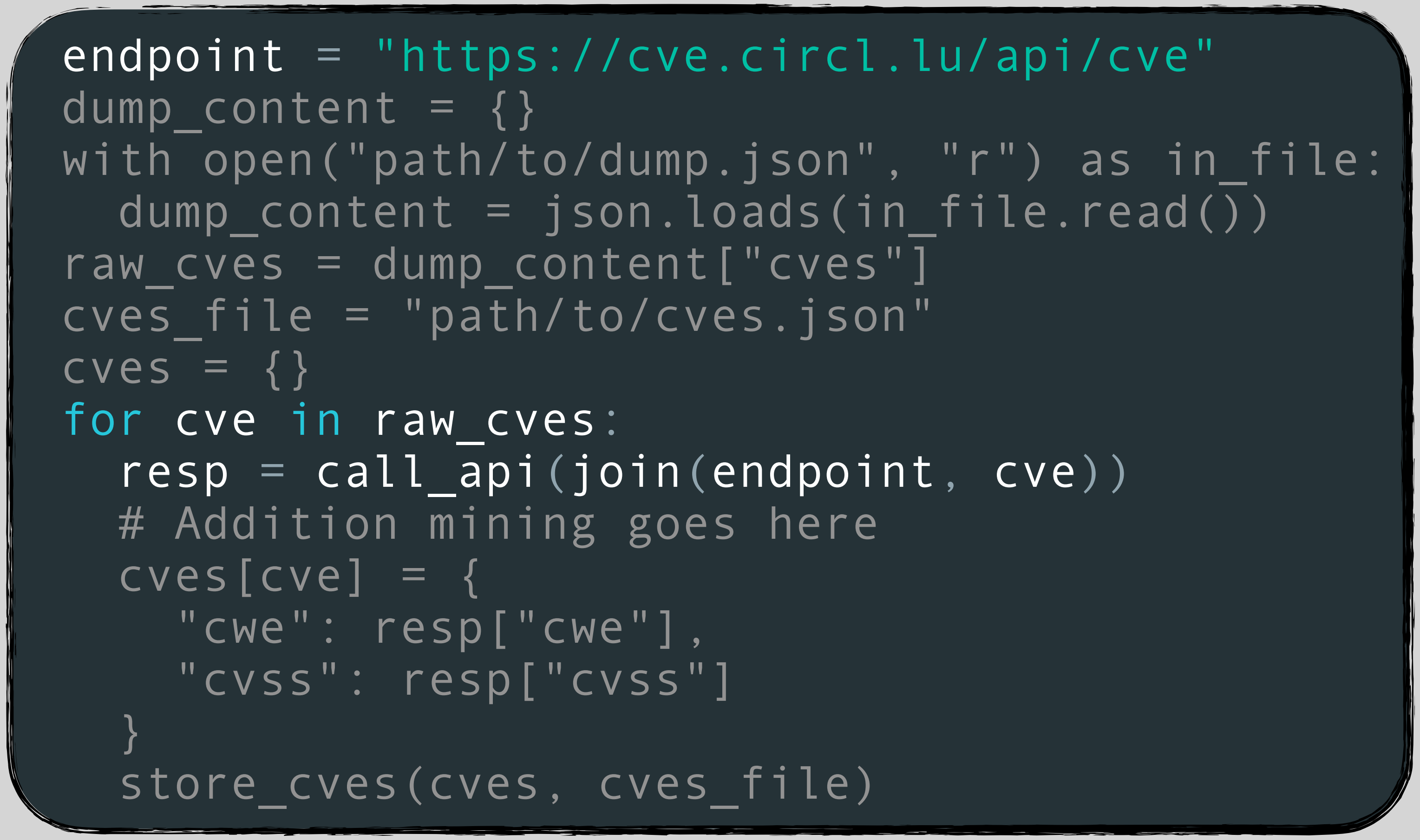

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We loop through CVEs and query additional data using CVE Search API.

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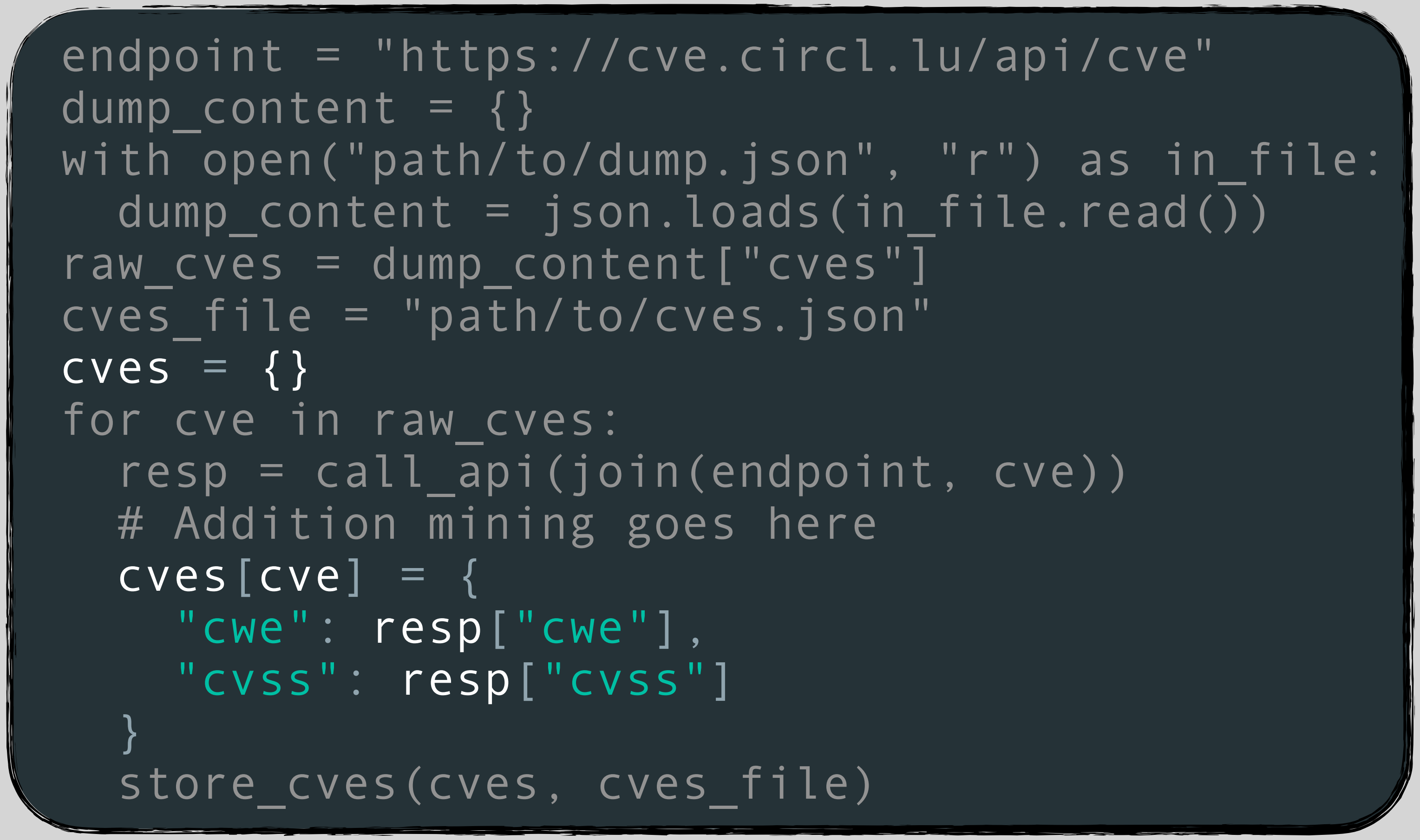

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```

We update the in-memory data structure.

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We periodically save the processed data into our storage.

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We periodically save the processed data into our storage.

In this respect, the way we organize our storage is critical. We should decide the **format** and the **mechanism** to store the processed data efficiently.

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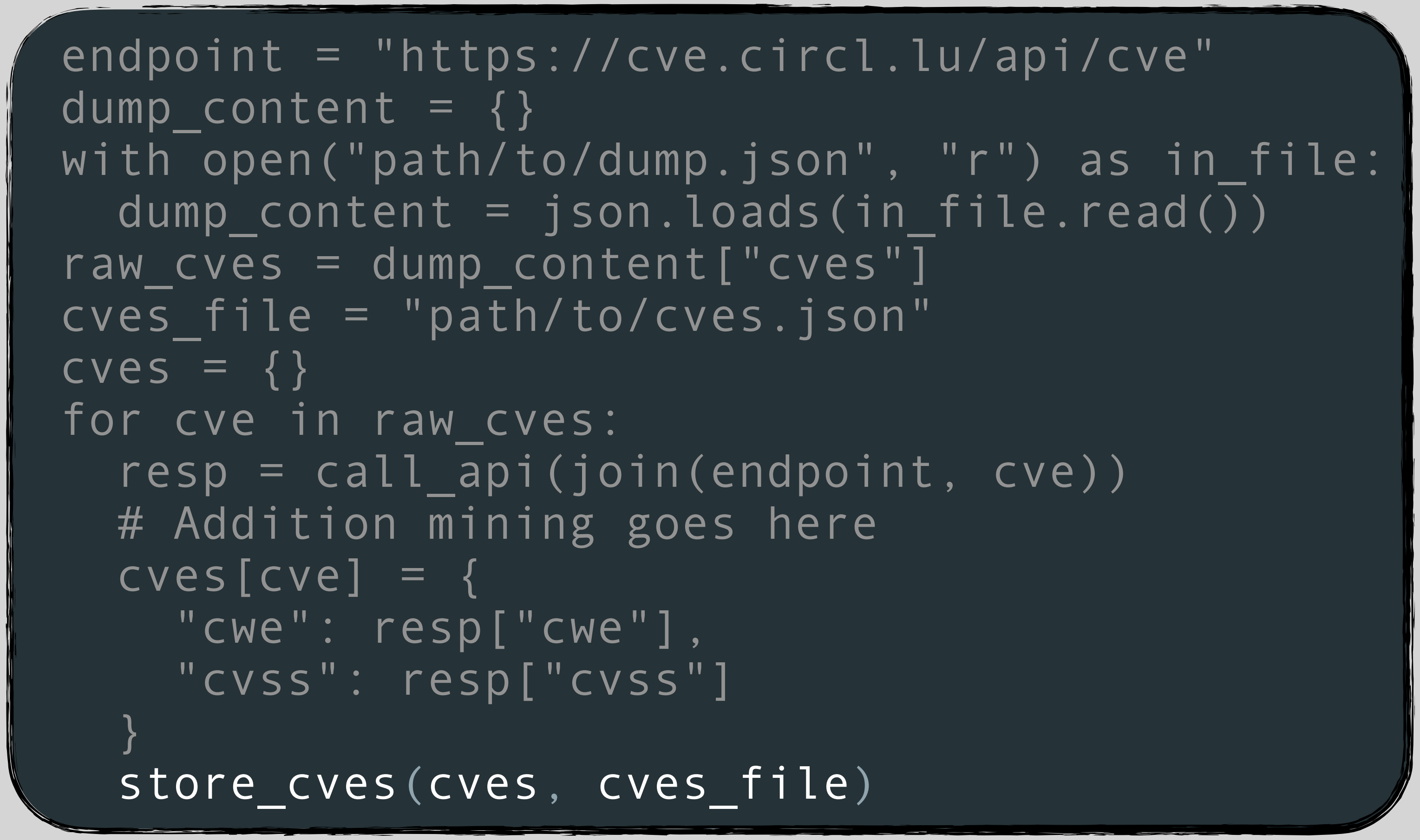

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```

JSON	Human-readable, handles nested data, nice diff, memory inefficient (can be compacted).
CSV	Straightforward and memory efficient, good diff, can’t handle nested data.
SQL DB	Perfect with deeply nested data, less straightforward to set up, no diff.

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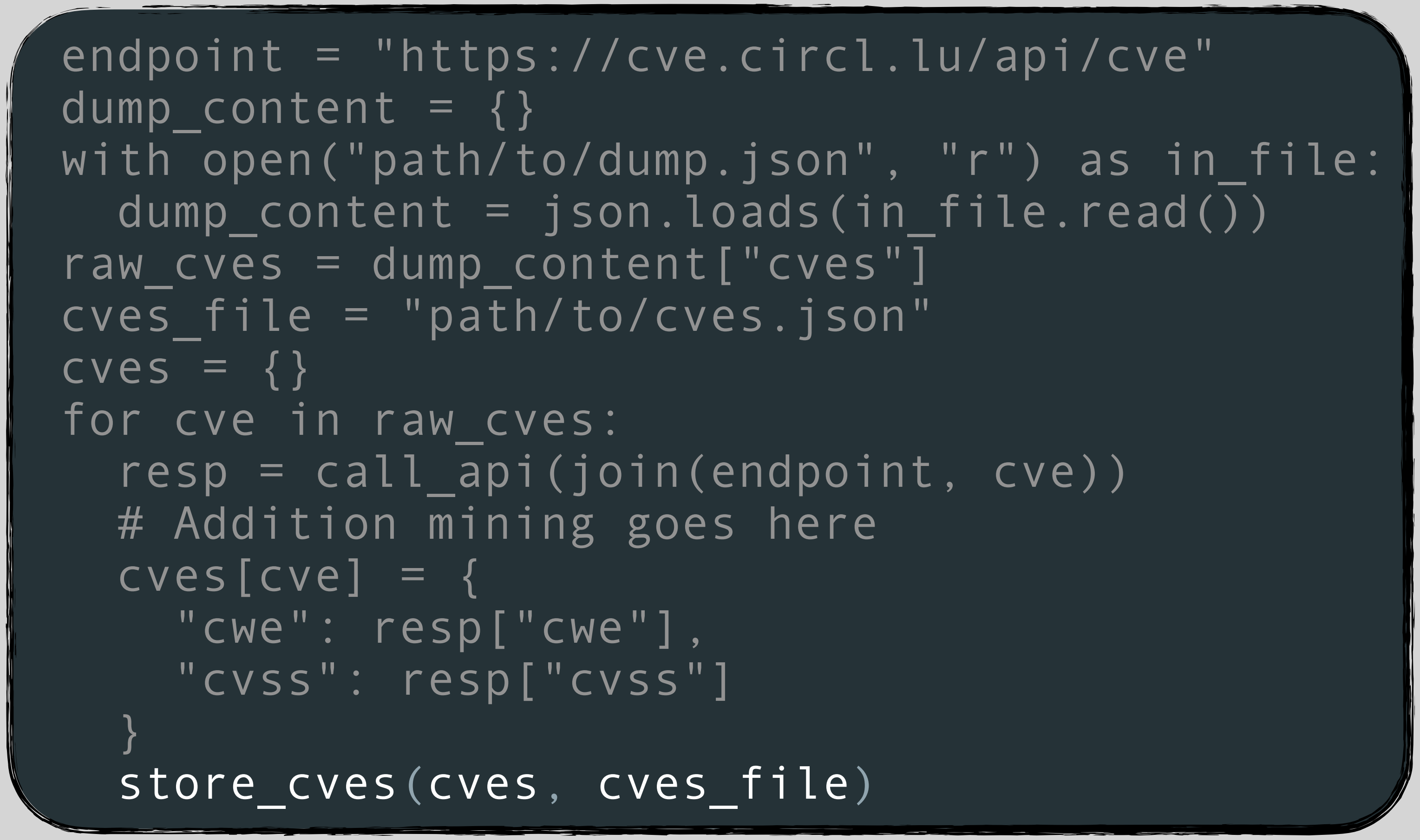

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```

Choose whichever you think is the best, depending on your needs. The important is to…

2 **Honour thy storage**

Store in different files, each with a **chunk of M data elements** (CVEs), to reduce the writing time.

In this respect, the way we organize our storage is critical. We should decide the **format** and the **mechanism** to store the processed data efficiently.

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Fundamentals of Mining Software Repositories for Vulnerability Prediction: The Practical Perspective

How to collect data from dumps and APIs? The first step is to load the dump into an … ough each

… you think is the … your needs, …

```
def store_chunk(items, filepath, num_chunk, lower, upper=None):
  chunk = {k: v for (k, v) in items[lower:upper]}
  num_chunk_str = "0" + str(num_chunk) if num_chunk < 10 else str(num_chunk)
  dest_file = join(dirname(filepath), num_chunk_str + "_" + basename(filepath))
  with open(dest_file, "w") as json_file:
    json.dump(chunk, json_file, indent=2)

def store_cves(data, filepath, chunk_size=5000, rewrite_past_chunks=False):
  items = [(k, v) for k, v in data.items()]
  selected = 0
  num_chunk = 0
  while len(items) - selected > chunk_size:
    upper = selected + chunk_size
    if rewrite_past_chunks:
      store_chunk(items, filepath, num_chunk, selected, upper)
    selected = upper
    num_chunk += 1
  if len(items) - selected > 0:
    store_chunk(items, filepath, num_chunk, selected)
```

```
  }
  store_cves(cves, cves_file)
```

storage

… erent files, … **chunk of M data elements** (CVEs), to reduce the writing time.

In this respect, the way we organize our storage is critical. We should decide the **format** and the **mechanism** to store the processed data efficiently.

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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Fundamentals of Mining Software Repositories for Vulnerability Prediction: The Practical Perspective

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    if rewrite_past_chunks:
      store_chunk(items, filepath, num_chunk, selected, upper)
    selected = upper
    num_chunk += 1
  if len(items) - selected > 0:
    store_chunk(items, filepath, num_chunk, selected)
```

Basically, each 5000 CVEs, a new file is stored and the writings happen on that file, untile reaching 5000 CVEs, and so on…

```
}
store_cves(cves, cves_file)
```

storage

...erent files, ... **chunk of M data elements** (CVEs), to reduce the writing time.

In this respect, the way we organize our storage is critical. We should decide the **format** and the **mechanism** to store the processed data efficiently.

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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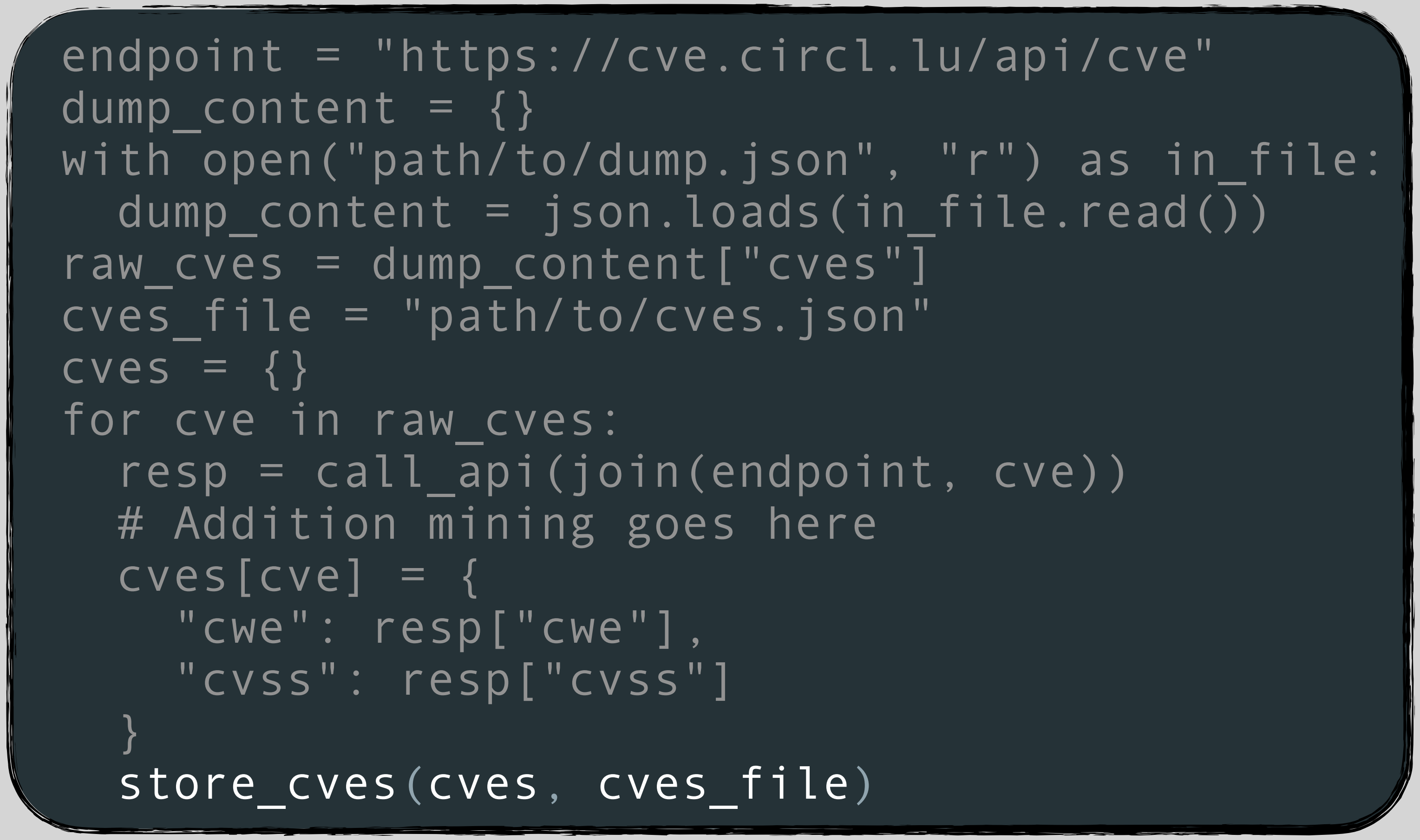
How to collect data from dumps and APIs? The first step is to load the dump into an **iterable data structure** (using any programming language), then loop through each element. During the loop, we can query missing data using the web API.



```
endpoint = "https://cve.circl.lu/api/cve"
dump_content = {}
with open("path/to/dump.json", "r") as in_file:
  dump_content = json.loads(in_file.read())
raw_cves = dump_content["cves"]
cves_file = "path/to/cves.json"
cves = {}
for cve in raw_cves:
  resp = call_api(join(endpoint, cve))
  # Addition mining goes here
  cves[cve] = {
    "cwe": resp["cwe"],
    "cvss": resp["cvss"]
  }
  store_cves(cves, cves_file)
```

The mining heavily relies on this loop. We should put in place some other good practices.

3 **Thou shalt not take hostage your machine**

Mining can take several days/weeks. Put in place several actions to improve your mining scripts.

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

Next on this lecture

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```python
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```

[Tip #1] Monitor the loop progress. Don't make a guess, but monitor the loop status using a **progress bar.** Other than using the terminal, you can also print the progress onto a file—good when running the script on a server.

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raw_cves = dump_content["cves"]
cves_file = "path/to/cves.json"
cves = {}
for cve in tqdm(raw_cves):
  resp = call_api(join(endpoint, cve))
  # Addition mining goes here
  cves[cve] = {
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```

[Tip #1] Monitor the loop progress. Don’t make a guess, but monitor the loop status using a **progress bar**. Other than using the terminal, you can also print the progress onto a file—good when running the script on a server.

I recommend the TQDM library, which implements a good-looking progress bar by just wrapping the iterable structure in a function.

```
80%|███████████     | 160/200 [02:00<08:00, 1.3it/s]
```

If each element takes about the same time, we have a good estimate of the duration of the loop.

TQDM project on PyPI: https://pypi.org/project/tqdm/

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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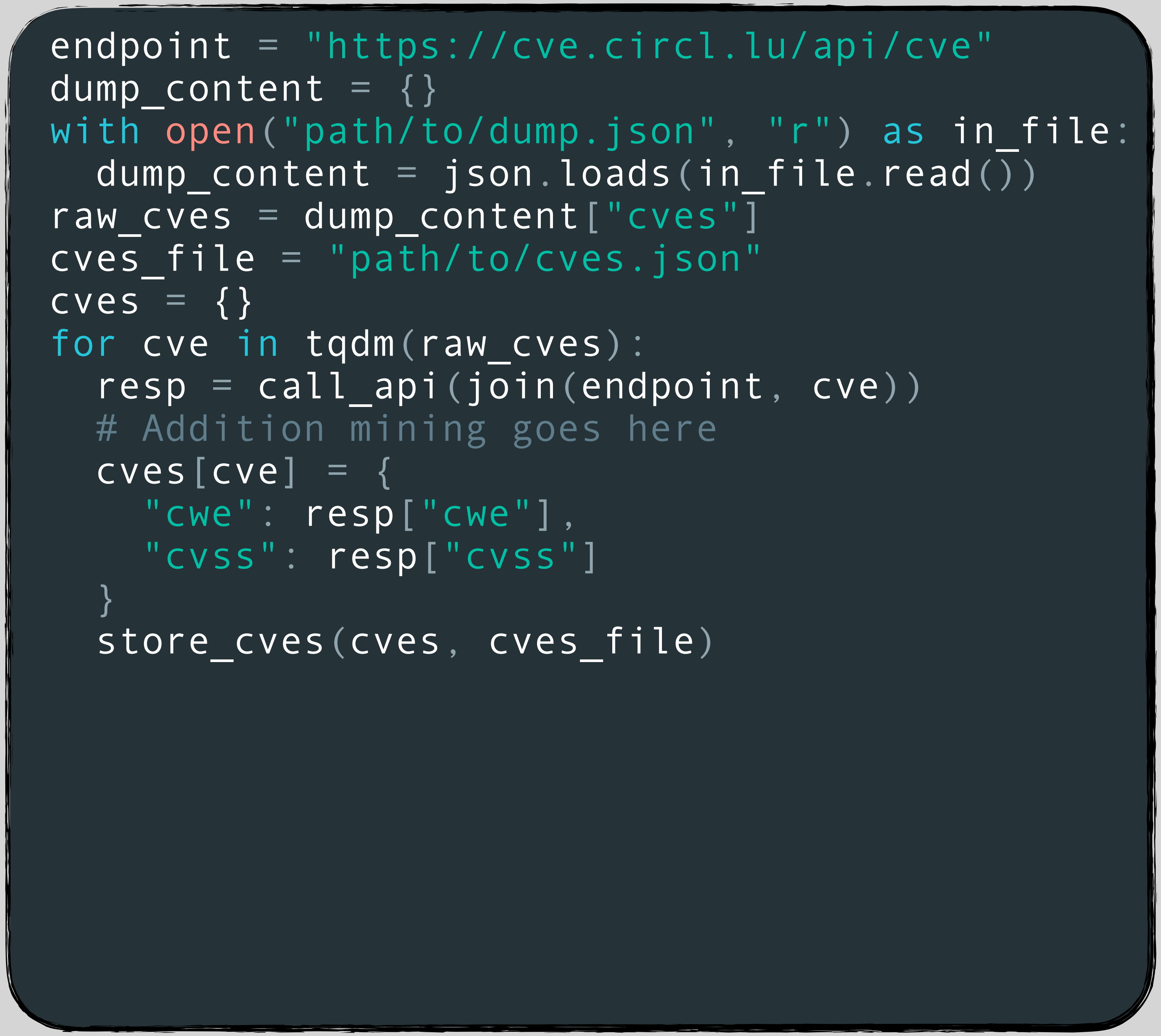
Fundamentals of Mining Software Repositories for Vulnerability Prediction: The Practical Perspective



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  # Addition mining goes here
  cves[cve] = {
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  }
  store_cves(cves, cves_file)
```

[Tip #2] Save intermediate results. Storing all the processed data at the end of the loop is not a smart move— things can go wrong (power outage, accidental SIGKILL), and we have to start over. However, doing it at every iteration can be costly. Hence, storing data every K iterations is a good **balance between speed and safety**.

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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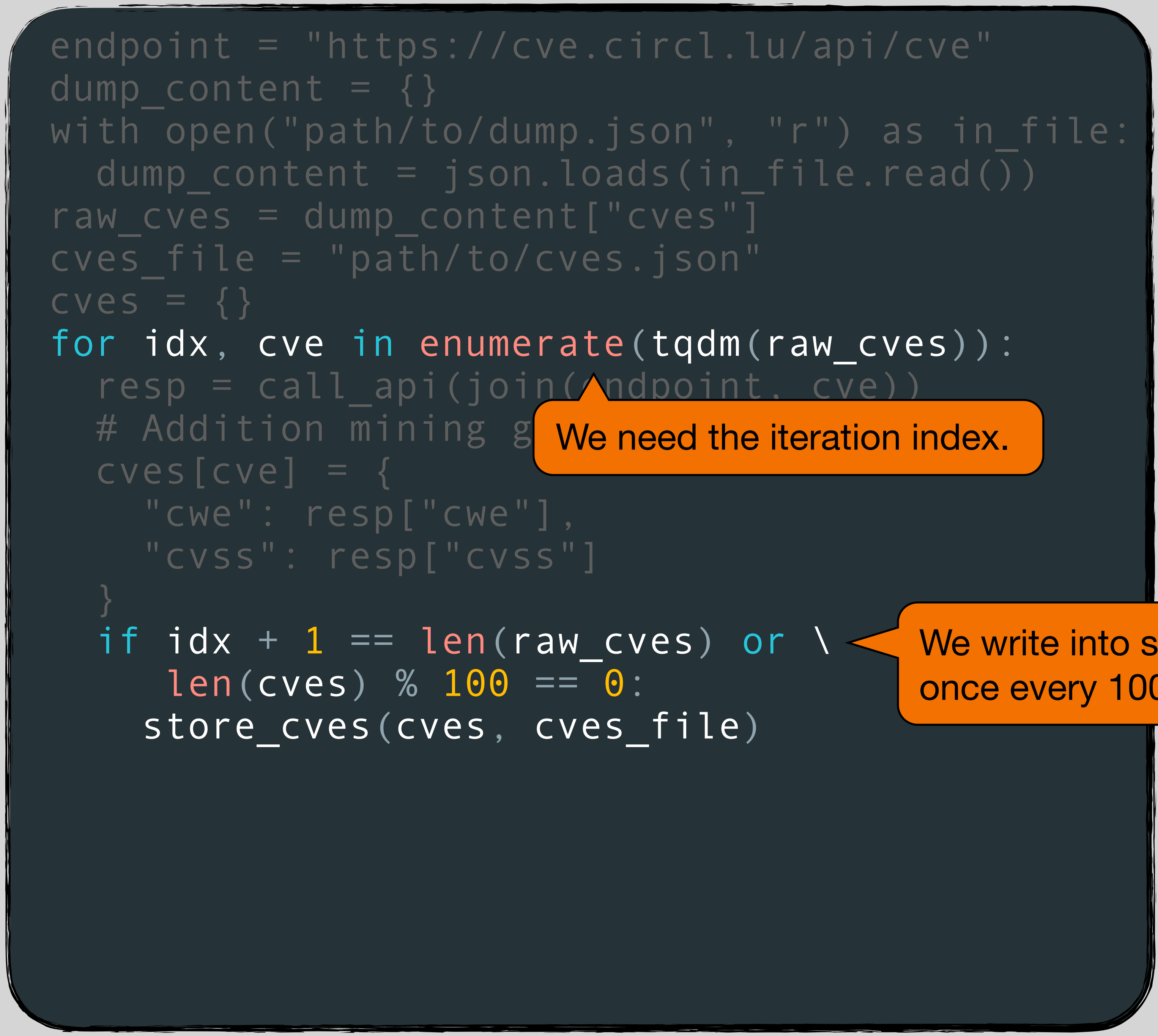

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cves_file = "path/to/cves.json"
cves = {}
for idx, cve in enumerate(tqdm(raw_cves)):
  resp = call_api(join(endpoint, cve))
  # Addition mining g
  cves[cve] = {
    "cwe": resp["cwe"],
    "cvss": resp["cvss"]
  }
  if idx + 1 == len(raw_cves) or \
     len(cves) % 100 == 0:
    store_cves(cves, cves_file)
```

We need the iteration index.

We write into storage at the last iteration or once every 100 CVEs successfully processed.

[Tip #2] Save intermediate results. Storing all the processed data at the end of the loop is not a smart move— things can go wrong (power outage, accidental SIGKILL), and we have to start over. However, doing it at every iteration can be costly. Hence, storing data every K iterations is a good **balance between speed and safety**.

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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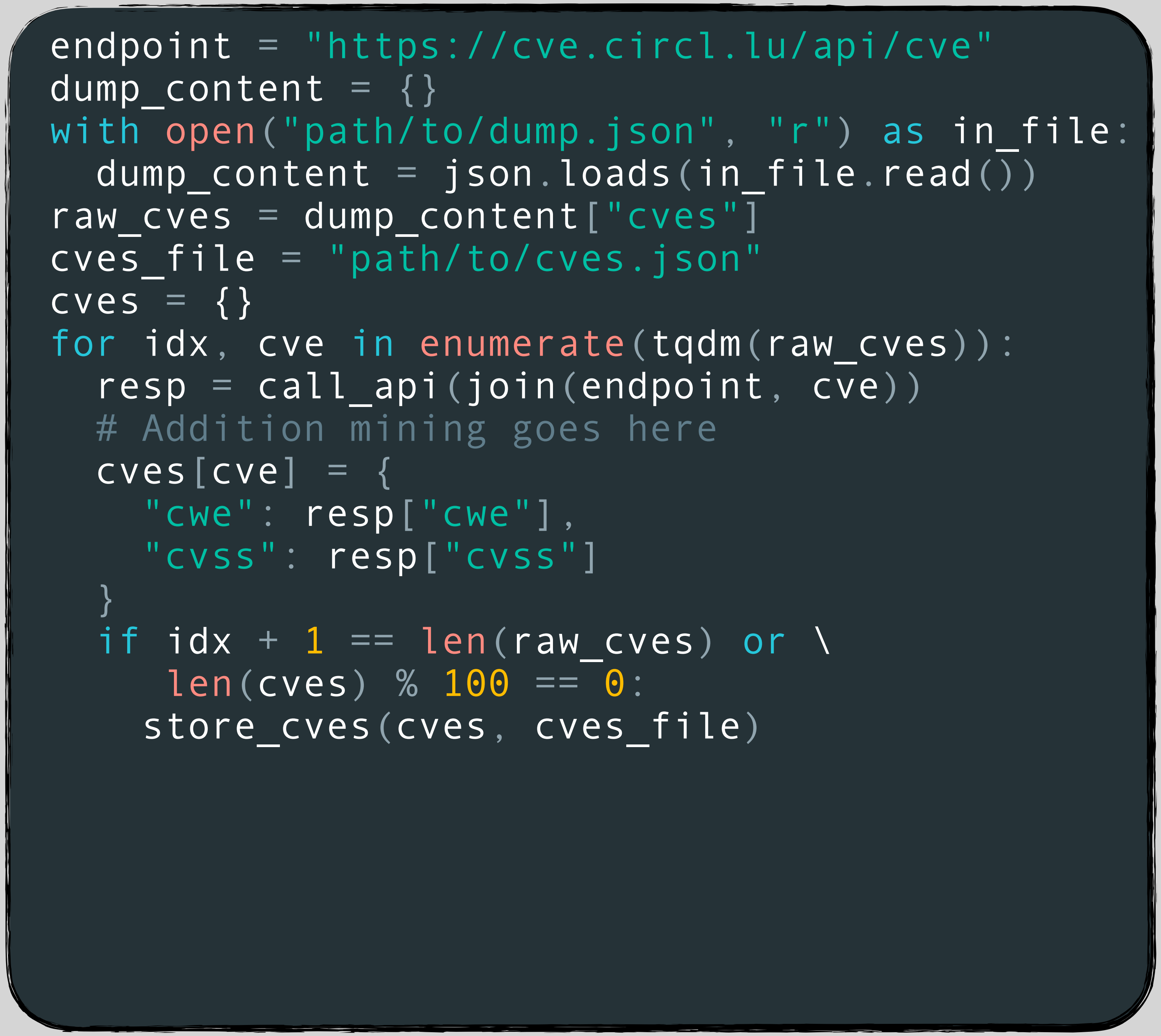

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  }
  if idx + 1 == len(raw_cves) or \
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    store_cves(cves, cves_file)
```

[Tip #3] Restart from the intermediate results. The intermediate results are not only meant for back-ups but can be used to **find the point where to start again after an interruption.** Basically, we read the file of processed CVEs and avoid re-processing them.

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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```
endpoint = "https://cve.circl.lu/api/cve"
dump_content = {}
with open("                                as in_file:
  dump_cont                                .read())
raw_cves = d
cves_file = "path/to/cves.json"
cves = read_cves(cves_file)
for idx, cve in enumerate(tqdm(raw_cves)):
  if cve in cves:
    continue
  resp = ca                               cve))
  # Additio
  cves[cve]
    "cwe": resp["cwe"],
    "cvss": resp["cvss"]
  }
  if idx + 1 == len(raw_cves) or \
     len(cves) % 100 == 0:
    store_cves(cves, cves_file)
```

We initialize by reading any file containing processed CVEs.

If a CVE has already been processed, skip it.

[Tip #3] Restart from the intermediate results. The intermediate results are not only meant for back-ups but can be used to **find the point where to start again after an interruption**. Basically, we read the file of processed CVEs and avoid re-processing them.

```
def read_cves(filepath):
  dn = dirname(filepath)
  bn = basename(filepath)
  data = {}
  for f in sorted(listdir(dn)):
    path = join(dn, f)
    if exists(path) and getsize(path):
      with open(path, "r") as in_file:
        data.update(json.load(in_file))
  return data
```

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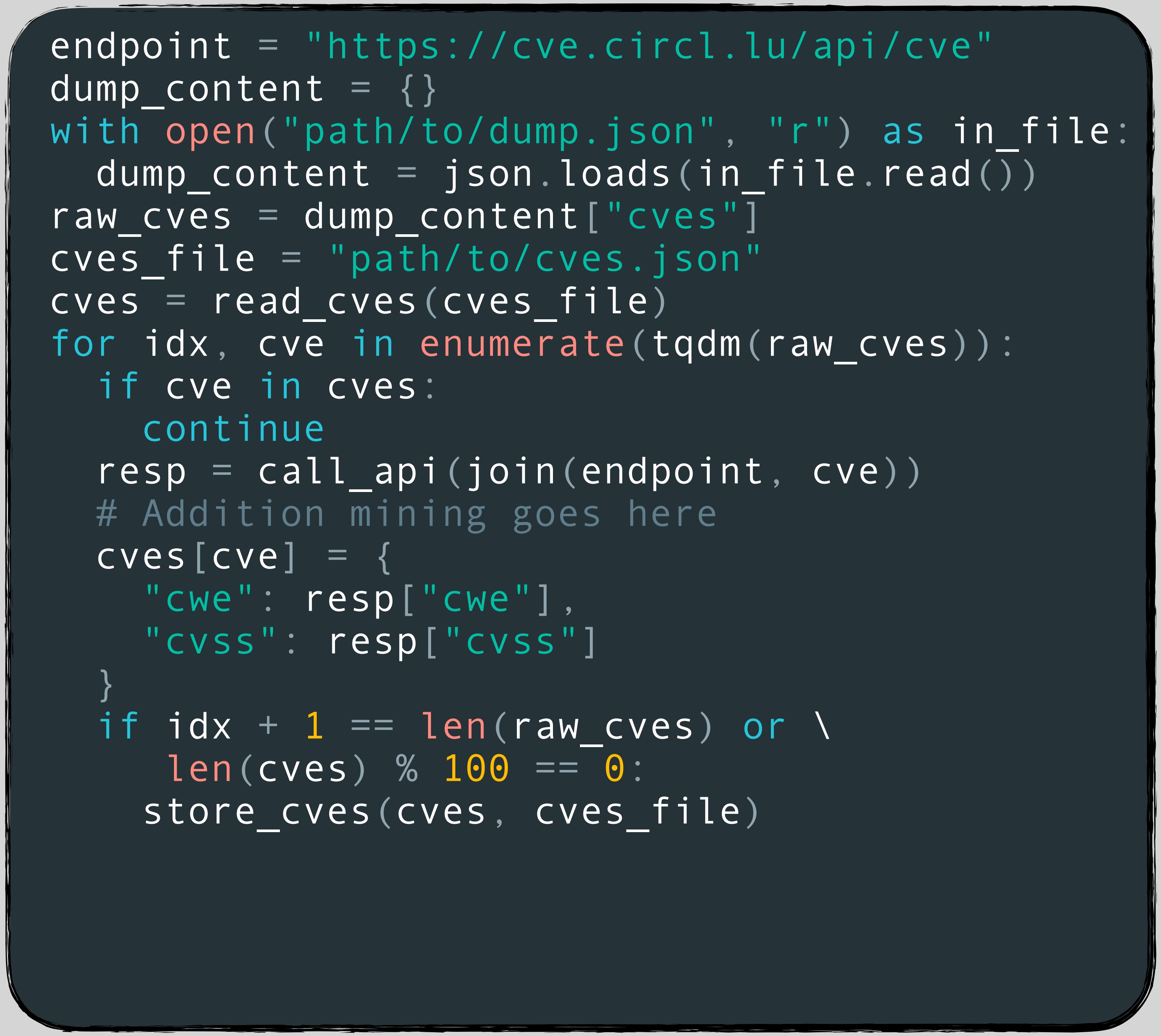

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endpoint = "https://cve.circl.lu/api/cve"
dump_content = {}
with open("path/to/dump.json", "r") as in_file:
  dump_content = json.loads(in_file.read())
raw_cves = dump_content["cves"]
cves_file = "path/to/cves.json"
cves = read_cves(cves_file)
for idx, cve in enumerate(tqdm(raw_cves)):
  if cve in cves:
    continue
  resp = call_api(join(endpoint, cve))
  # Addition mining goes here
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  if idx + 1 == len(raw_cves) or \
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```

[Tip #4] Enable graceful interruption. Sometimes we have to interrupt the script manually. However, interrupting during a file writing has the risk of corrupting its content: we lose our progress. Hence, we can intercept the CTRL+C (SIGINT), set a flag to true, and stop the loop in a safe state (e.g., between iterations) to avoid damage.

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```
endpoint = "https://cve.circl.lu/api/cve"
dump_content = {}
with open("path/to/dump.json", "r") as in_file:
  dump_content = json.loads(in_file.read())
raw_cves = dump_con
cves_file = "path/t
cves = read_cves(cv
stop_signal = False
signal.signal(signal.SIGINT, signal_handler)
for idx, cve in enumerate(tqdm(raw_cves)):
  if stop_signal:
    break
  if cve in cves:
    continue
  resp = call_api(join(endpoint, cve))
  # Addition mining goes here
  cves[cve] = {
    "cwe": resp["cwe"],
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  if idx + 1 == len(raw_cves) or \
     len(cves) % 100 == 0:
    store_cves(cves, cves_file)
```

We can use a custom handler triggered when a SIGINT is received.

[Tip #4] Enable graceful interruption. Sometimes we have to interrupt the script manually. However, interrupting during a file writing has the risk of corrupting its content: we lose our progress. Hence, we can intercept the CTRL+C (SIGINT), set a flag to true, and stop the loop in a safe state (e.g., between iterations) to avoid damage.

The handler just sets a global variable to true, queried at the start of each iteration.

```
def signal_handler(sig, frame):
  global stop_signal
  print('Going to gracefully stop')
  stop_signal = True
```

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It is known that **things never go as expected**. It happens continuously: we run our fantastic mining script before ending the work day. We go back home, arrange something with our friends, eat or drink something, and then go to sleep.

The next day at the office we discovered something terrible: the script crashed 10 minutes after we closed our office's door!

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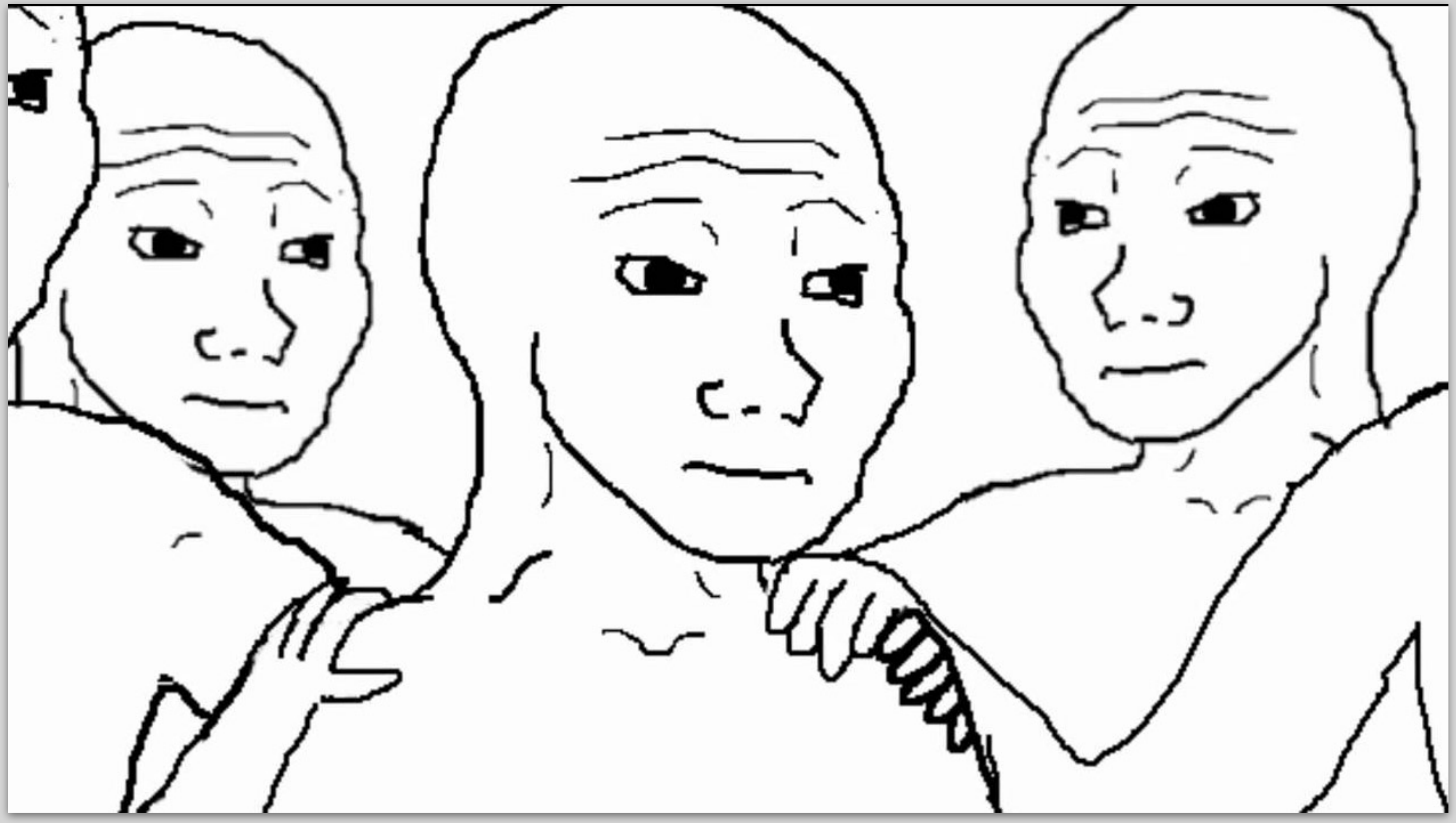

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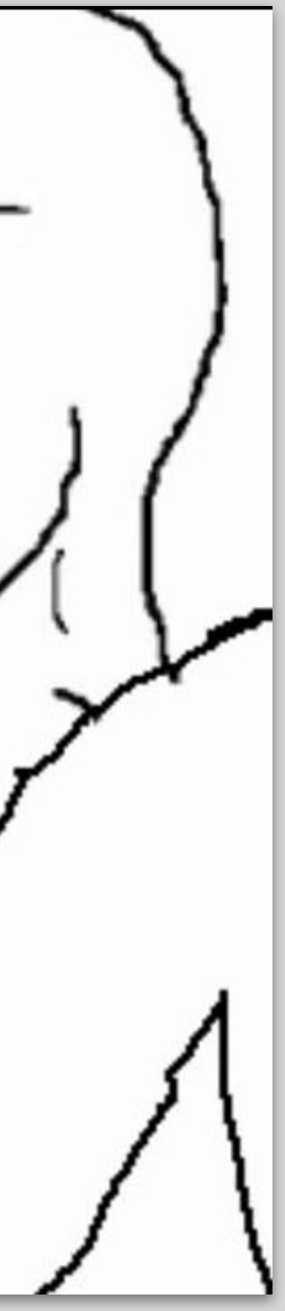

It is time to introduce another commandment:

4 **Thou shalt not ignore corner cases**

Make your script **resistant to unforeseen events**. We could wrap all the loop logic inside a great *try-catch* block that captures any unexpected exception.

TMP

The idea is to catch the exception and skip that iteration. At the same time, we **temporarily store** the problematic CVEs in a dedicated file, with the associated exception message as well.

Later, we can inspect this file, try to figure out a way to fix the issue, and re-run the loop to include the discarded CVEs.

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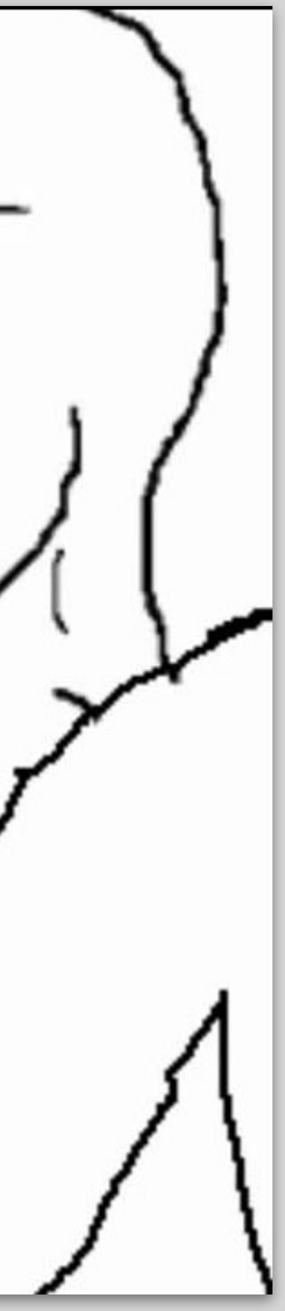

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Later, we can inspect this file, try to figure out a way to fix the issue, and re-run the loop to include the discarded CVEs.

↓

Yet, there might be cases when we can’t fix the CVE, e.g., some critical data are entirely missing or too malformed to be fixed.

BAD

The idea is to solve as many issues as possible. When not possible, we **permanently store** the problematic CVEs in another dedicated file, with the associated exception message as well.

REJECTED

The CVE number had been allocated but was not approved for various reasons (duplicate, not a real vulnerability, etc.). **Example**: CVE-2012-2701

NON-EXISTENT

The CVE “number” appears in a dump but does not point to a really-existing CVE due to the invalid format. **Examples**: CVE20163325, CVE-2012-087

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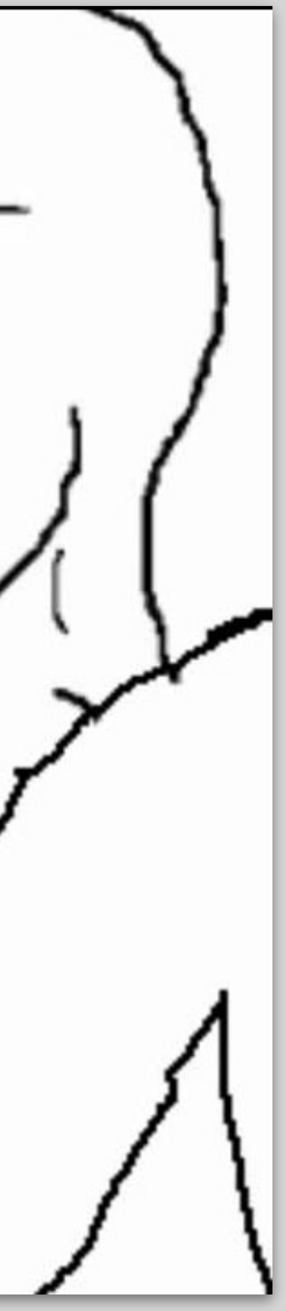

TMP

The idea is to catch the exception and skip that iteration. At the same time, we **temporarily store** the problematic CVEs in a dedicated file, with the associated exception message as well.

BAD

The idea is to solve as many issues as possible. When not possible, we **permanently store** the problematic CVEs in another dedicated file, with the associated exception message as well.

5 **Thou shalt not keep your secrets**

Keep track of everything, especially the data that you discard. Do it for **transparency**—and so, the study's credibility—and for **your future** self!

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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Our set of collected CVEs may need **some further refinement**. Previously, we just checked whether a CVE was "sufficiently valid" to be involved in the study, but there are some other **quality checks** that we should put in place. We initiate the **data preparation** phase.

6 **Thou shalt apply all pre-processing at once**

Data preparation is not a transaction. We make an initial preparation to arrange the data in an **exportable format**. Then, we further prepare the data to extract the dataset for **training and testing**.

Cell "Data Preparation"

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Explore Data

Standardize Formats

Drop Out-of-scope

Fix/Impute Data

Drop Invalid

Cell “Data Preparation”

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- **Explore Data**
- Standardize Formats
- Drop Out-of-scope
- Fix/Impute Data
- Drop Invalid

It’s essential to **profile** our data with sufficient effort to understand their nature and decide how to handle them. Investing no time in doing this will cost you a lot. Here is another commandment:

7 **Thou shalt not put your faith in the collected data**

The data collected are not exempt from errors—e.g., the CVSS Base Score could be 100 due to an extra zero typed. Ensure the data have the values you expect.

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- Explore Data
- **Standardize Formats**
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- Drop Invalid

Sometimes we want to convert the data into a **more suitable/ readable format**. For example, if the dates report the time zone, we can convert them into the *yyyy-mm-dd* format as we do not need it.

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Explore Data

Standardize Formats

Drop Out-of-scope

Fix/Impute Data

Drop Invalid

Standardized formats are easier to inspect, so we can **quickly identify data outside our scope**, e.g., CVEs published after 2021-01-01.

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- Explore Data
- Standardize Formats
- Drop Out-of-scope
- **Fix/Impute Data**
- Drop Invalid

Whenever possible, we should identify possible errors in data and try to fix them. The most common case is **missing data**. There are cases in which null can be safely intended as 0. Other times, null really means “missing information”. If that information is too-critical, we might think of discarding those CVEs.

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- Explore Data
- Standardize Formats
- Drop Out-of-scope
- Fix/Impute Data
- **Drop Invalid**

After all these steps, we might discover CVEs having “weird data”. As seen in the example before, there might be CVEs with a CVSS Base Score equal to 100. We cannot safely say that the intended number was 10, so it is safer to drop that CVE. **It’s better to have less noise than to have lots of data**.

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ats
e

Yet, even after cleaning, we could still have forgotten something, i.e., letting **erroneous data circumvent the filters** or **discarding valid data**. Are we really sure we have implemented everything correctly? We are software engineers, so we should test at least our final results.

8 **Thou shalt not put your faith in the processed data**

We should do **post-condition verification**: read the files with the prepared data and ensure all the steps had the intended effect.

Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

Next on this lecture

Fundamentals of Mining Software Repositories for Vulnerability Prediction: The Practical Perspective

Now, we can go for the second part of the data preparation: preparing them in a suitable format for the ML models.

ML models expect data in a **tabular format** (e.g., a pandas DataFrame). Each row represents the **observation** (CVE, commit, etc.), depending on the granularity of our task. The columns are dedicated to (1) the ground truth labels and (2) the features.

Indices	Label	Feature #1	Feature #2	…	Feature #k
0	⊗	100	0.1		1
1	✪	200	0.05		2
…	…	…	…		…
N	⊗	50	0.025		10

Cell “Dataset Setup”

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The first step is to decide what goes into the rows! We have to combine all the various files we obtained in the previous phase and express any data at the targeted level. For example, if the target are *commits*, then each row should represent a commit!

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Select the data to be directly used as features or run algorithms to compute additional metrics that could not be mined directly.

9 **Thou shalt not be shy on the feature set**

Try to involve as many features as possible. Consider reasonable metrics only, i.e., those that (might) have some correlation with the label. Avoid **shortcut features**.

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Select the data and/or run algorithms to assign labels. If this cannot be done, rely on (semi-)manual approaches.

10 **Remember the ground truth, to keep it reliable**

Never underestimate the importance of a good, sound, and reliable ground truth. The models' performance is **highly influenced by this choice**.

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When running empirical studies, we should consider using **validation schemes**, e.g., random or time-aware cross-validations. Since we are preparing the data for the learners, we can already prepare all the *N* pairs of training and test sets in this phase.

❗ Depending on the **degree of realism** of our validation, we might need to re-assign the labels and/or extract some features. Within a validation round, **we are not supposed to look at the data of other rounds!**

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Let's suppose we use a traditional random 10-fold cross-validation. We need to create 10 training sets and 10 test sets.

Let's suppose Feature #2 is computed depending on the value of Feature #1 **of ALL observations.**

$$f_2(x) = \frac{f_1(x)}{\sum_x f_1(x)}$$

The pre-computed Feature #2 column is invalid! We have to re-compute it again on the training set!

Round #1

Training

Indices
5
83
120
253
1245
2210

Test

Indices
15
110
2145

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Round #1

Training

Indices	Feature #1	Feature #2
5	1	0.67
83	2	0.13
120	3	0.20
253	4	0.27
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$$\sum_x f_1(x) = 15$$

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We store this sum to compute each test instance's Feature #2 value. The test instances **NEVER LOOK at other test instances!**

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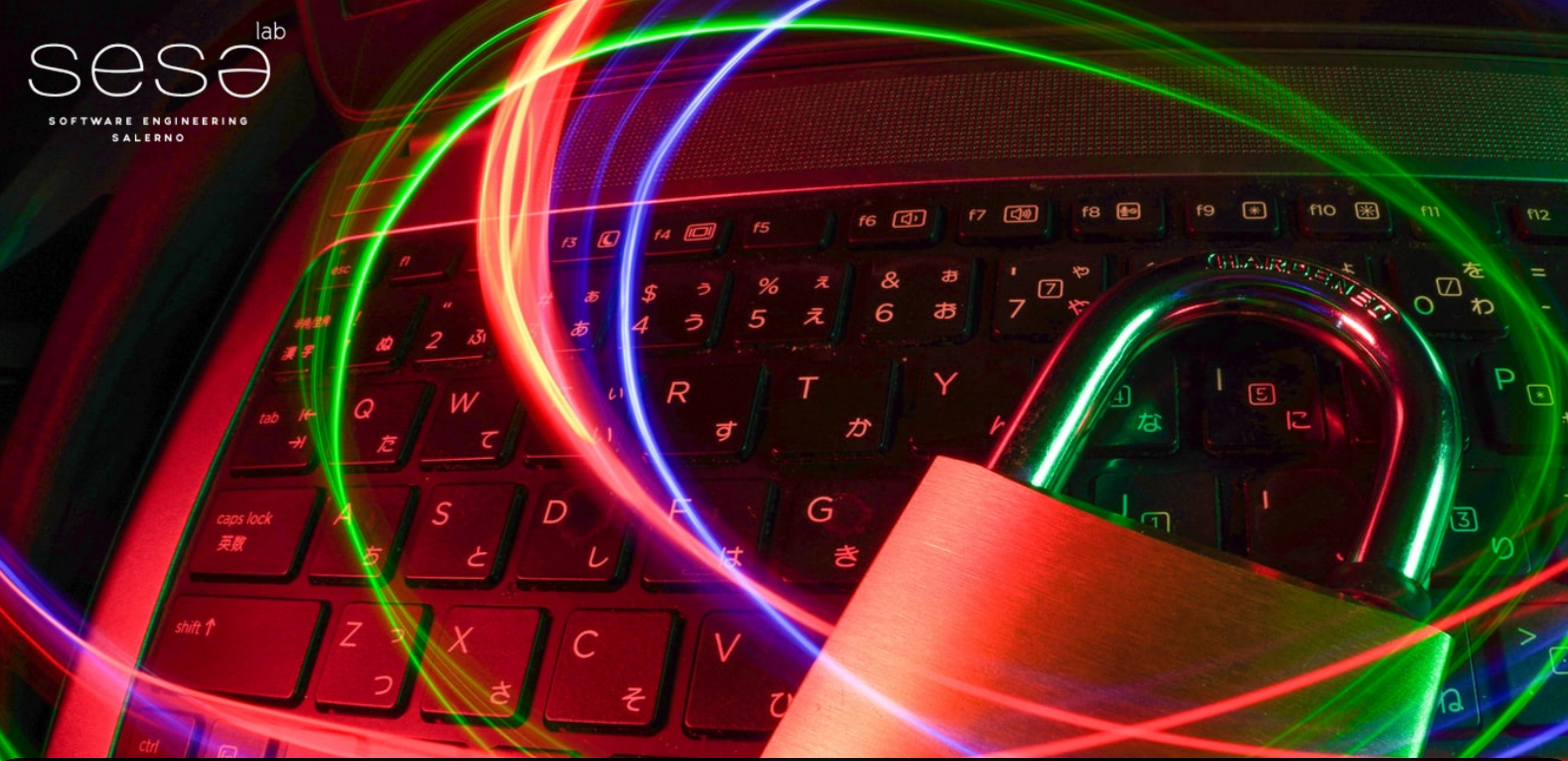

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Mining Software Repositories for Vulnerability Prediction: Lessons Learned, Challenges, and Recommendations

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