# Software Heritage

## Towards A New Era for Software Engineering, Cybersecurity, and AI

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Inria and Université Paris Cité

September 8–12, 2026
CBSoft 2026, São Paulo

Software Heritage
THE GREAT LIBRARY OF SOURCE CODE

# Outline


1. Meet Software Heritage
2. From archive to revolutionary infrastructure
3. Software for research: reference archive — ACAD_ADOPTION
4. Research on software: datasets from the archive — DATASETS
5. Selected highlight: Impact on software studies — ESE_STUDIES
6. A Very Large Telescope to explore the software development galaxy
7. Selected highlight: Improving Open Source Security with SWH(Sec) — SECURITY
8. Selected highlight: AI and transparent LLMs — CODECOMMONS
9. One last thing
10. Conclusion

Software Heritage

THE GREAT LIBRARY OF SOURCE CODE

Inria with unesco

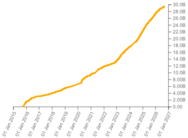
# The largest open source code archive: one infrastructure, open, shared, non profit

Unique digital common good *built in France since 2015*

**Cultural Heritage** | **Industry** | **Research** | **Public Administration**

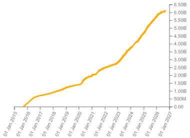
Source files

29,523,977,803



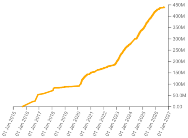
Commits

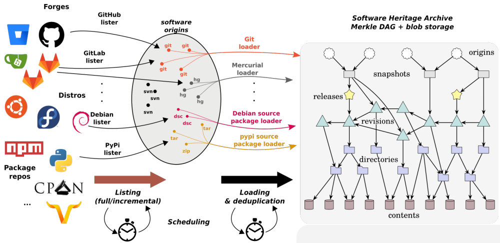
6,112,189,339



Projects

441,196,029






**5000+ platforms**

**All versions, all history development in a single graph**

- **58.7 × $10^9$** nodes
- **1041 × $10^9$** edges
- ~ **3 PB** of storage

A revolutionary **infrastructure** ensures **availability** guarantees **integrity** enables **traceability**

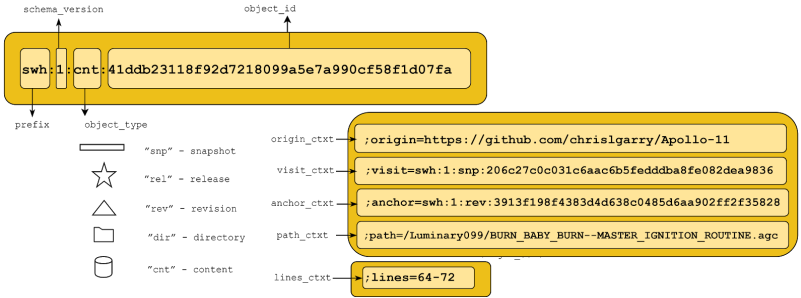
Microsoft, Technology Innovation Institute, HUAWEI, cnrs, Infosys, cea, Ministère de l'Enseignement Supérieur et de la Recherche, aws, Google, Université Paris Cité, openinventionnetwork

AdaCore, Canadian Research Knowledge Network, GitHub, Premier Ministre – Direction interministérielle du numérique, Università di Pisa, Sorbonne Université, Scuola Normale Superiore, Université de Lorraine, Sant'Anna, NWO, université Paris-Saclay

# The Software Hash identifier (SWHID)

## Software Heritage Identifiers (SWHID)

see swhid.org




50+B
intrinsic,
decentralised,
cryptographic

Full fledged *source code references* for traceability, integrity and reproducibility

- Linux Foundation SPDX 2.2
- IANA-registered "swh:"
- WikiData property P6138

Examples: Apollo 11 AGC excerpt, Quake III rsqrt
Guidelines available, see the HOWTO

ISO/IEC 18670, see swhid.org

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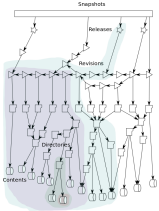
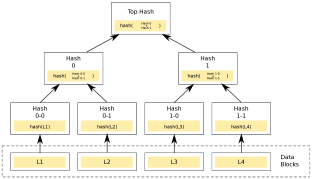
# From archive to revolutionary infrastructure

Modern "Library of Alexandria", *international, non profit, long term* initiative
addressing the needs of *industry, research, culture and society as a whole*

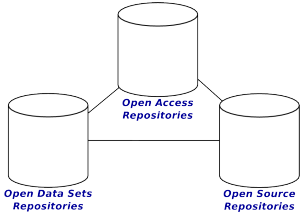
*Software Graph*



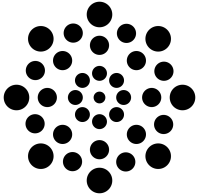

*Software Blockchain*




*Open Science* pillar




*Big Code*



Today we focus on

**Open Science • Large-scale analysis • Cybersecurity • AI**

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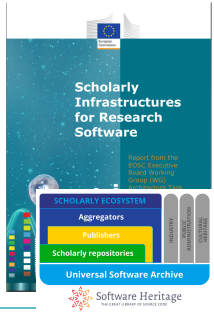
# An example is worth a thousand words

- Browse (e.g. Apollo 11 [excerpt], your work may be already there !)
- Trigger archival, use the updateswh browser extension, configure the webhooks
- Get and use SWHIDs (full specification available online)
- Cite software with biblatex-software package from CTAN
  - Overleaf ACMART template available
- Example in journals: article from IPOL
- Example with Parmap: devel on Github, archive in SWH, curated deposit in HAL
- Extracting all the software products for Inria, for CNRS, for CNES, for LIRMM or for Rémi Gribonval using HalTools
- Curated deposit in SWH via HAL, see for example: LinBox, SLALOM, Givaro, NS2DDV, SumGra, Coq proof, ...
- Example use in research articles:
  - compare Fig. 1 and conclusions in the 2012 version and the updated version
  - SWHID in a replication experiment

# A few adoption indicators

## Policy




- Recommendations in ANR 2023 guidelines (p. 17)
- HAL+SWH in the Open Science software booklet

## Projects

eosc | FAIRCORE4EOSC
Core Components Supporting a FAIR EOSC

The CodeMeta Project

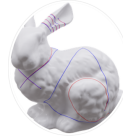
eosc | FAIR-IMPACT
Expanding FAIR solutions across EOSC

## Users and collaborations

### What are they "referencing"?

| source | n | percentage |
|---|---|---|
| **Not available** | 2868 | 46.22 |
| GitHub | 1151 | 18.55 |
| software heritage | 387 | 6.24 |
| zenodo | 142 | 2.29 |
| r package | 70 | 1.13 |
| cran | 56 | 0.90 |
| r package version | 54 | 0.87 |
| gitlab | 35 | 0.56 |

### Graphics Replicability Stamp Initiative



b/Surf: Interactive Bézier Splines on Surface Meshes

Claudio Mancinelli, Giacomo Nazzaro, Fabio Pellacini, Enrico Puppo
IEEE Transactions on Visualization and Computer Graphics (TVCG)

doi | Repository

# Best practices to disseminate

## Artifact Evaluation Committees

**current status**

- many guidelines developed in the 2010's ignore Software Heritage
- ACM DL or Zenodo deposit of a zip + DOI still required

**state of the art**

- archive on Software Heritage
- use the qualified SWHID

## Software citation

*state of the art*

- include codemeta.json (or citation.cff, better if generated from codemeta.json)
- generate biblatex entry, and use biblatex-software (CTAN, acmart.cls, etc.)

*Want the full story?* The course notes ***The Source Code of Science***

Illustration: AI-generated (Google Gemini), author-directed; provenance record in the book's appendix.

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# The full graph in the AWS Open Data collection

https://registry.opendata.aws/software-heritage/

**Registry of Open Data on AWS**

## Software Heritage Graph Dataset

digital preservation | free software | open source software | source code

### Description

Software Heritage is the largest existing public archive of software source code and accompanying development history. The Software Heritage Graph Dataset is a fully deduplicated Merkle DAG representation of the Software Heritage archive.The dataset links together file content identifiers, source code directories, Version Control System (VCS) commits tracking evolution over time, up to the full states of VCS repositories as observed by Software Heritage during periodic crawls. The dataset's contents come from major development forges (including GitHub and GitLab), FOSS distributions (e.g., Debian), and language-specific package managers (e.g., PyPI). Crawling information is also included, providing timestamps about when and where all archived source code artifacts have been observed in the wild.

### Update Frequency

Data is updated yearly

### License

Creative Commons Attribution 4.0 International.By accessing the dataset, you agree with the Software Heritage Ethical Charter for using the archive data and the terms of use for bulk access.

### Documentation

https://docs.softwareheritage.org/devel/swh-dataset/graph/athena.html

### Managed By

Software Heritage

See all datasets managed by Software Heritage.

### Contact

### Resources on AWS

**Description**
Software Heritage Graph Dataset

**Resource type**
S3 Bucket

**Amazon Resource Name (ARN)**
`arn:aws:s3:::softwareheritage`

**AWS Region**
`us-east-1`

**AWS CLI Access (No AWS account required)**
`aws s3 ls --no-sign-request s3://softwareheritage/`

**Description**
S3 Inventory files

**Resource type**
S3 Bucket

**Amazon Resource Name (ARN)**
`arn:aws:s3:::softwareheritage-inventory`

**AWS Region**
`us-east-1`

**AWS CLI Access (No AWS account required)**
`aws s3 ls --no-sign-request s3://softwareheritage-inventory/`

# Example: most popular commit verbs (stemmed)

## Query using Amazon Athena

```
SELECT COUNT(*) AS C, word FROM (
        SELECT word_stem(lower(split_part(
         trim(from_utf8(message)),' ', 1)))
        AS word FROM revision
   WHERE length(message) < 1000000)
WHERE word != ''
GROUP BY word
ORDER BY C
DESC LIMIT 20;
```

## Results

Completed | Time in queue: 272 ms | Run time: 33.545 sec | Data scanned: 94.51 GB

**Results** (20) | Copy | Download results

Search rows | 1

| # | c | word |
|---|---|---|
| 1 | 271573294 | updat |
| 2 | 163328012 | merg |
| 3 | 140044381 | add |
| 4 | 105800317 | fix |
| 5 | 103646653 | ad |
| 6 | 52891401 | bump |
| 7 | 50067041 | initi |
| 8 | 45609622 | creat |
| 9 | 42633225 | remov |
| 10 | 32230842 | chang |
| 11 | 23110410 | delet |
| 12 | 20734745 | new |
| 13 | 16644508 | commit |
| 14 | 15651821 | test |

# Going beyond SQL

## State-of-the-art graph compression from social networks

Paolo Boldi, Antoine Pietri, Sebastiano Vigna, Stefano Zacchiroli

Ultra-Large-Scale Repository Analysis via Graph Compression

SANER 2020, 27th Intl. Conf. on Software Analysis, Evolution and Reengineering. IEEE

## Results

Full graph structure (58.7 B nodes, 1.04 T edges) in 400 GiB RAM

- traversal time is tens of ns per edge
- bidirectional traversals implemented
- beware: metadata access is still *off RAM*

~~Java~~ Rust and gRPC APIs available …

docs.softwareheritage.org/devel/swh-graph/grpc-api.html

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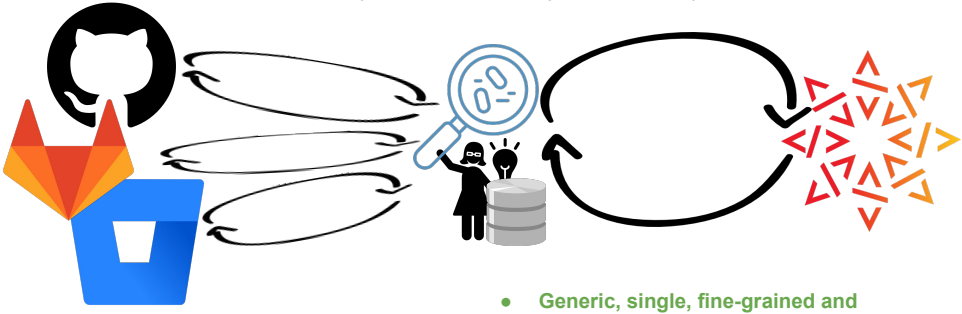
# Mining Android Applications on Software Heritage

*RQ: how to build a specific dataset for a given research question?*



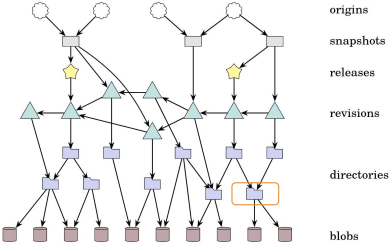
- **Specific and limited API**
- **Hardly reproducible**

- **Generic, single, fine-grained and unlimited API**
- **Growing number of source codes**
- **Easy to update the dataset**

*(from the Inria/IRISA DiverSE team)*

# Using the SWH merkle dag to identify android repositories

Identify android application repositories = Find the AndroidManifest.xml among the sources

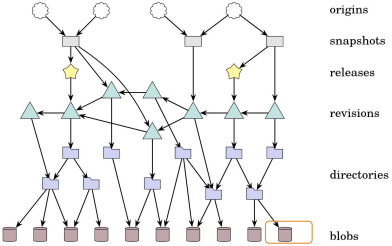



SWH Merkle DAG, Antoine Pietri

1) Iterate over the graph nodes until you find a directory node containing a file named "AndroidManifest.xml".

# Using the SWH merkle dag to identify android repositories

Identify android application repositories = Find the AndroidManifest.xml among the sources

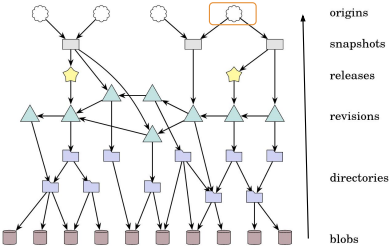



SWH Merkle DAG, Antoine Pietri

2) Extract the SWH identifier of the blob corresponding to the AndroidManifest.xml and download the corresponding file through the SWH Web API

# Using the SWH merkle dag to identify android repositories

Identify android application repositories = Find the AndroidManifest.xml among the sources




SWH Merkle DAG, Antoine Pietri

3) Traverse the graph in backward direction to the origin node and get the repository url

# Bottomline

Broad variety of sources in *one open dataset*

reduces usual GH bias

Reference simple *standard data format*

VCS and forge details are abstracted away

Simplifies reproducibility packages

no need to create a full copy, *just list the SWHIDs!*

Software Heritage does the heavy lifting for you

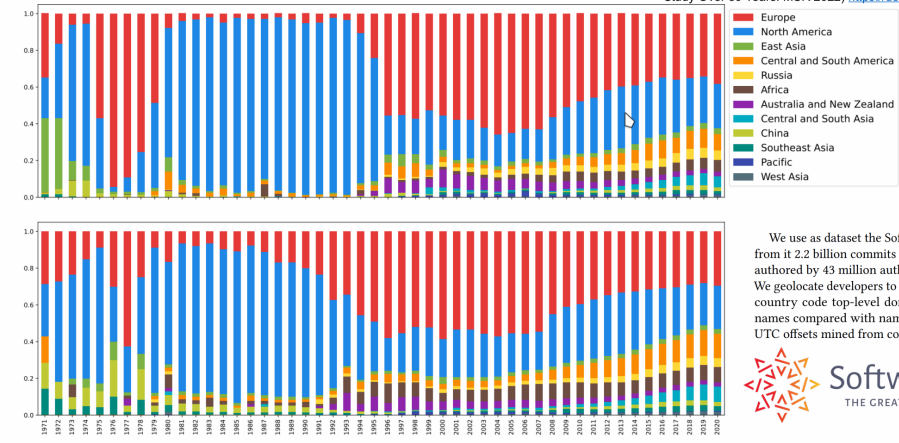
no need to scrape/download repositories all over again

# Example: (Open) Source Code comes from all over the world

MSR '22, May 23–24, 2022, Pittsburgh, PA, USA

Davide Rossi and Stefano Zacchiroli

Geographic Diversity in Public Code Contributions: An Exploratory Large-Scale Study Over 50 Years. MSR 2022) https://doi.org/10.1145/3524842.3528471

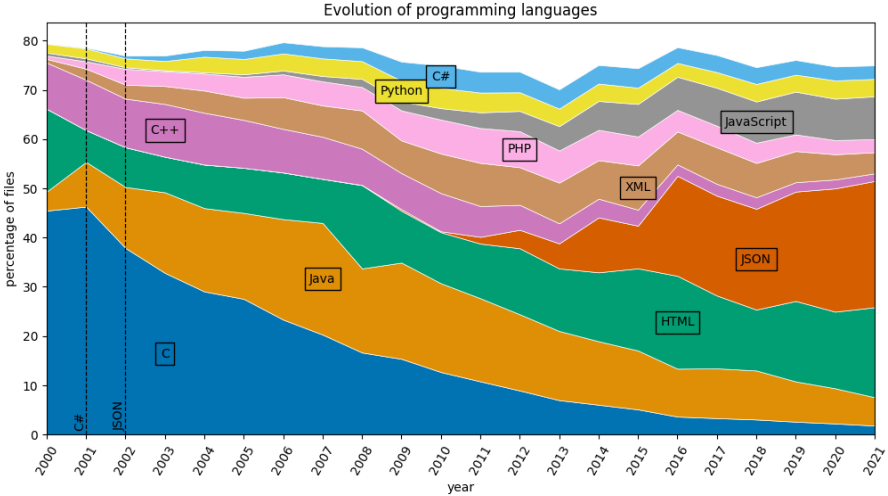



We use as dataset the Software Heritage archive [3] and analyze from it 2.2 billion commits archived from 160 million projects and authored by 43 million authors during the 1971–2021 time period. We geolocate developers to 12 world regions, using as signals email country code top-level domains (ccTLDs) and author (first/last) names compared with name distributions around the world, and UTC offsets mined from commit metadata.

Software Heritage
THE GREAT LIBRARY OF SOURCE CODE

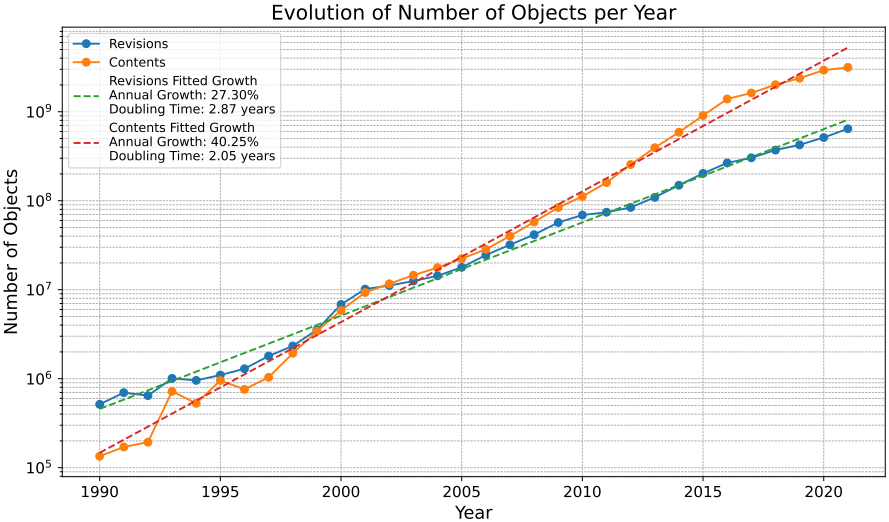
**Figure 3: Ratio of commits (above) and active authors (below) by world zone over the 1971–2020 period.**

# Example: Programming language evolution in (Open) Source




A. Desmazières, R. Di Cosmo, V. Lorentz
50 years of programming language evolution through the Software Heritage Looking Glass
International Conference on Mining Softwre Repositories (MSR) 2025.
https://hal.science/hal-04924849/

# Example: (Open) Source Code grows at an exponential rate




Software Heritage

Get the data and the code

# Example: Institutional contribution analysis

Question:

can we leverage the Software Heritage graph to map contributions from a research institution in the galaxy of software development?

Answer: let's try

- Extract: projects and contributions using email domain matching in the Software Heritage graph.
- Deduplicate: Cluster forks/copies using commit metadata, select a canonical repository.
- Enrich: Add GitHub metadata (topics, README, etc.) for context and visibility.
- Analyze: Compute key metrics on impact, contributor domains, and research relevance.

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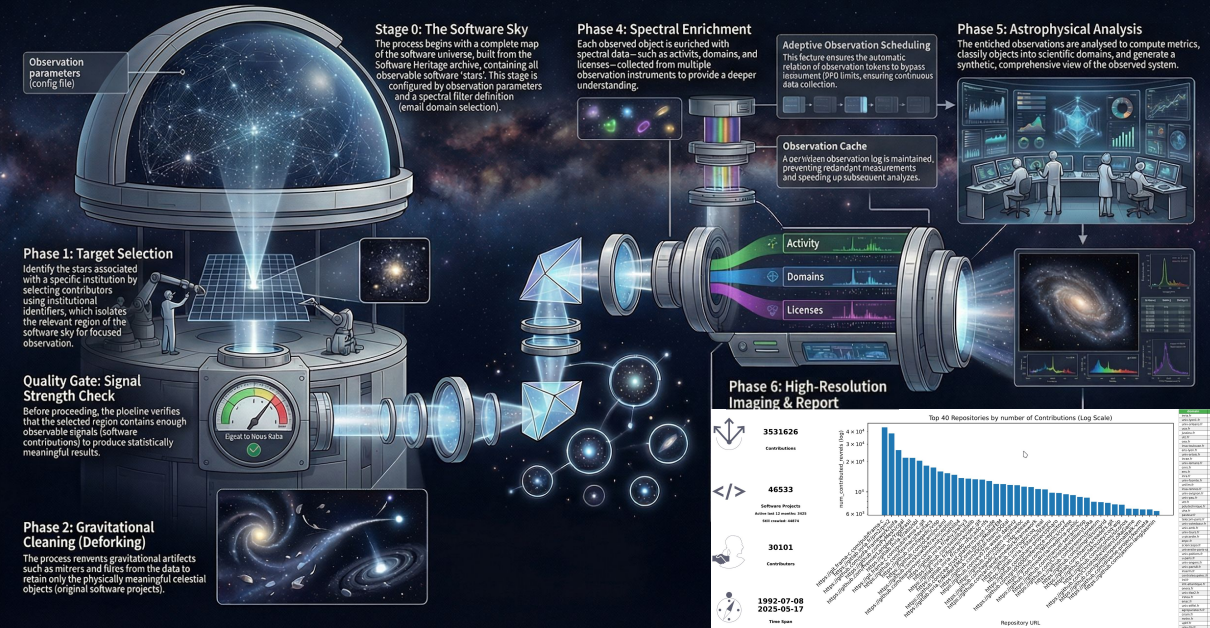
# From the **Software Sky** to **Institutional Insight:** Anatomy of an Observational Pipeline



# First SWH VLT pictures — Brazilian academic software

**1445630**

**Contributions**

**37027**

**Software Projects**

**Active last 12 months: 489**

**Still crawled: 33269**

**14040**

**Contributors**

**1993-07-28**
**2026-03-05**

**Time Span**

*38 BR academic domains, 10+ contributions with a BR academic email:*
USP, UNICAMP, UNESP, UFRJ, UFMG, UFRGS, UnB, IMPA, LNCC, CBPF, FIOCRUZ, EMBRAPA, INPE, PUC-Rio, FGV, FAPESP, CNPq, …

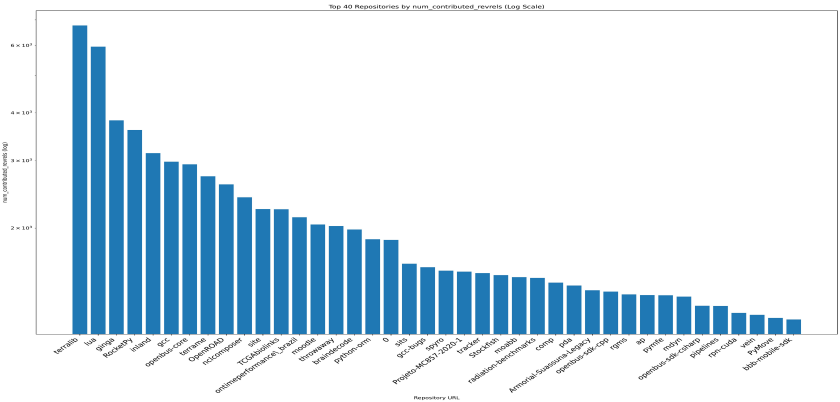
# Brazilian (academic) software major contributions

**1445630**
Contributions

**37027**
Software Projects
Active last 12 months: 489
Still crawled: 33269

**14040**
Contributors

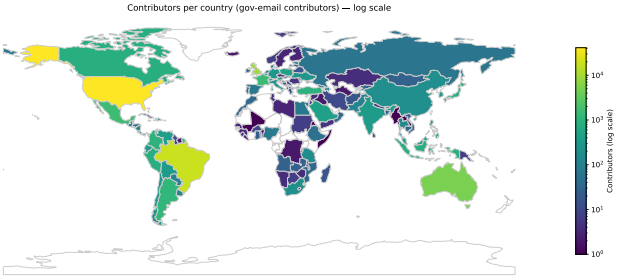
**1993-07-28**
**2026-03-05**
Time Span

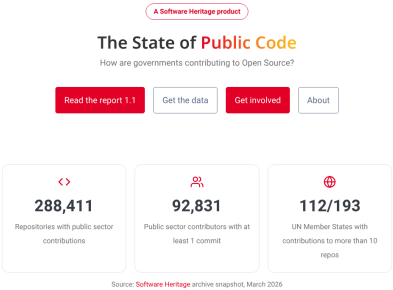



| domain | count |
|---|---|
| usp.br | 2973 |
| ufpe.br | 2101 |
| unicamp.br | 1236 |
| uff.br | 1124 |
| ufrj.br | 1108 |
| ufc.br | 806 |
| puc-rs.br | 785 |
| ufrgs.br | 436 |
| ufmg.br | 415 |
| ufpr.br | 376 |
| unesp.br | 363 |
| ufsm.br | 317 |
| ufsc.br | 277 |
| puc-rio.br | 273 |
| unb.br | 247 |
| ufv.br | 229 |
| ufscar.br | 190 |
| ufba.br | 154 |
| unifesp.br | 97 |
| inpe.br | 75 |
| fgv.br | 59 |
| ita.br | 39 |
| impa.br | 36 |
| embrapa.br | 33 |
| fiocruz.br | 33 |
| uerj.br | 33 |
| ipt.br | 18 |
| incc.br | 14 |
| pucsp.br | 8 |
| cnpq.br | 6 |
| cbpf.br | 4 |
| fapesp.br | 2 |

Software Heritage is the only infrastructure capable of producing these metrics

# The Public Code Observatory *unveiled at UN Open Source Week 2026*




- Brazil is second worldwide: 17,725 public sector contributors (US 41,253, UK 9,252)
- `gov.br` is the largest government email domain on the planet, nearly 2x the next one
- Brazilian contributors reach ~4.4 projects each — world median ~2.2

stateofpubliccode.org

*With UN ODET and UNESCO • gov-domain contributions: a floor, not a ceiling*

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## Programme

*France 2030 PTCC — 5 years (2024–2028) — 8 research teams*

Co-leaders: Olivier Barais (Inria, DiverSE) · Stefano Zacchiroli (Télécom Paris, ACES)

### Partners — academic

- APR — LIP6, Sorbonne Université *(prog. languages, static analysis MOPSA, verification)*
- ACES — Télécom Paris *(cybersecurity, software supply chain)*
- CEA List *(static analysis: Frama-C, Binsec)*

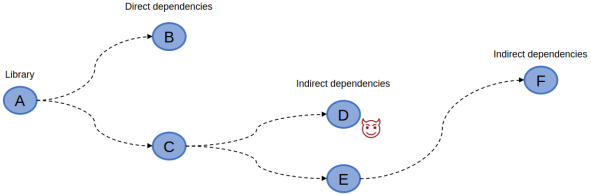
### Partners — Inria

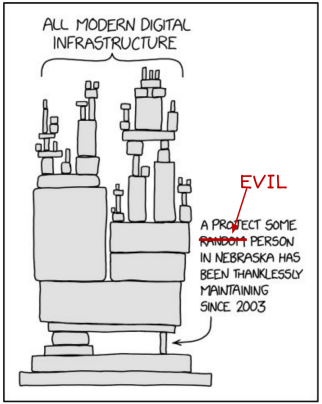
- DiverSE — supply chain security
- RMOD — reverse engineering (Moose)
- Software Heritage — archive, infrastructure
- Spirals — self-protective systems, web security
- Whisper — Linux kernel, Coccinelle

# Software supply chain attacks

## Reusing OSS via dependencies

- Software dependencies: a popular way of reusing open source software.
- Software product $A$ uses functionalities implemented in OSS product $B$ ... and so on.



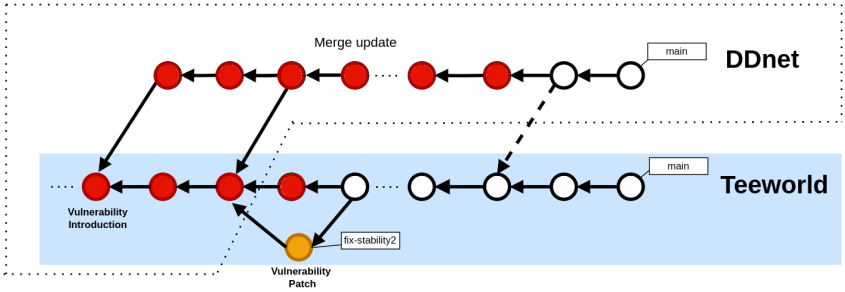




based on xkcd.com/2347

## Attacking the software supply chain

- Attacking undermaintained "leaf" packages (e.g., D) → efficient attack strategy
- Many documented attacks: event-stream (2018), node-ipc (2022), XZ utils (2024), ...

- Any change to a piece of software (*commit*) can introduce a new vulnerability.
- Or it can fix an existing vulnerability.
- What happens if a project is forked between introduction and fix of a vulnerability?
- It inherits the vulnerability, … until the change with the fix is integrated.



# An universal knowledge base about public code vulnerabilities

## Vision

- Software Heritage is the perfect (and only) place where to build an universal knowledge base that maps known vulnerabilities to public code artifacts.
- SWH can provide an open data API mapping SWHIDs to CVEs, that knows about *all public commits* and can be leveraged to increase open source security.

## EU Cyber Resilience Act (CRA)

- Key helper to abide to CRA obligations, coming into effect ~Q3 2026.
- SWH funding member of the Open Regulatory Compliance Working Group.

## Roadmap

- Context: SWHSec project (PTCC-funded, 2023-2027).
- Current status: working prototype that processes OSV.dev data and use it to "color" the entire SWH commit graph (~6 billion commits) with vulnerability information.

# References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On the Informativeness of Security Commit Messages: A Large-scale Replication Study.
To appear in EASE 2026, ACM, Glasgow, UK.

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To appear in EASE 2026, ACM, Glasgow, UK.

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Solal Rapaport, Laurent Pautet, Samuel Tardieu, Stefano Zacchiroli.
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ASE 2025, IEEE, Seoul, South Korea. Pages 2183–2194.

# Outline


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# Software Heritage and Generative AI, first contacts

October 19, 2023

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### Principles

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2. The *initial training data extracted from the Software Heritage archive* must be fully and precisely identified by, for example, publishing the corresponding SWHID identifiers (note that, in the context of Software Heritage, public availability of the *initial training data* is a given: anyone can obtain it from the archive). This will enable use cases such as: studying biases (fairness), verifying if a code of interest was present in the training data (transparency), and providing appropriate attribution when generated code bears resemblance to training data (credit), among others.
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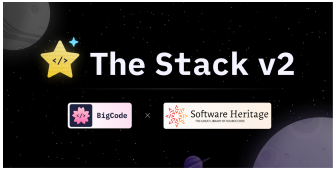
February 2024

Yes, it's possible!



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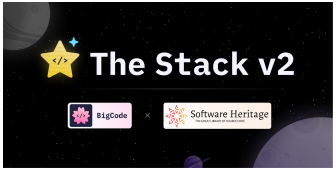

But it's hard…

# Lessons learned

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**Transparency is easy**: SWHID (undergoing ISO standardisation) and Software Heritage
N.B. : may be mandated by regulations!

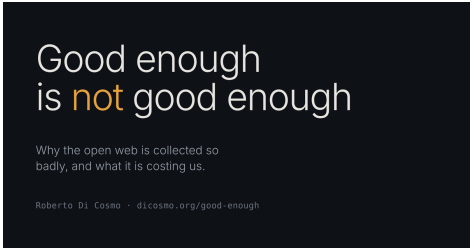
**Opt out is complex**: who is *the real right owner*? (similar issues to license compliance)

+

- **Building the training set** is complex: e.g. includes **license compliance** alike work **at massive scale**
- Generating **attribution information** on model output **is more complex** than license compliance

We need **a coordinated effort** to ensure fully open models will succeed!

# “Good enough” is not good enough *why the open web is collected so badly*

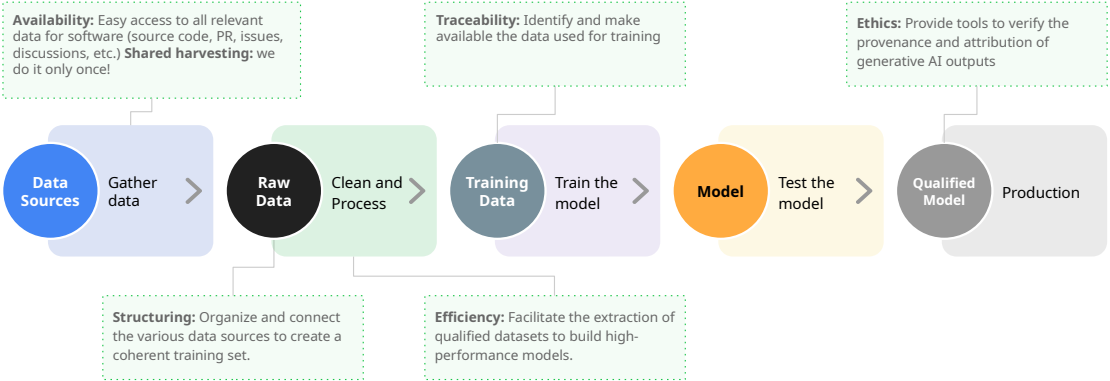



dicosmo.org/good-enough

- Massive multiple scraping — every collector re-fetches every site, over and over, for material that has not changed
- AI bots — Software Heritage itself was hit by waves of automated collection: services unresponsive, engineers blocking addresses instead of building
- Waste of resources — bills explode for everyone, and the open web closes down one emergency measure at a time

CodeCommons: collect once, share widely — *one logical collection, many copies*

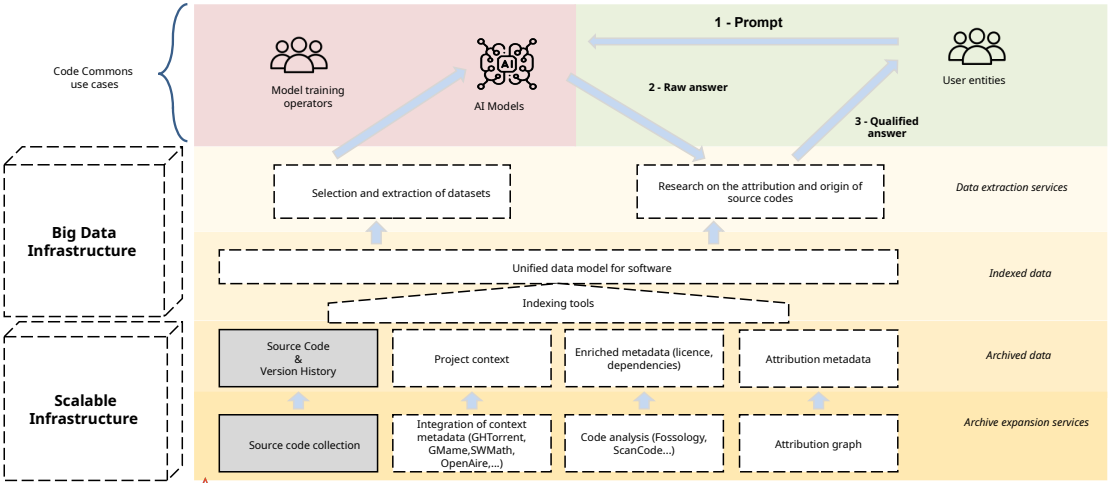
# A STEP FORWARD: CodeCommons






Solutions

# CodeCommons: bird’s eye view (technical focus)



# CodeCommons

## Open, responsible, and transparent AI: Our shared goal

**CodeCommons** is an ambitious project to create the world's most comprehensive digital commons for code

Building on the existing foundation of Software Heritage, the largest publicly available source code archive, CodeCommons aims to bring into one place all the **critical** and **qualified** information needed to create **smaller**, **better** datasets for the next generation of AI tools.

At its core, the project prioritizes transparency and traceability, enabling model builders and users to **respect creators' rights** while promoting **sovereign** and **sustainable** AI.

**Learn more**

**Meet the teams**

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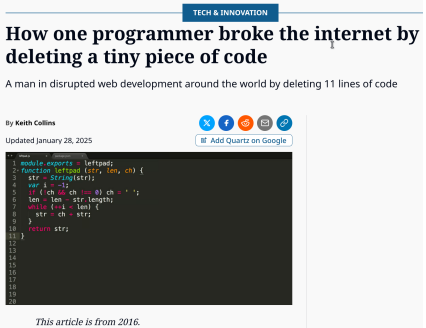
# Deep (infra)structural dependencies!

## An early warning: left-pad (March 2016)



TECH & INNOVATION

**How one programmer broke the internet by deleting a tiny piece of code**

A man in disrupted web development around the world by deleting 11 lines of code

By Keith Collins

Updated January 28, 2025

Add Quartz on Google

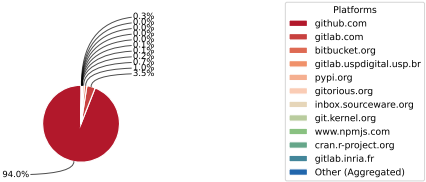
```
module.exports = leftpad;
function leftpad (str, len, ch) {
  str = String(str);
  var i = -1;
  if (!ch && ch !== 0) ch = ' ';
  len = len - str.length;
  while (++i < len) {
    str = ch + str;
  }
  return str;
}
```

*This article is from 2016.*

See the Wikipedia article:

- Facebook, PayPal, Netflix, Spotify affected
- web broken worldwide ~2.5 hours

## A clear and present danger




*Color encodes systemic exposure (largest share = highest concentration risk).*

Used by **Brazilian academic** devs *(Source: Software Heritage)*

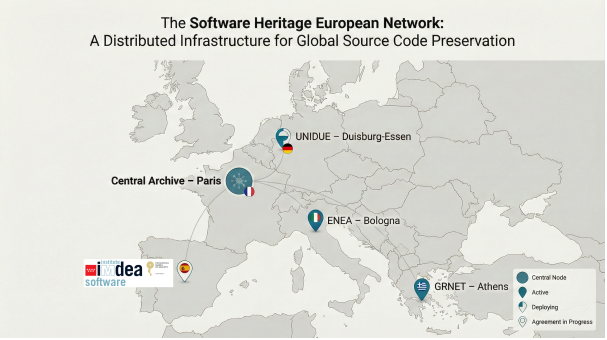
"*If GitHub or PyPI disappeared tomorrow,*
research would not just slow down
— *it would stop.*"

# An ecumenical approach to sovereign fallback of build chains is possible

## Add support for fallback in key package managers

*npm, PyPI, Maven Central, Cargo, CPAN, RubyGems, Packagist, …*

## Realize ecumenical resilience




*"When a registry fails — the world continues to build."*

Four sovereign mirrors today.

**Brazil could host the first one beyond Europe.**

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# A growing and active community

## Core Team

## Ambassadors

## All together, 2026 Symposium

Software Heritage

# A rally flag for a grand vision

Bring together academia, industry, governments, communities

*"to build a reference, global infrastructure for open and better software"*

## Software Heritage is

- vendor neutral, open source
- a worldwide, long term initiative

## Software Heritage enables

- archival, reference, integrity
- qualification, sharing and reuse

## Call to action

- leverage for AI, Cyber, SwEng
- get involved research, code
- promote for AEC, Journals, etc.
- fund the long term mission

## Annual report 2025

## 5 years in 5 minutes

## Get these slides