Software Heritage

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

Roberto Di Cosmo

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Inria and Université de Paris Cité

April 1st, 2025

Software Heritage

THE GREAT LIBRARY OF SOURCE CODE

Outline

Open Science

Short Bio: Roberto Di Cosmo

Computer Science professor in Paris, now working at INRIA

- *35+ years* of research (Theor. CS, Programming, Software Engineering, Erdos #: 3)
- *25+ years* of Free and Open Source Software
- *15+ years* building and directing structures for the common good

1999 *DemoLinux* – first live GNU/Linux distro

2007 *Free Software Thematic Group*
150 members 40 projects 200Me

2008 *Mancoosi project* www.mancoosi.org

2010 *IRILL* www.irill.org

2015 *Software Heritage* at INRIA

2018 *National Committee for Open Science*, France

2021 *EOSC Task Force on Infrastructures for Software*, European Union

Software *Source Code* is Precious Knowledge

Harold Abelson, Structure and Interpretation of Computer Programs (1st ed.) 1985

"Programs must be written for people to read, and only incidentally for machines to execute."

Apollo 11 source code (excerpt)

```
P63SPOT3        CA      BIT6            # IS THE LR ANTENNA IN POSITION 1 YET
                EXTEND
                RAND    CHAN33
                EXTEND
                BZF     P63SPOT4        # BRANCH IF ANTENNA ALREADY IN POSITION 1

                CAF     CODE500         # ASTRONAUT:    PLEASE CRANK THE
                TC      BANKCALL        #               SILLY THING AROUND
                CADR    GOPERF1
                TCF     GOTOPOOH        # TERMINATE
                TCF     P63SPOT3        # PROCEED       SEE IF HE'S LYING

P63SPOT4        TC      BANKCALL        # ENTER         INITIALIZE LANDING RADAR
                CADR    SETPOS1

                TC      POSTJUMP        # OFF TO SEE THE WIZARD ...
                CADR    BURNBABY
```

Covid Sim (excerpt)

```
/**
 * @brief The basic unit of the simulation and is associated to a geographical location.
 *
 * Interventions (e.g., school closures) are tracked at this level. It contains a list of its
 * members (people), places (schools, universities, workplaces etc.), road networks, links to
 * airports etc.
 */
struct Microcell
{
        /* Note use of short int here limits max run time to USHRT_MAX*ModelTimeStep - e.g. 65536*0.25=16384 days=44 yrs.
           Global search and replace of 'unsigned short int' with 'int' would remove this limit, but use more memory.
        */

        int n; // Number of people in microcell
        int adunit; // admin unit microcell belongs to
        int* members; // array of members/hosts of microcell

        int* places[MAX_NUM_PLACE_TYPES]; // list of places (of various place types) within microcell
        unsigned short int NumPlacesByType[MAX_NUM_PLACE_TYPES]; // number of places (of various place types) within mircocell
        unsigned short int keyworkerproph, move_trig, place_trig, socdist_trig, keyworkerproph_trig;
        unsigned short int move_start_time, move_end_time;
        unsigned short int place_end_time, socdist_end_time, keyworkerproph_end_time;
        TreatStat moverest, treat, vacc, socdist, placeclose;
        unsigned short int treat_trig, vacc_trig;
        unsigned short int treat_start_time, treat_end_time;
        unsigned short int vacc_start_time;
        IndexList* AirportList;
};
```

Len Shustek, Computer History Museum 2006

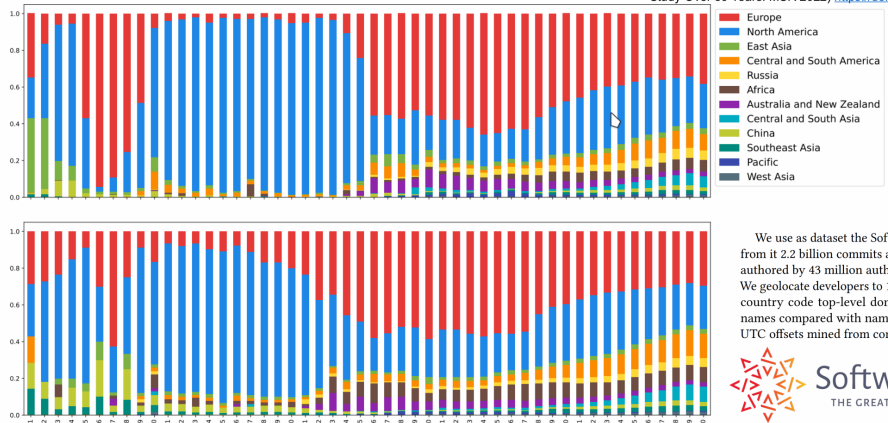
"Source code provides a view into the mind of the designer."

(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

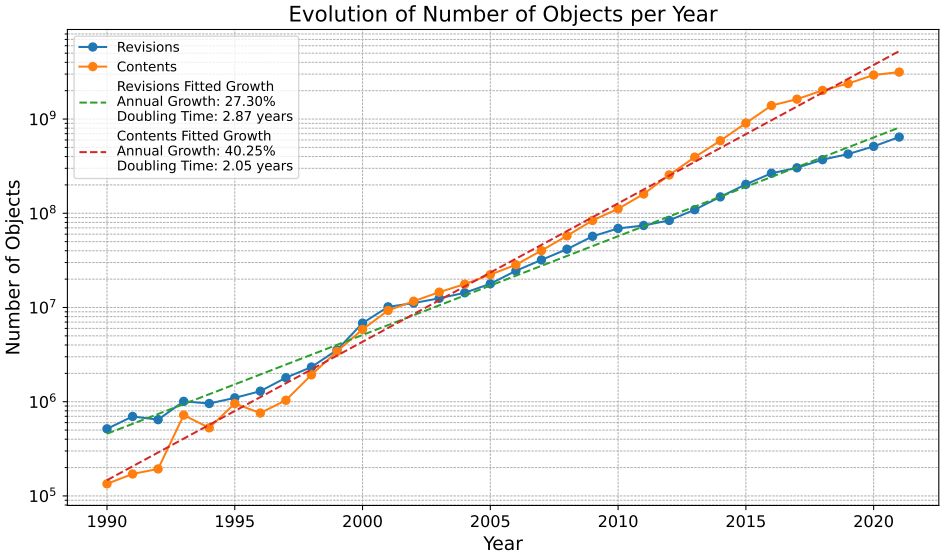


We use as dataset the Software Heritage archive [3] and analyze from it 2.2 billion commits archived from 160 million projects and authored by 43 million authors during the 1971–2021 time period. We geolocate developers to 12 world regions, using as signals email country code top-level domains (ccTLDs) 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.

(Open) Source Code grows at an exponential rate

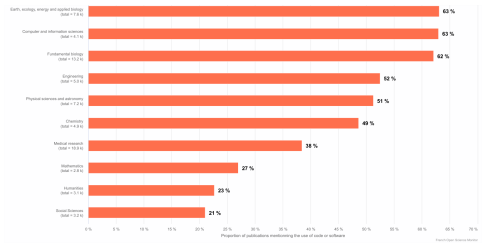


(Open Source) Software is *precious technical and scientific knowledge*

Yuval Noah Harari (on COVID 19)

"*The real antidote [to epidemic] is* scientific knowledge *and* global cooperation."

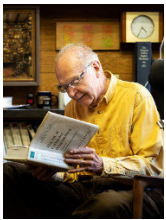
Software powers modern research



20%+ articles use software, all disciplines

2024 French Open Science Monitor

We can still talk to the early inventors



"Telling historical stories is the best way to teach. It's much easier to understand something if you know the threads it is connected to."

Donald E. Knuth
Len Shustek
CACM, January 2021

We need a *dedicated infrastructure* to preserve and share *all* this knowledge!

Outline

Open Science

Software Heritage

THE GREAT LIBRARY OF SOURCE CODE

Collect, preserve and share *all* software source code

Preserving our heritage, enabling better software and better science for all

Reference catalog

find and reference all software source code

Universal archive

preserve and share all software source code

Research infrastructure

enable analysis of all software source code

A *universal* archive as a shared infrastructure

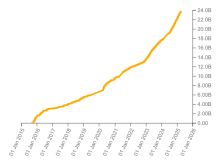
One infrastructure
open and shared

Inria

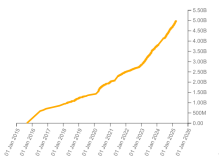
unesco

The largest archive ever built

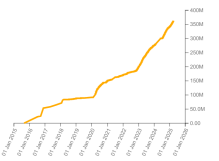
Source files
23,828,196,855



Commits
5,006,891,310



Projects
362,987,832



Directories
18,809,563,175

Authors
90,221,599

Releases
106,890,095

Bitbucket 2,818,626 origins	56,983 origins	git 33,472 origins
29,046 origins	debian 142,984 origins	90,755 origins
GitHub 266,235,919 origins	gitiles 24,614 origins	GitLab 5,803,610 origins
git 3,824 origins	Gogs 422 origins	1,966,688 origins
Guix 56,248 origins	GNU 354 origins	heptapod 1,358 origins
launchpad 654,759 origins	Maven 415,606 origins	NixOS 34,420 origins
npm 4,070,945 origins	4,941 origins	Packagist 380,156 origins
PAGURE 72,459 origins	Phabricator 198 origins	pub.dev 63,003 origins
621,919 origins	SOURCEFORGE 382,368 origins	stagit 343 origins

Sharing the vision

United Nations
Educational, Scientific and
Cultural Organization

Donors, members, sponsors

Diamond sponsors

Platinum sponsors

Gold sponsors

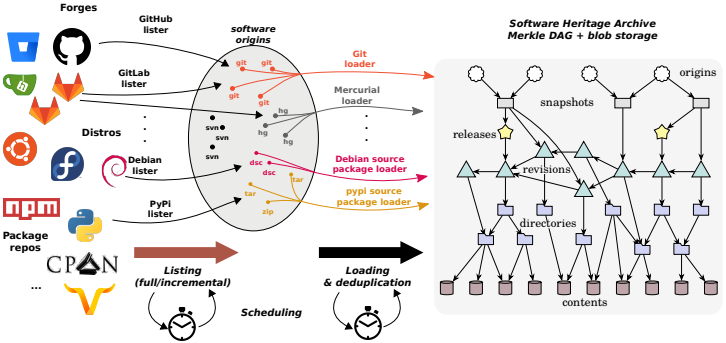
Silver sponsors

Bronze sponsors

And many more ...

www.softwareheritage.org/support/testimonials

The archive, under the hood



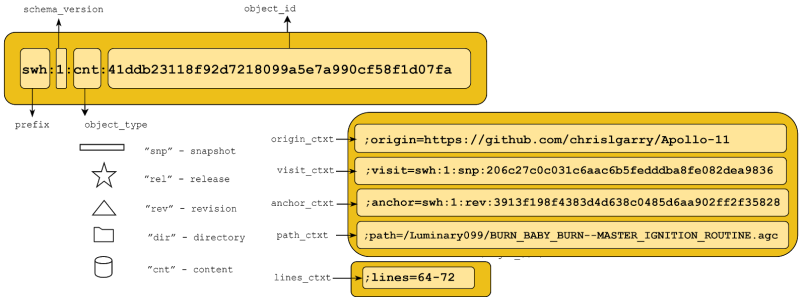
Global development history permanently archived in a uniform data model

- over 23 billion unique source files from over 360 million software projects
- ~2PB (compressed) blobs, ~50 B nodes, ~800 B edges

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

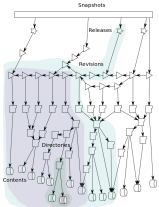
Examples: Apollo 11 AGC excerpt, Quake III rsqrt
Guidelines available, see the HOWTO

Breaking news: standardisation, see swhid.org - DIS 18670

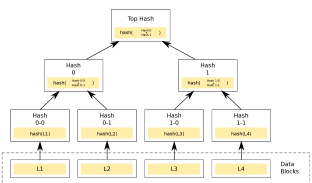
A revolutionary infrastructure

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

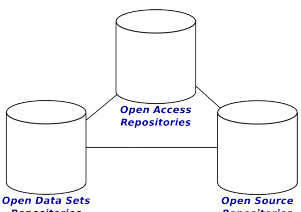
Software Graph



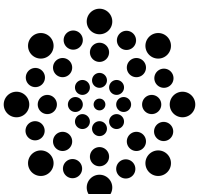
Software Blockchain



Open Science pillar



Big Code



One infrastructure, *shared*: more efficient, less waste …

… supporting a broad range of applications

Outline

Open Science

A walkthrough

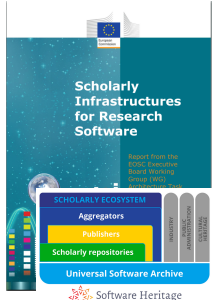
- Browse (e.g. Apollo 11 [excerpt], your work may be already there !)
- Trigger archival, use the updateswh browser extension, configure the webhooks
- Get and use SWHIDs (full specification available online)
- Cite software with biblatex-software package from CTAN
  - Overleaf ACMART template available
- 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

Outline

Open Science

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

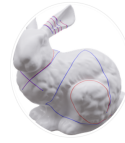
eosc | FAIR-IMPACT
Expanding FAIR solutions across EOSC

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)

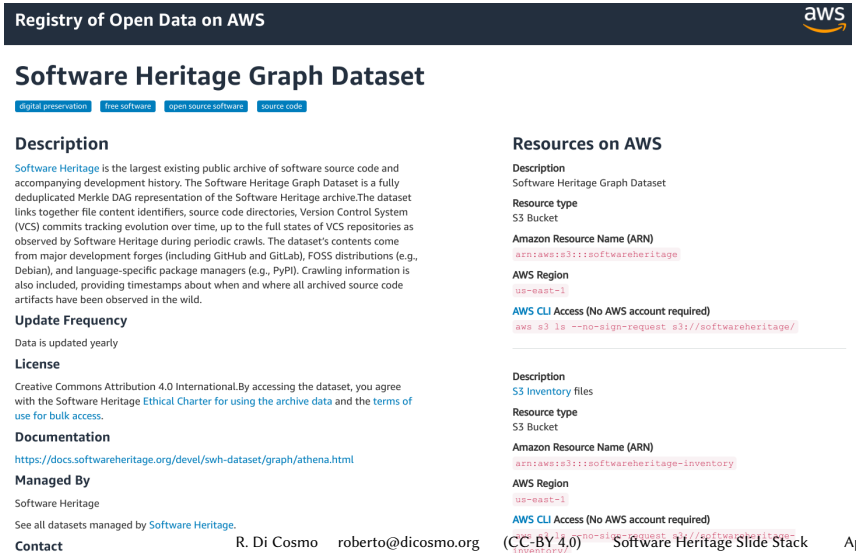
doi | Repository

Outline

Open Science

The full graph in the AWS Open Data collection

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



Registry of Open Data on AWS

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`

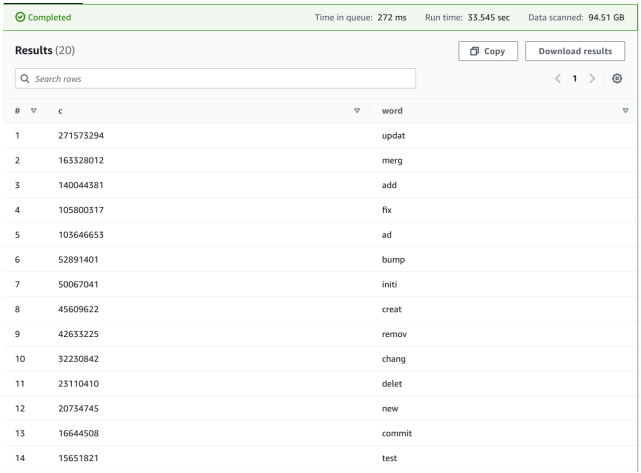
AWS CLI Access (No AWS account required)
`aws s3 ls --no-sign-request s3://softwareheritage-inventory/`

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

Outline

Open Science

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 (50 B nodes, 800 B 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 …

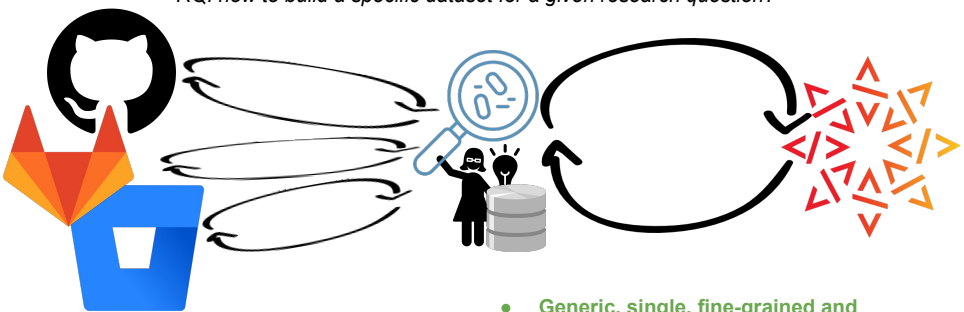
docs.softwareheritage.org/devel/swh-graph/grpc-api.html

Outline

Open Science

Mining Android Applications on Software Heritage

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



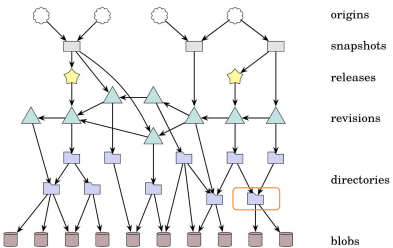
- **Specific and limited API**
- **Hardly reproducible**

- **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

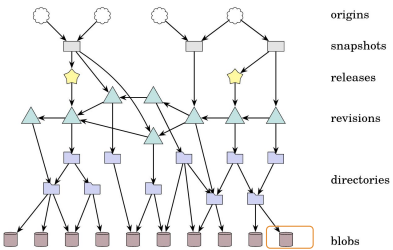


SWH Merkle DAG, Antoine Pietri

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

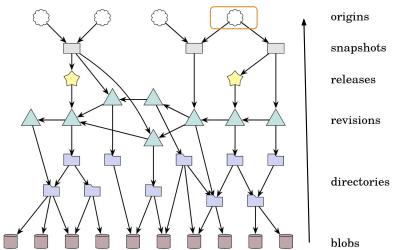


SWH Merkle DAG, Antoine Pietri

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

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.

Intermezzo: analysis of the UBA contribution to Open Source

140002

Revision Relationships

7333

Software Projects

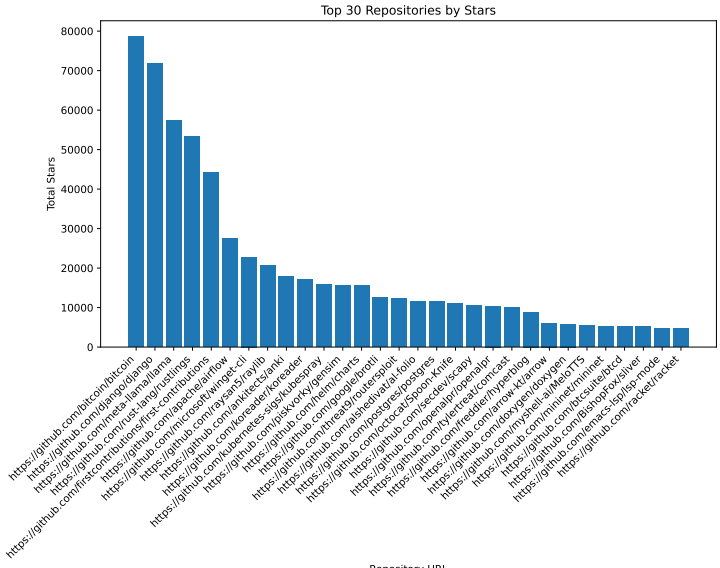
1928

Contributors

1998-05-25
2025-01-02

Time Span

Intermezzo: analysis of the UBA contribution to Open Source, cont'd



Outline

Open Science

Open source security

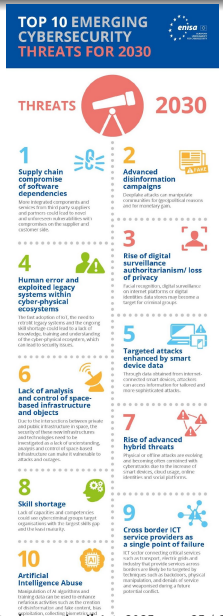
Open source software can be freely used, copied, and modified.

Open Source Software (OSS) is everywhere

- Huge boost for innovation! (e.g., reduced time to market)
- 96% of (non-open) software products depend on open source (2022).
- Open source is at the heart of the global digital infrastructure.

With great exposure comes great scrutiny…

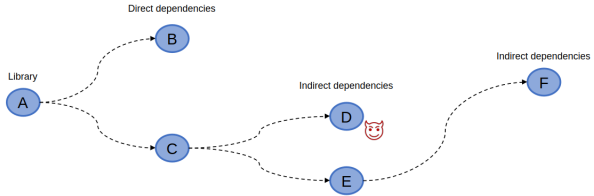
- …by both good and bad actors.
- OSS is more and more targeted by attackers.
- Increased policy attention to secure OSS, e.g.:
  - US: Biden's executive orders (2022, Jan 2025!)
  - EU: CRA, progressively coming into effect

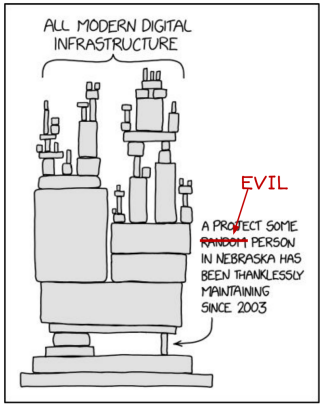


Software supply chain attacks

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), ...

Securing open source with Software Heritage

What does Software Heritage bring to the table?

- The largest archive that guarantees the:
  1. availability,
  2. integrity, and
  3. traceability of (OSS) source code.
- A universal, open knowledge base of *facts* about open source software…
- …that can be leveraged by everyone (not only the big players) to secure OSS.

SWHSec project

swhsec.github.io

- 2023–2027 R&D project, funded by French national CampusCyber
- 8 research teams, including SWH core

Axes: (1) extending SWH with security info + (2) code analysis, dependency analysis, vulnerability tracking, automatic vulnerability fixing, … at SWH scale.

Outline

Open Science

Software Heritage and Generative AI, first contacts

October 19, 2023

Software Heritage Statement on Large Language Models for Code

Principles

1. Knowledge derived from the Software Heritage archive must be given back to humanity, rather than monopolized for private gain. The resulting *machine learning models* must be made available under a suitable open license, together with the documentation and toolings needed to use them.
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Software Heritage and Generative AI, first contacts

October 19, 2023

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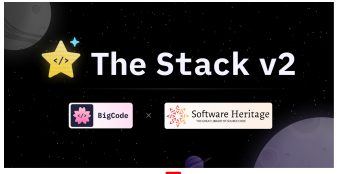
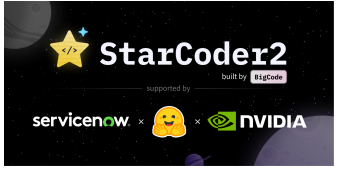
February 2024

Yes, it's possible!





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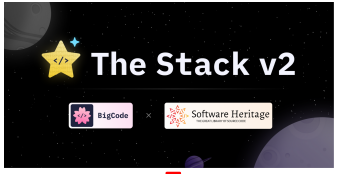
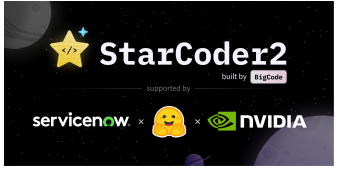
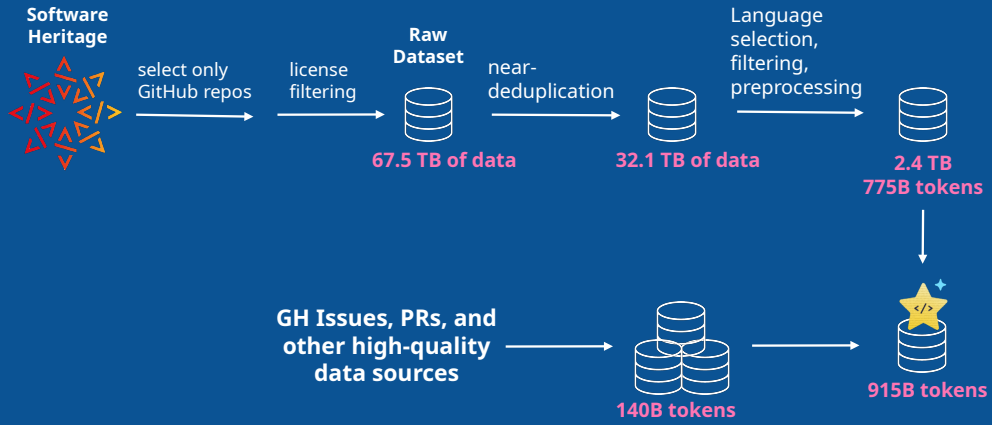




But it's hard…

The Stack v2

Data collection pipeline fully open and transparent built by BigCode



This slide is courtesy of Leandro Von Werra and Harm de Vries

Lessons learned

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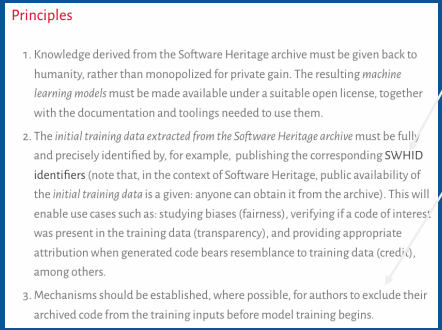

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(similar issues to license compliance)

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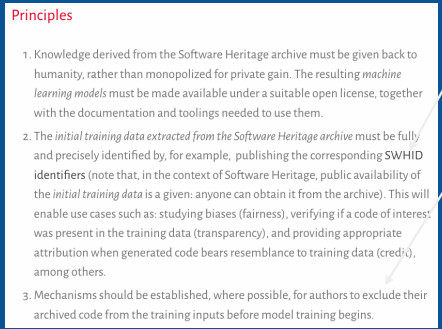

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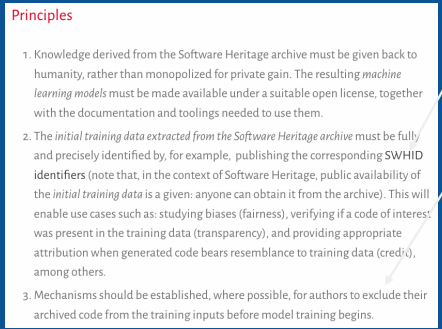

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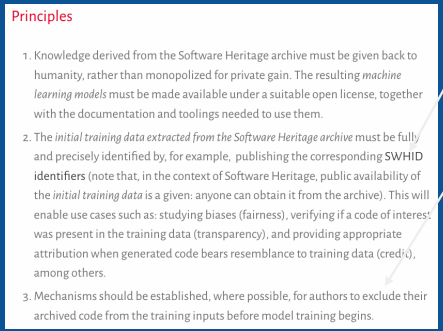

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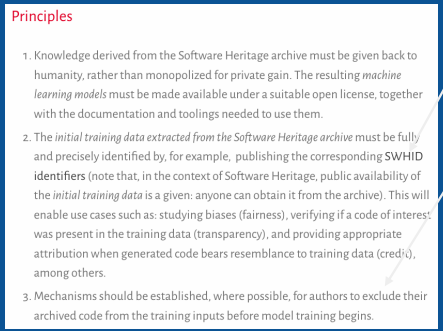

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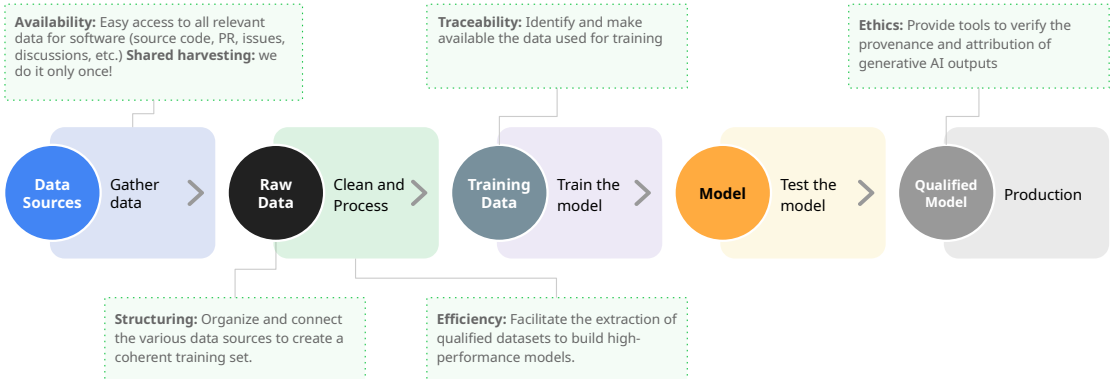
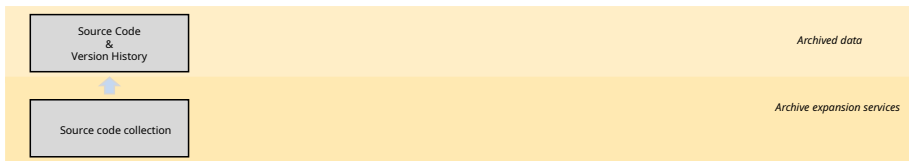
We need **a coordinated effort** to ensure fully open models will succeed!

A STEP FORWARD: CodeCommons



Solutions

CodeCommons: bird’s eye view (technical focus)



Software Heritage
THE GREAT LIBRARY OF SOURCE CODE

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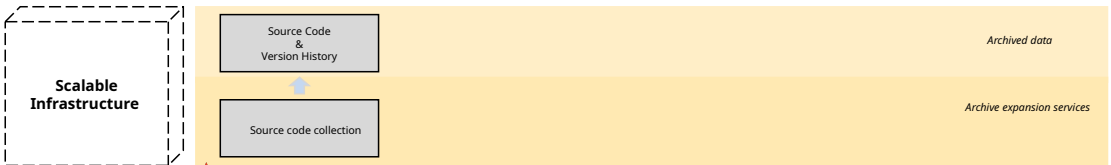

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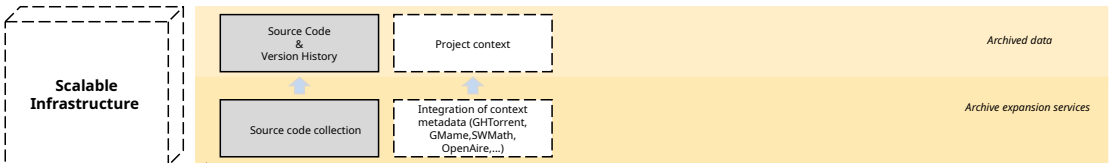

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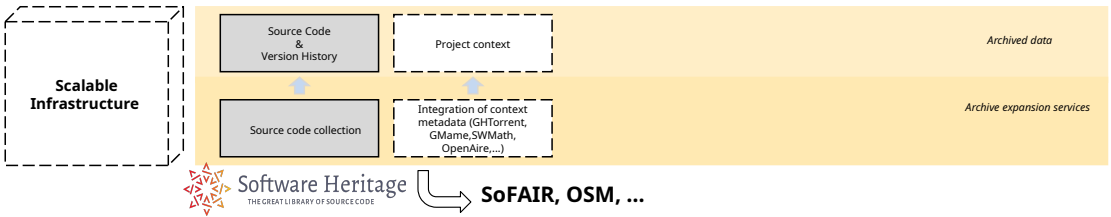

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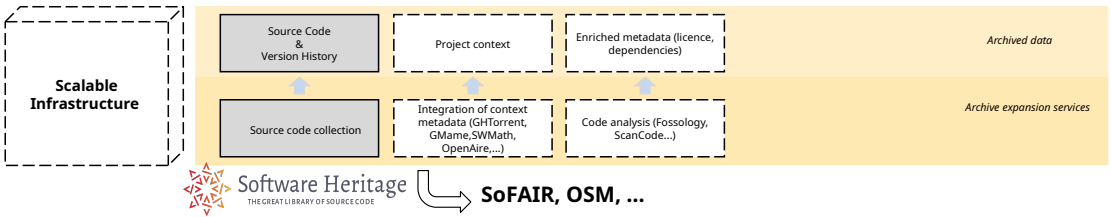

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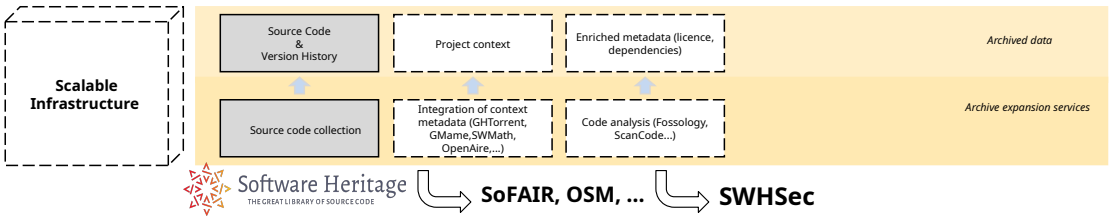

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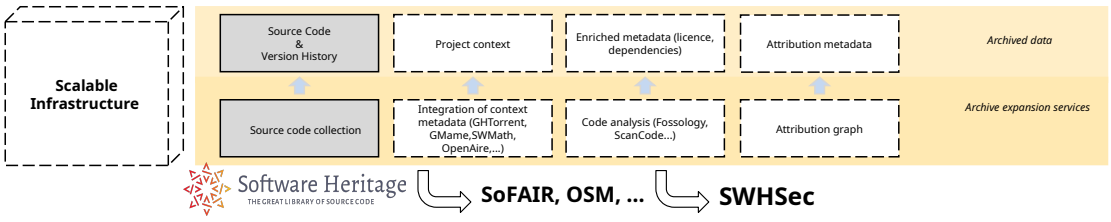

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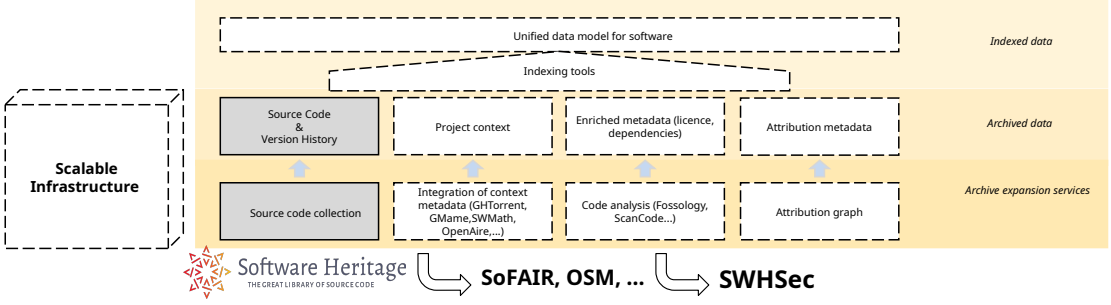

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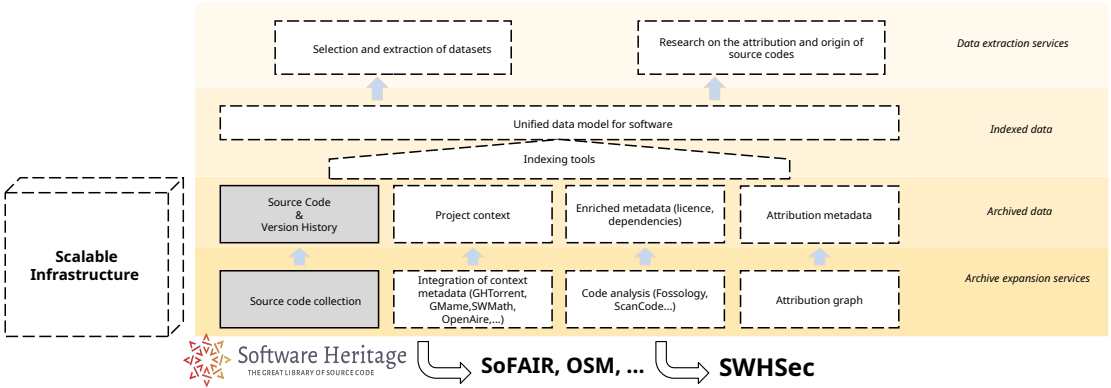

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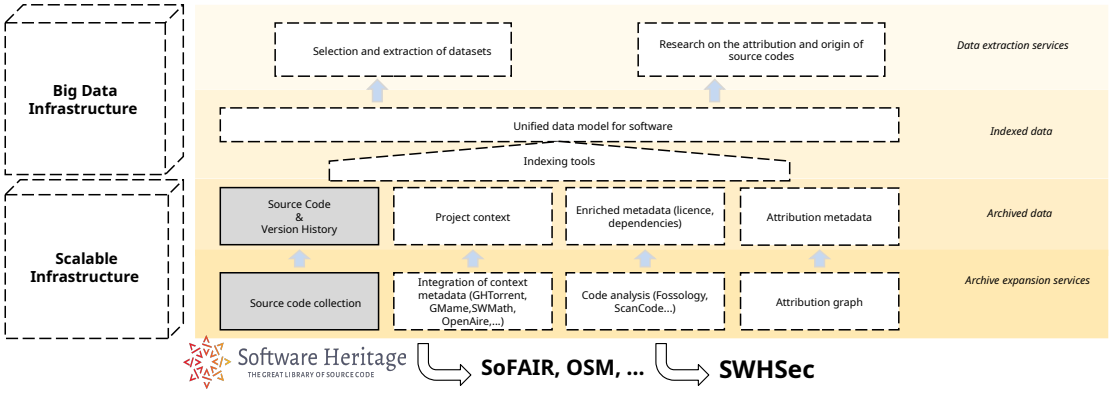

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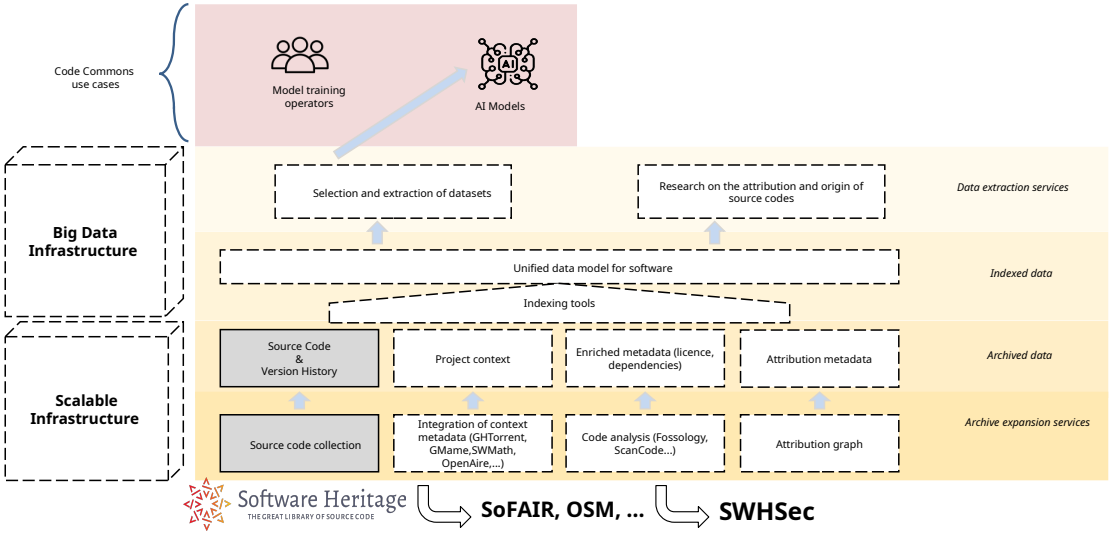

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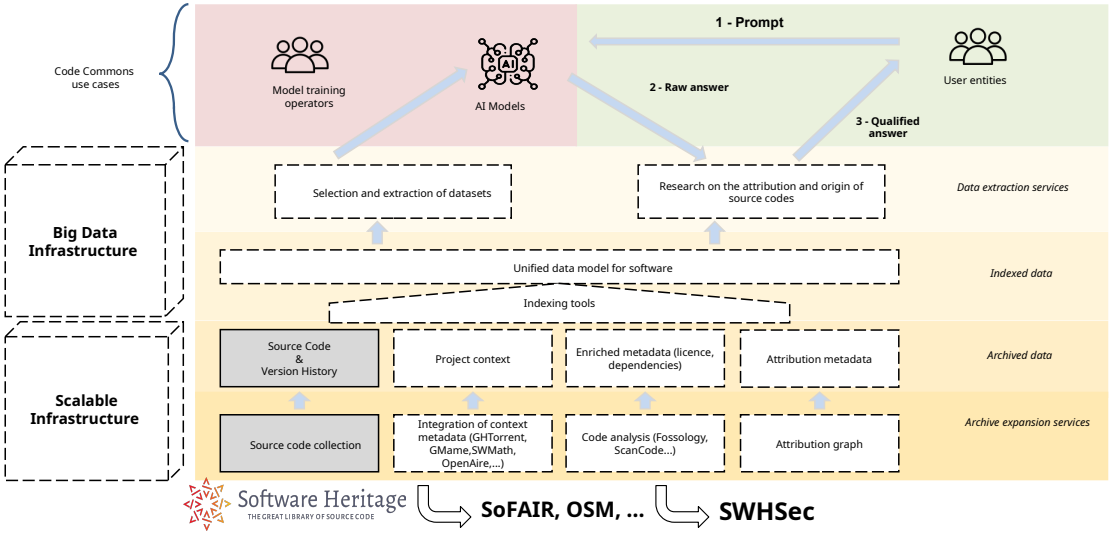

CodeCommons

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

Outline

Open Science

A growing and active community

Core Team

All together, 2024 Symposium

Ambassadors

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

- include it in Open Science policy, show it to students, colleagues: they will adopt it
- get involved: research challenges, open source infrastructure

Annual report 2024

5 years in 5 minutes