User-Controlled Privacy: Taint, Track, and Control

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ETH zürich

Data protection: How things stand

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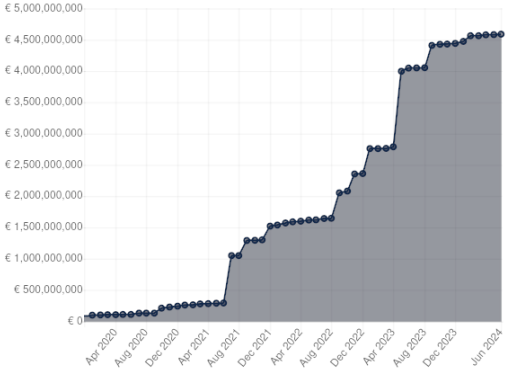
Everything is fines...

Over €4.5B in GDPR fines since 2018



Source: `www.enforcementtracker.com/?insights`, retrieved 2024/07/10

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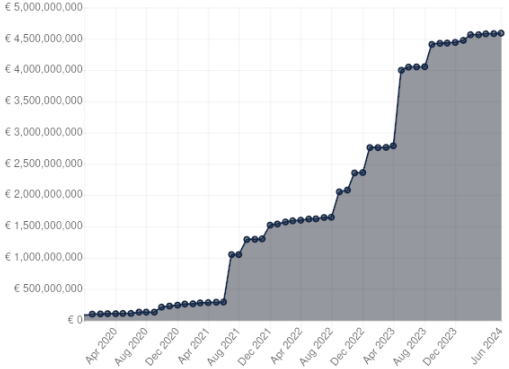

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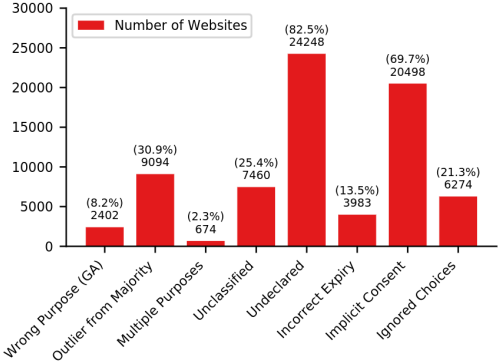
... but not everything is fine

A vast majority of websites are still non-compliant



Source: Bollinger et al. (2022)

Enforcing ex-ante rather than ex-post

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Privacy by Design...

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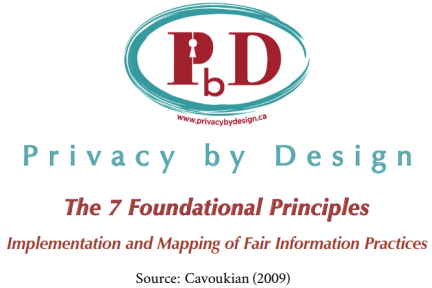

Source: Cavoukian (2009)

... is a legal obligation

Data protection by design and by default.

[T]he controller shall [...] implement appropriate technical and organisational measures [...] to meet the requirements of this Regulation.

— Art. 25(1) GDPR

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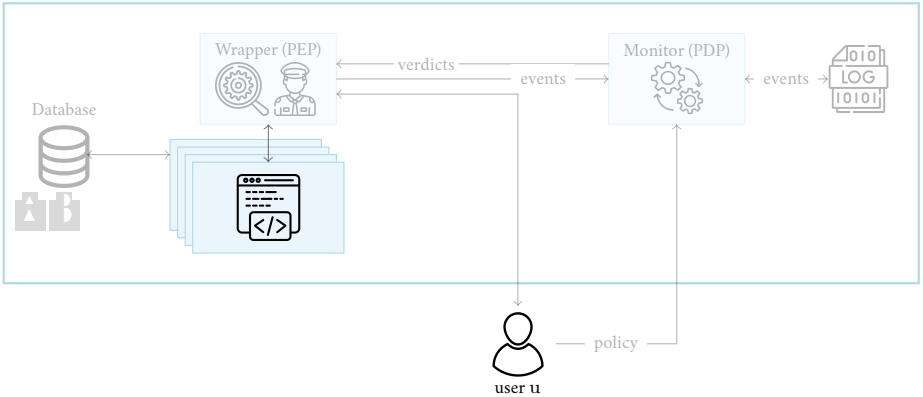

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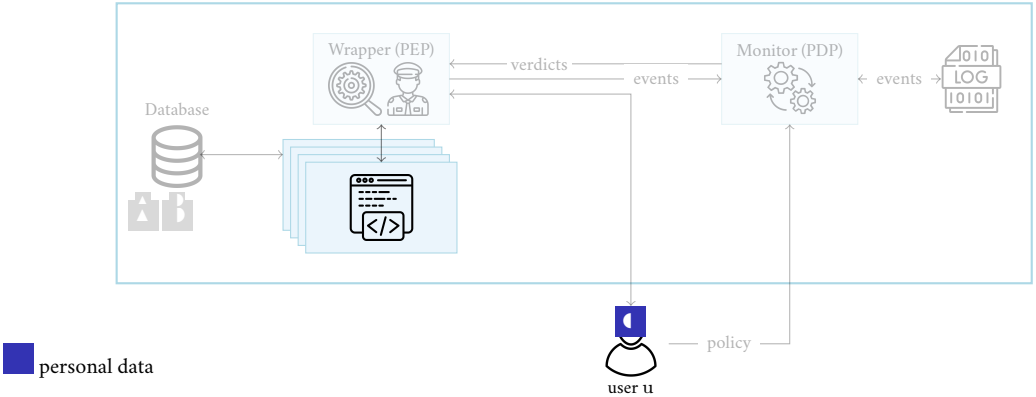

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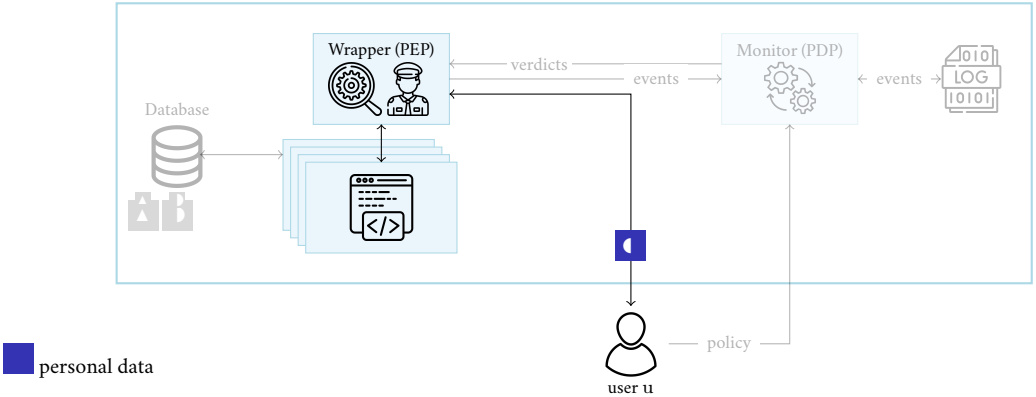

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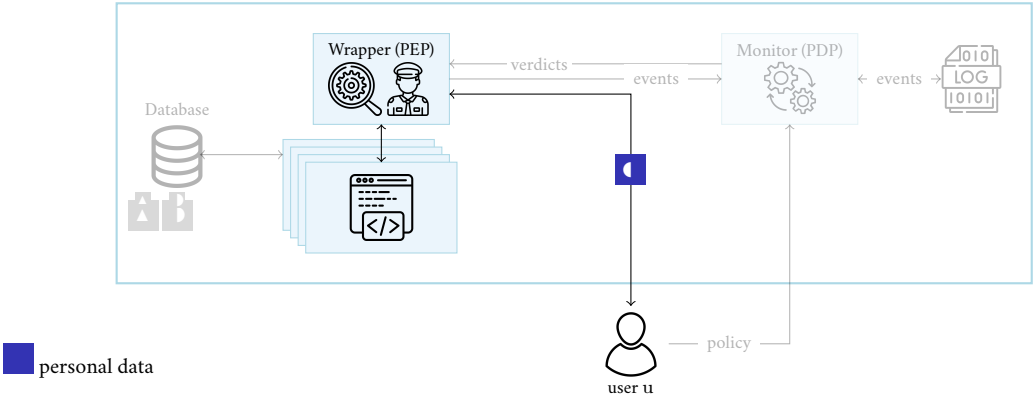

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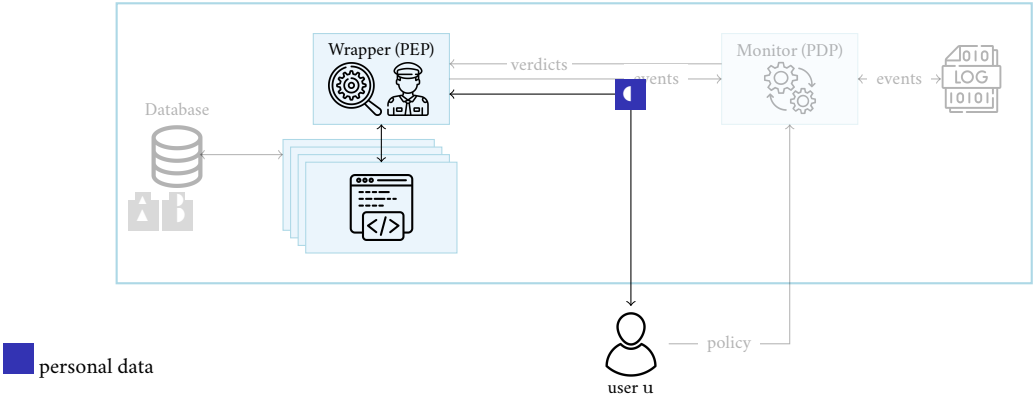

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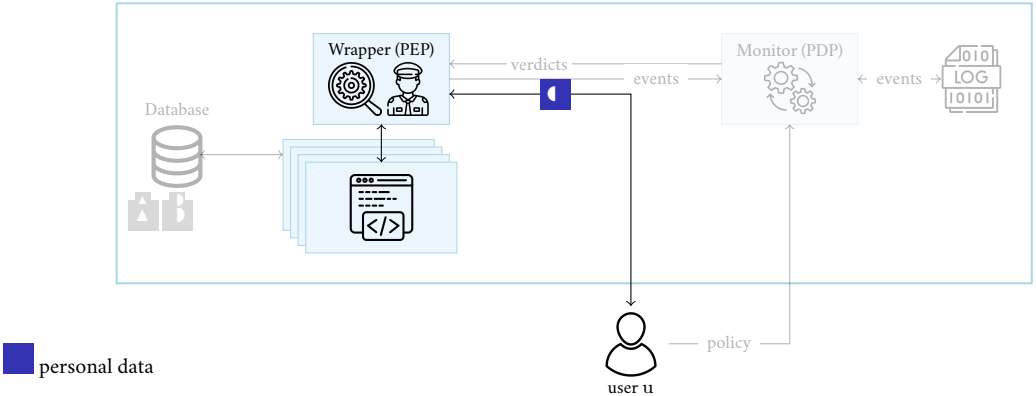

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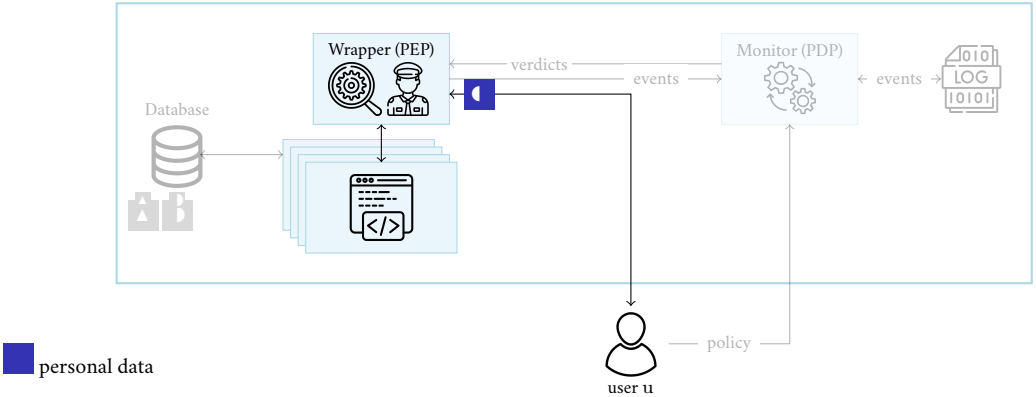

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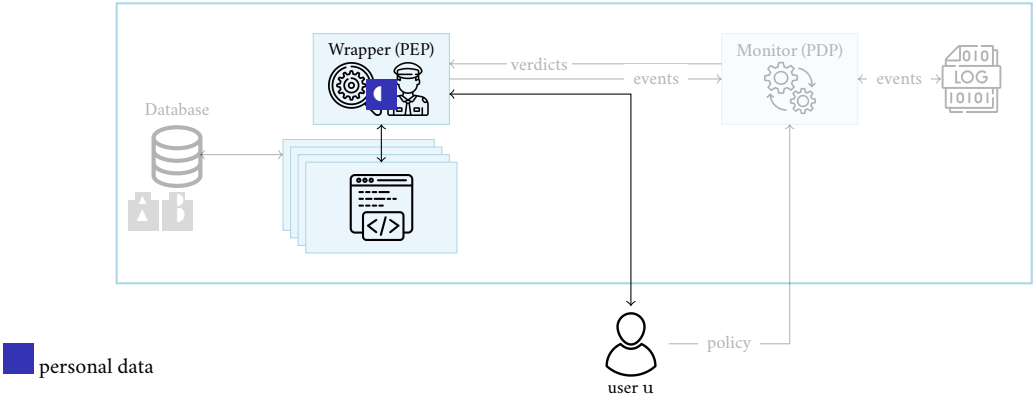

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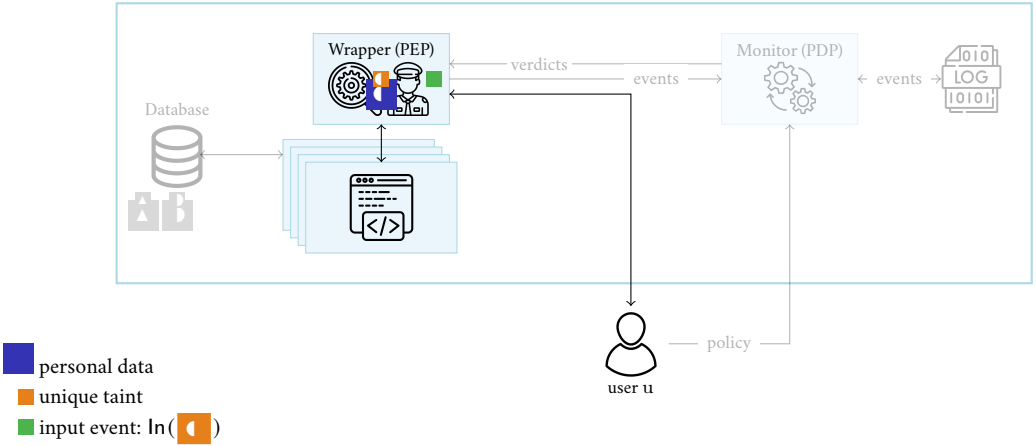

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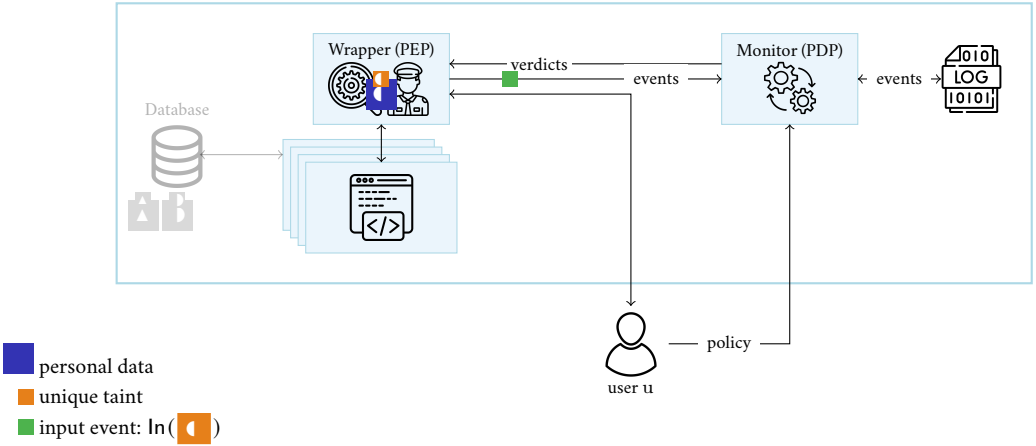

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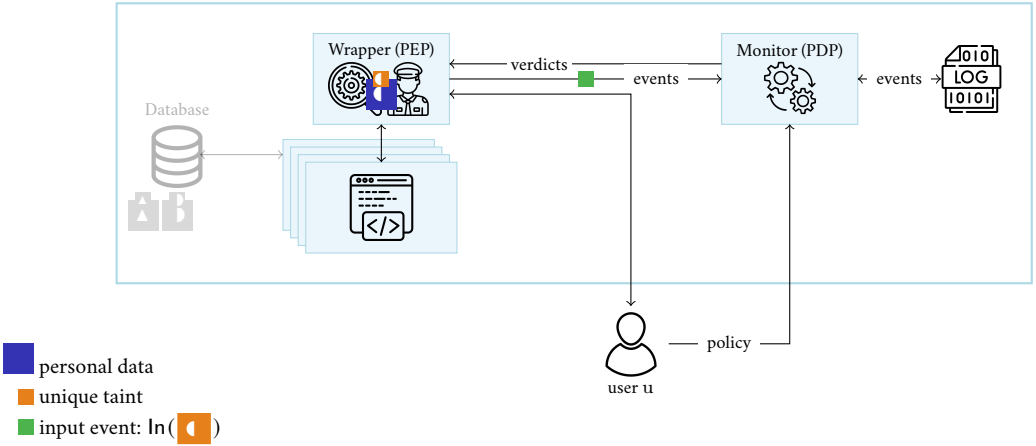

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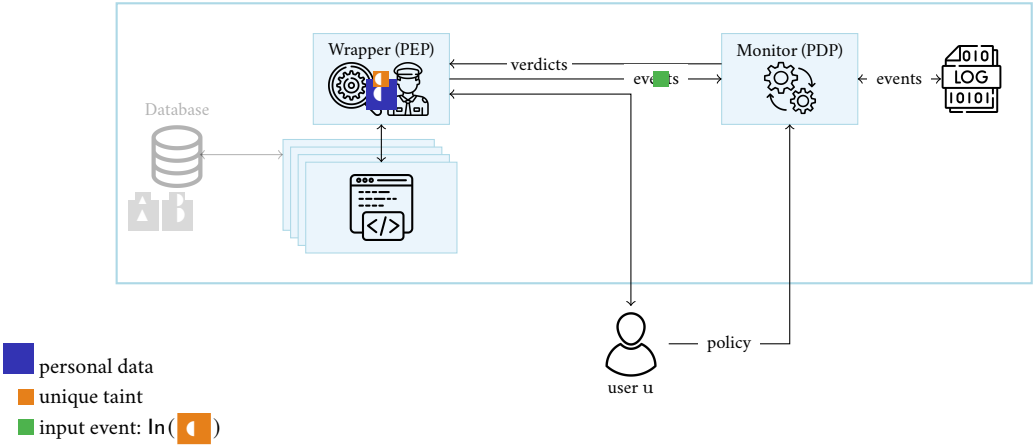

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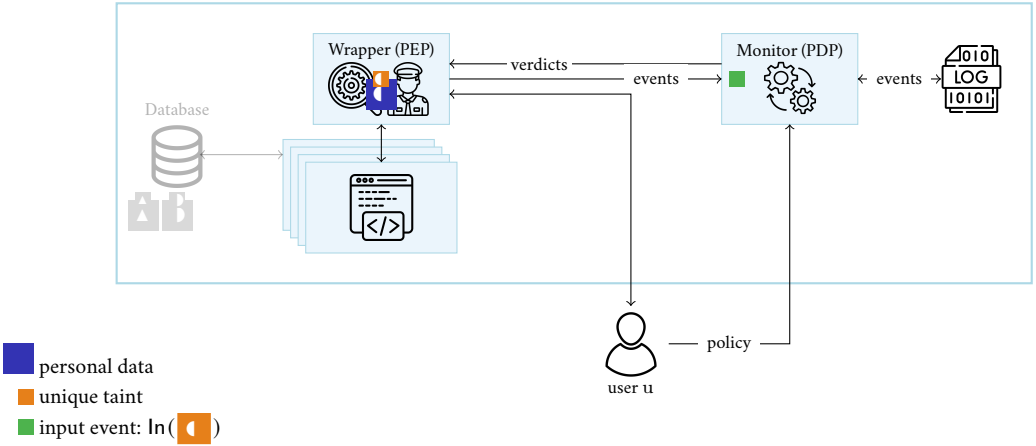

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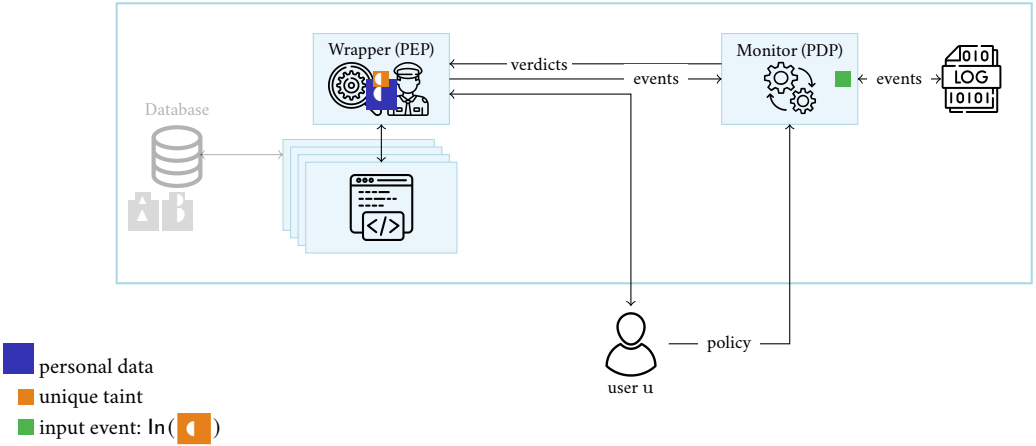

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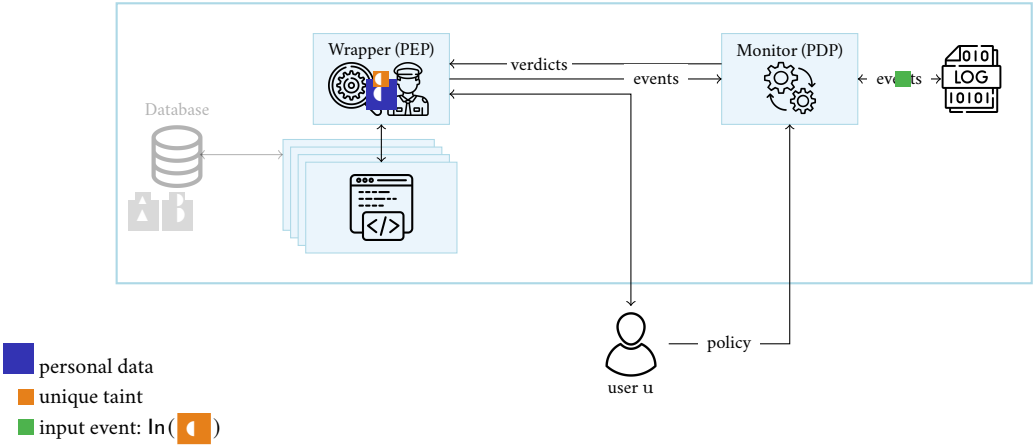

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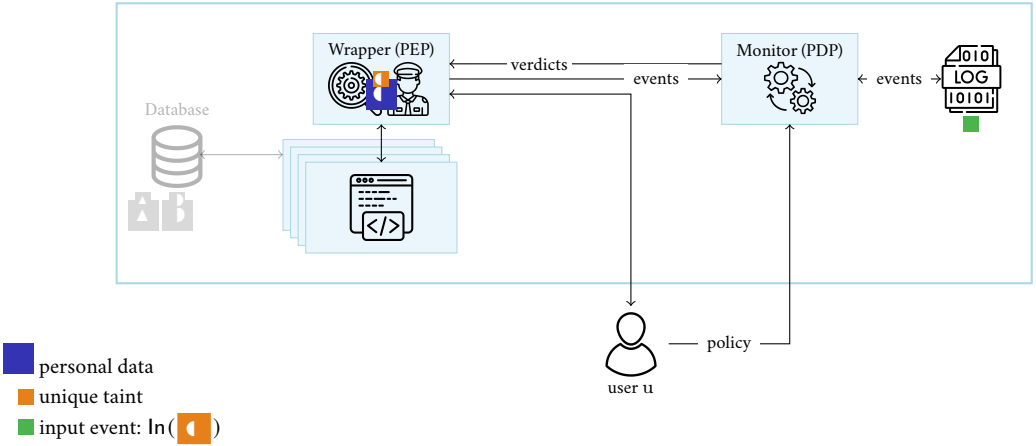

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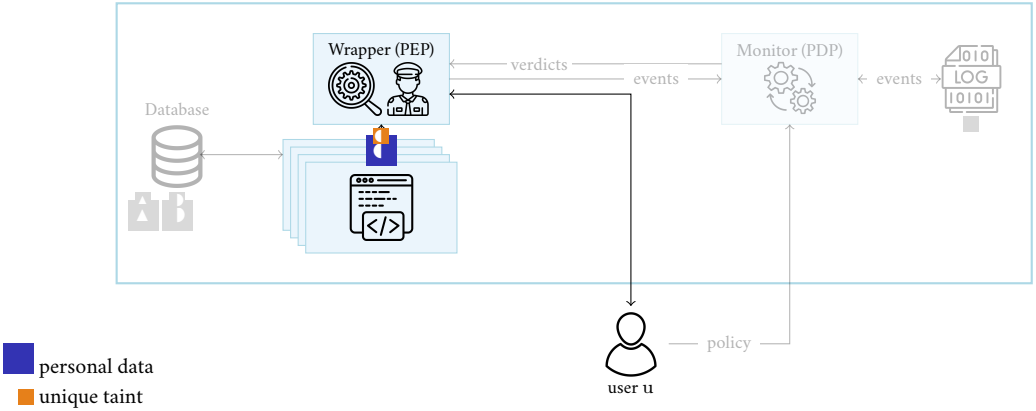

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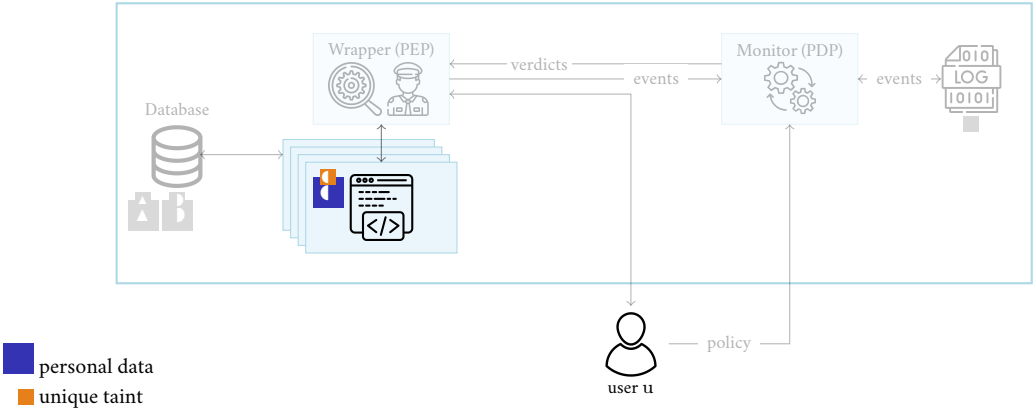

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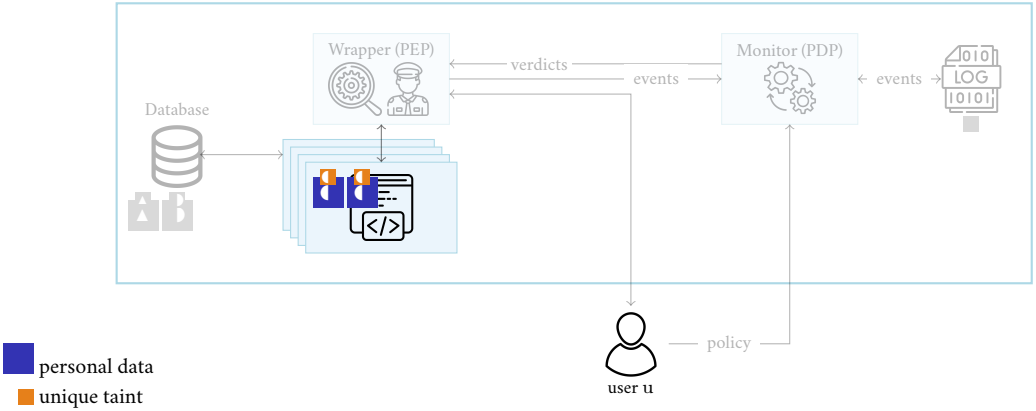

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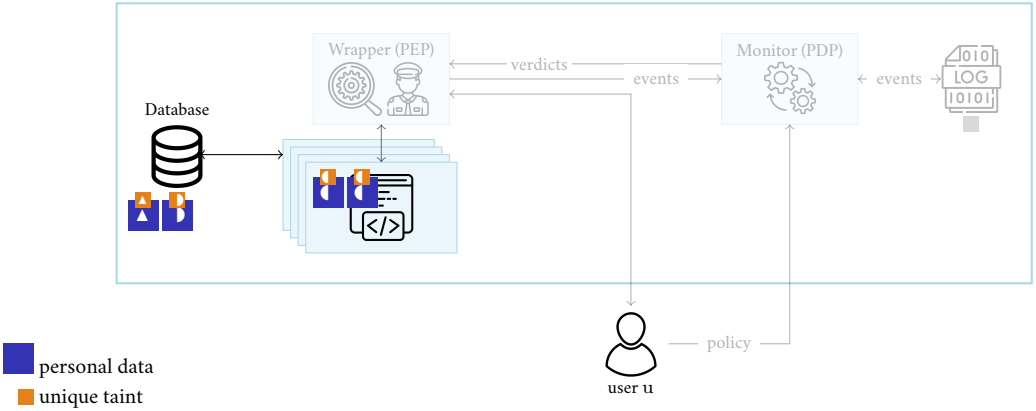

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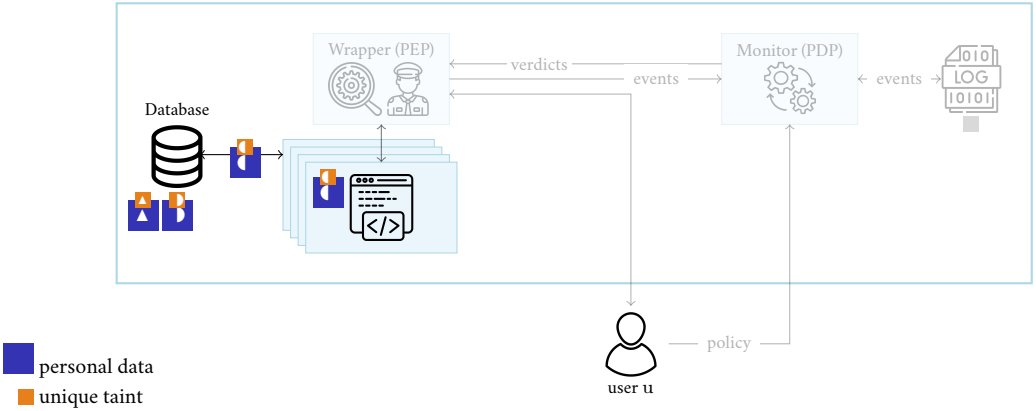

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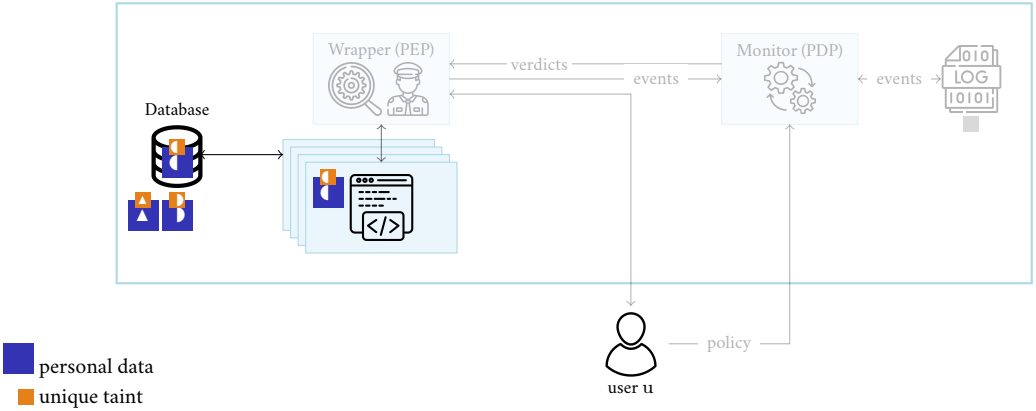

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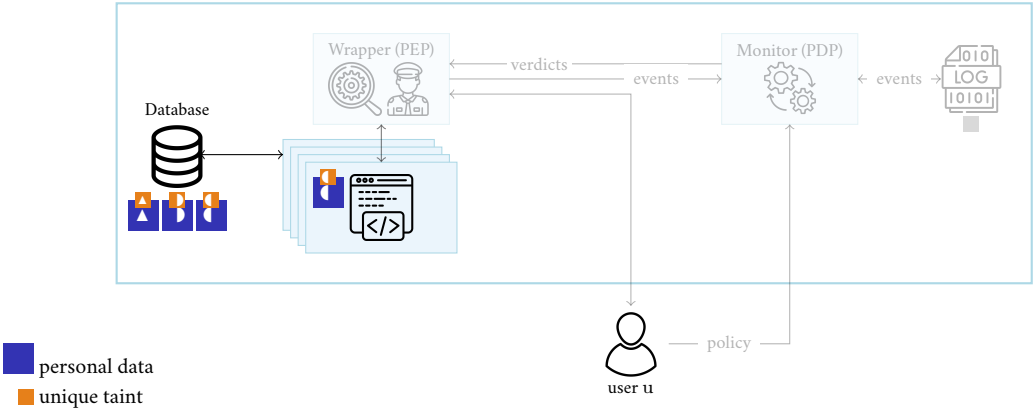

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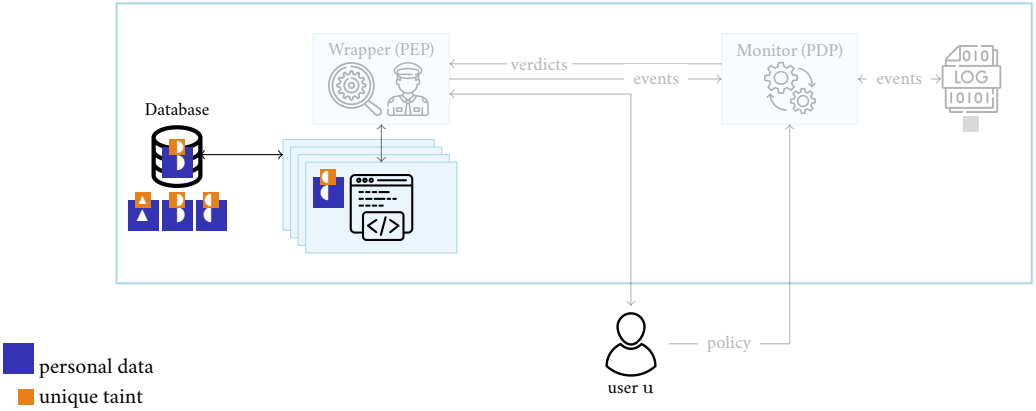

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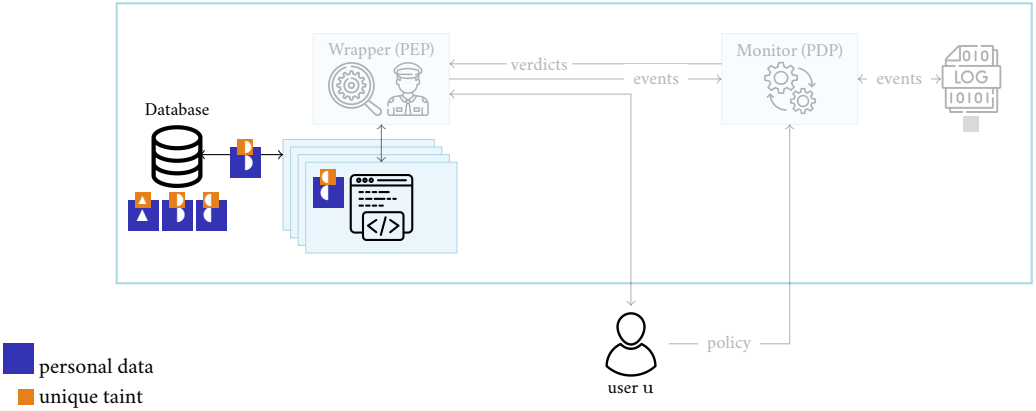

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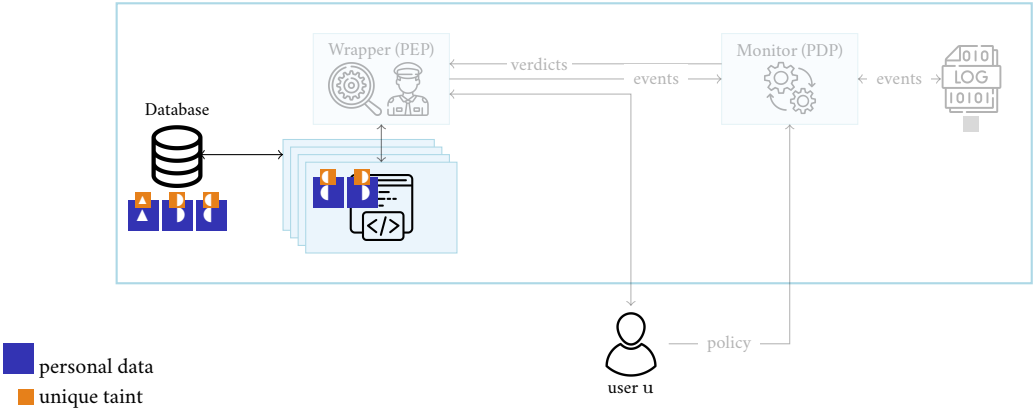

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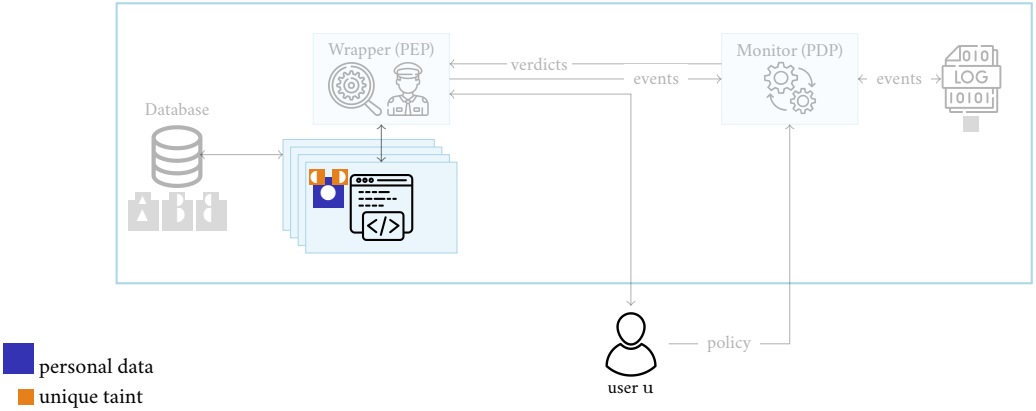

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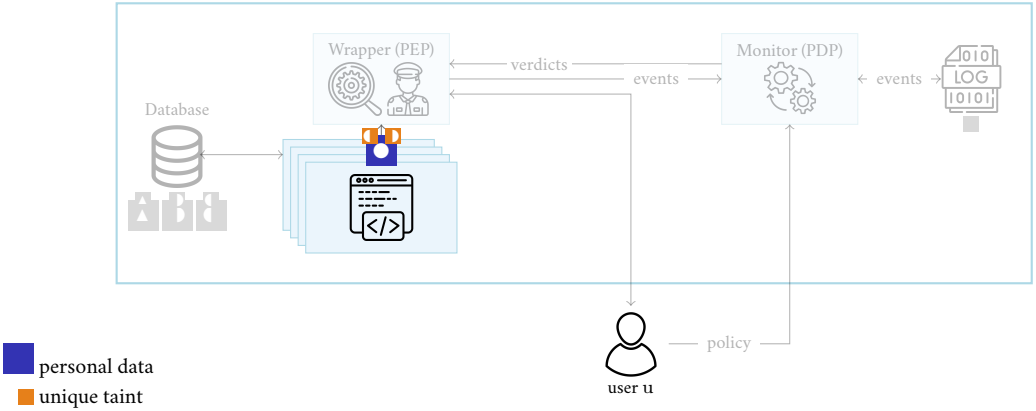

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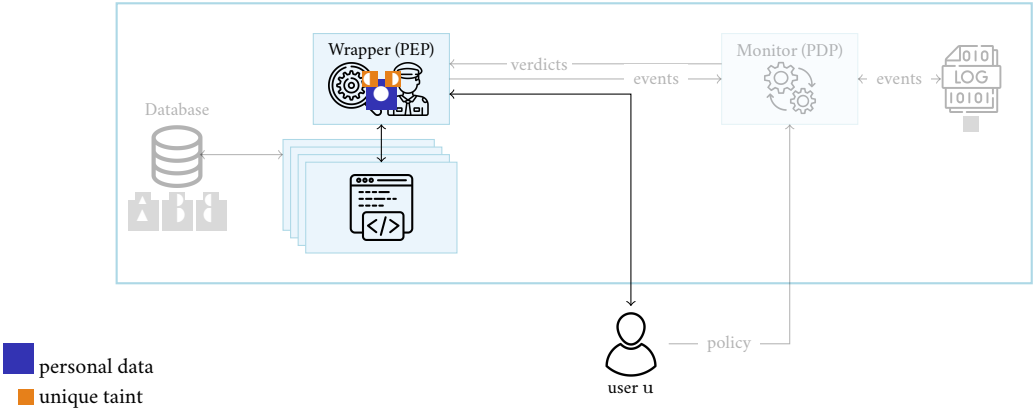

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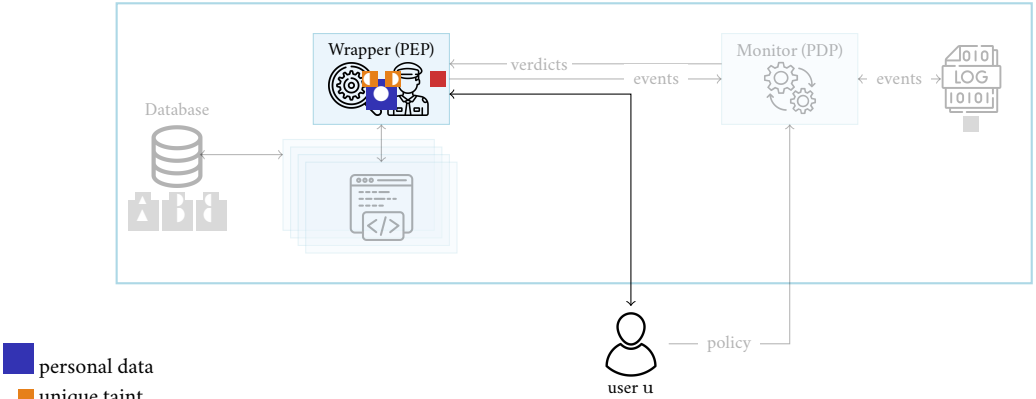

personal data

unique taint

output + interference events: Out(u, p,), Itf(,), Itf(,)

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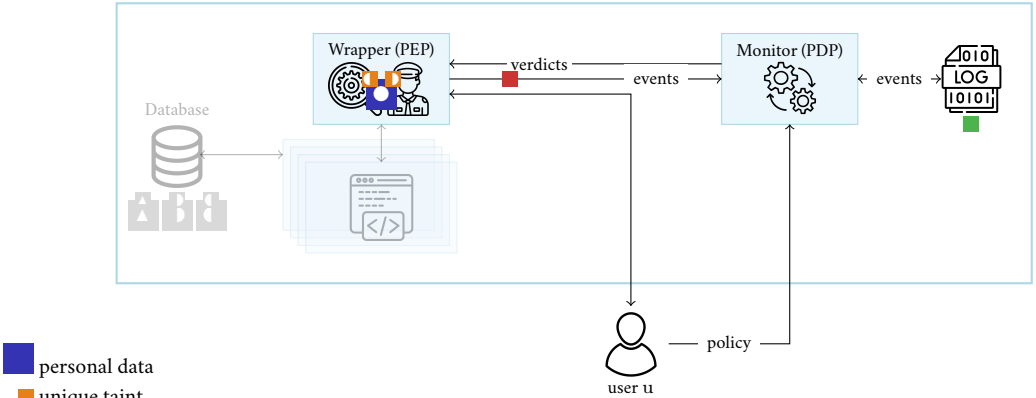

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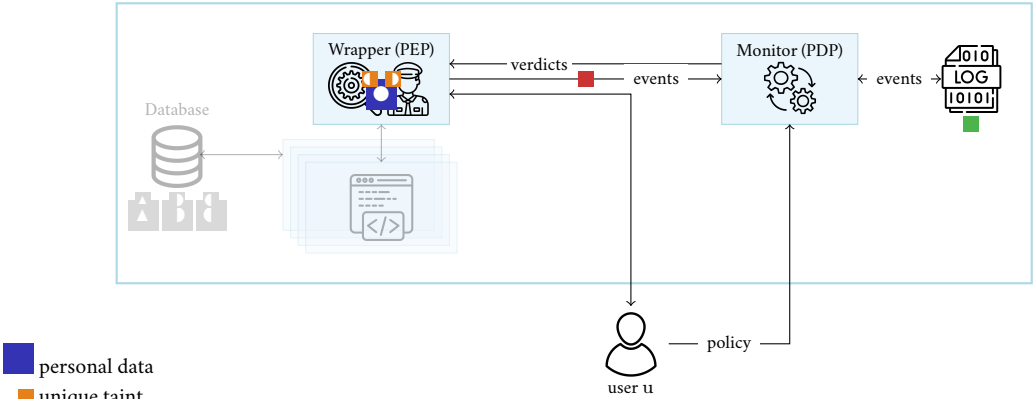

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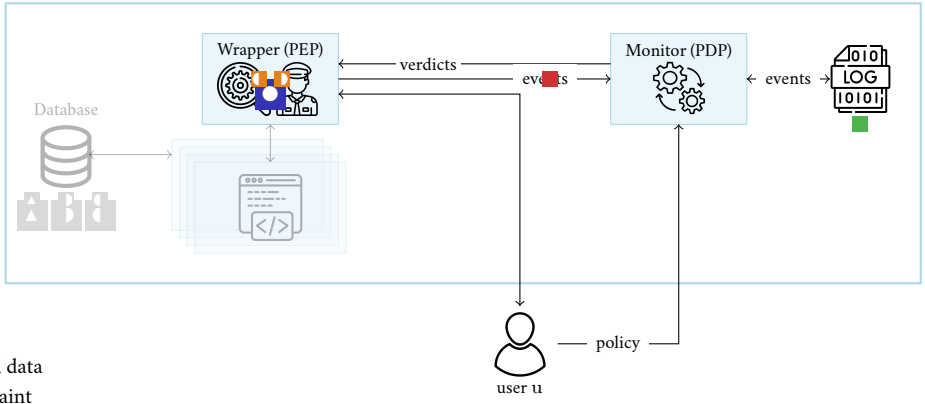

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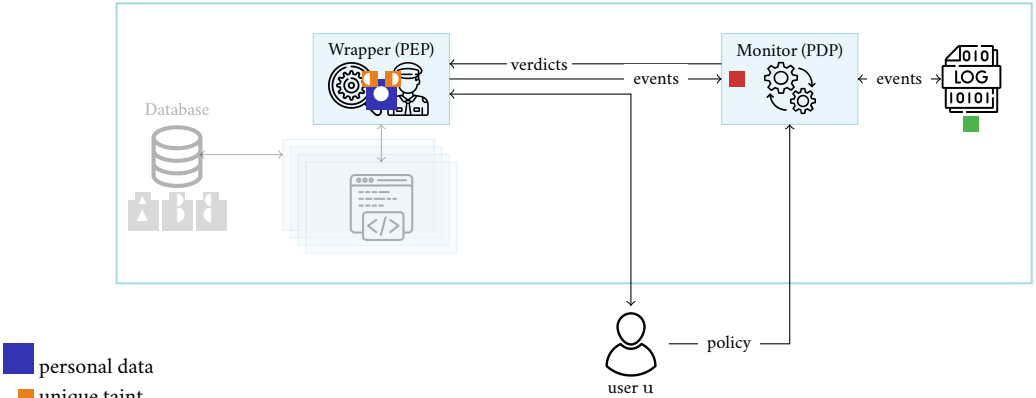

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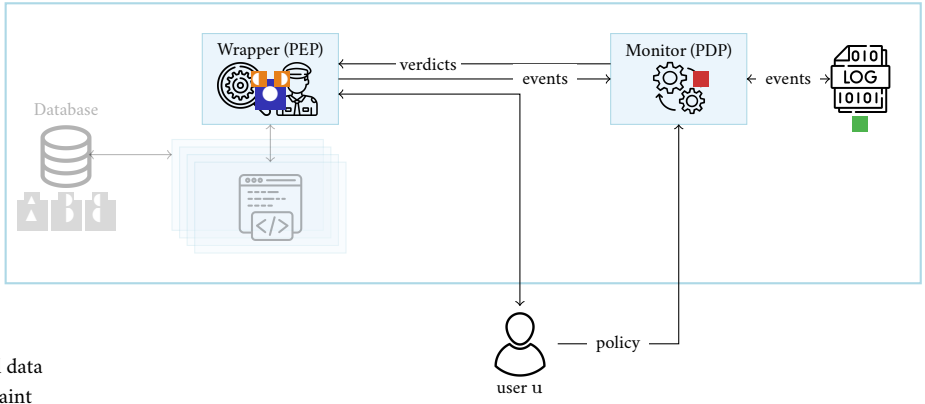

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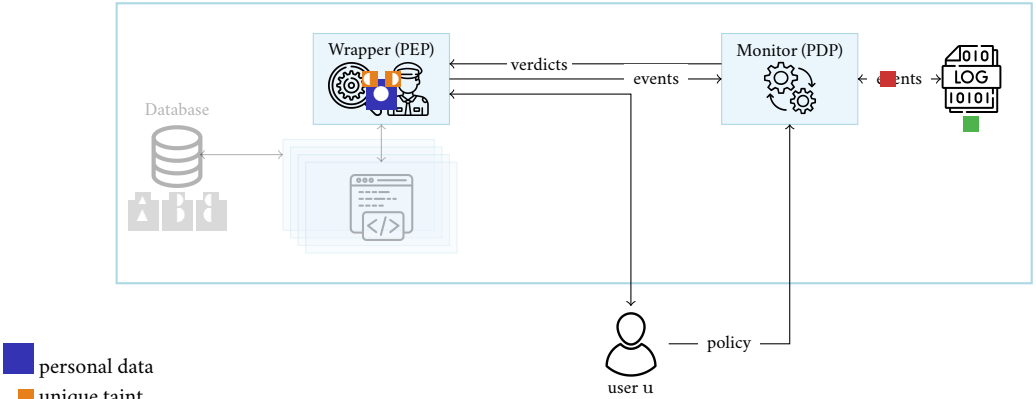

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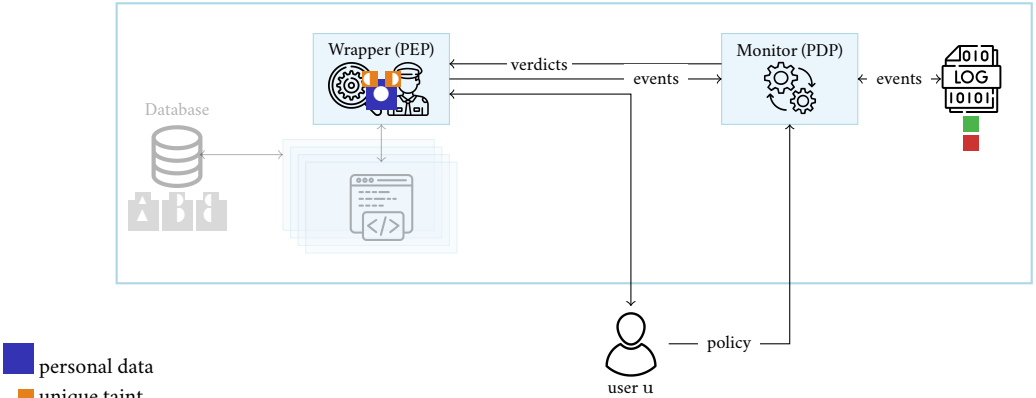

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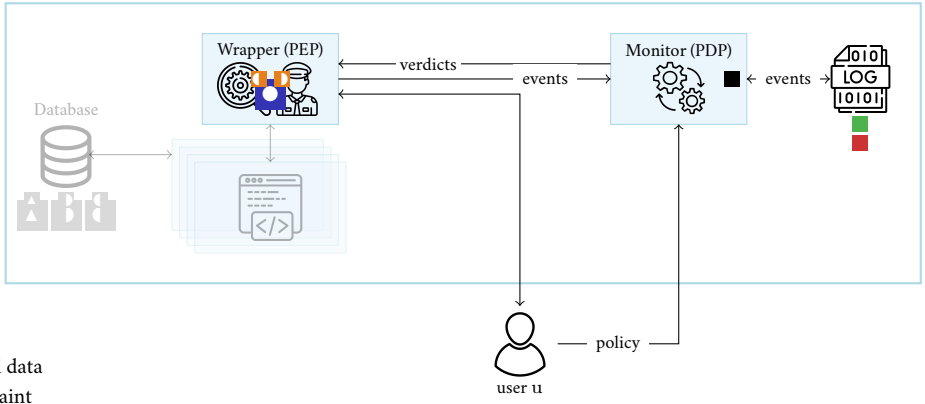

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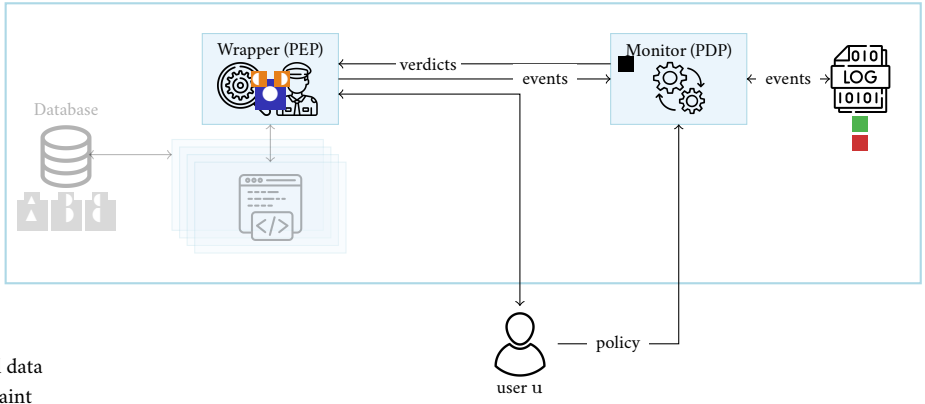

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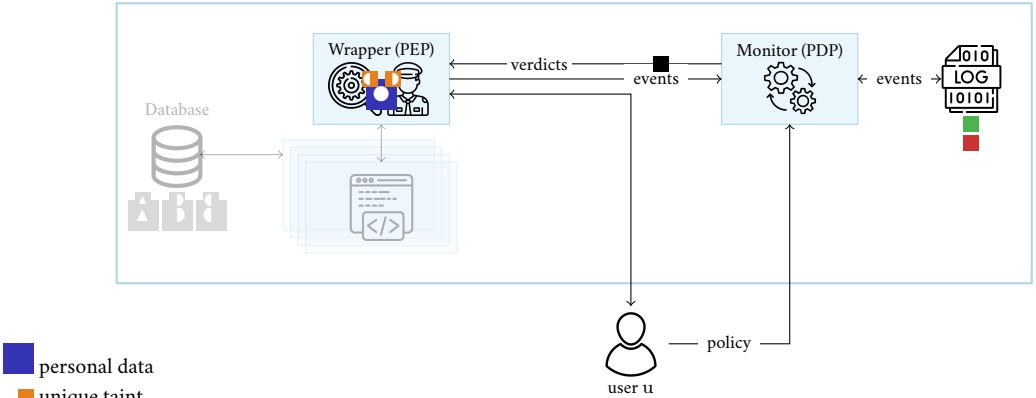

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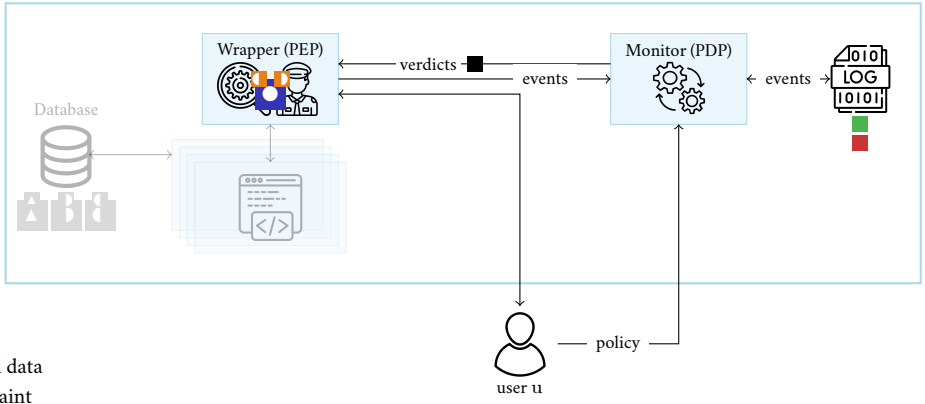

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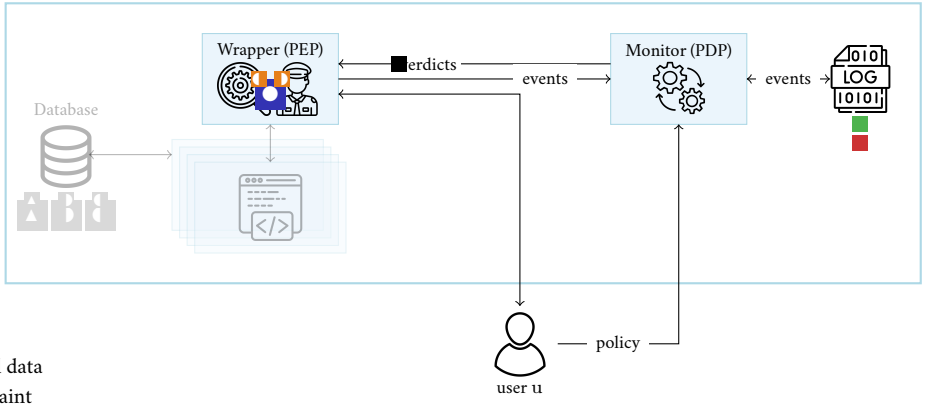

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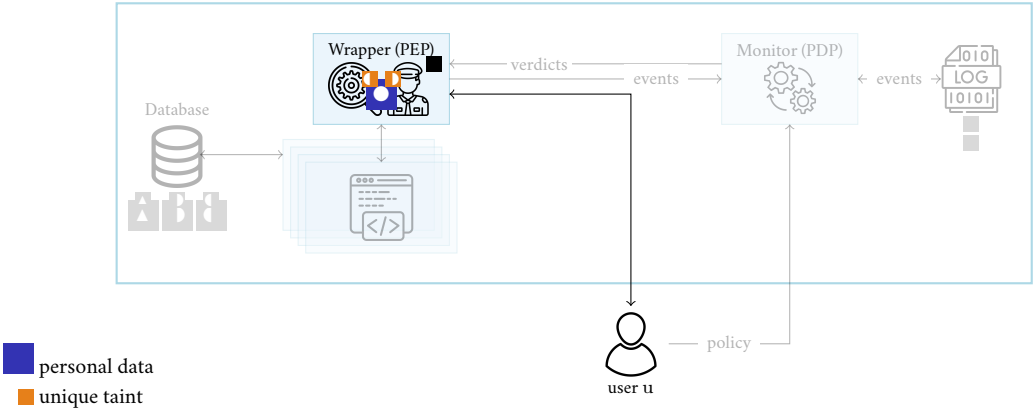

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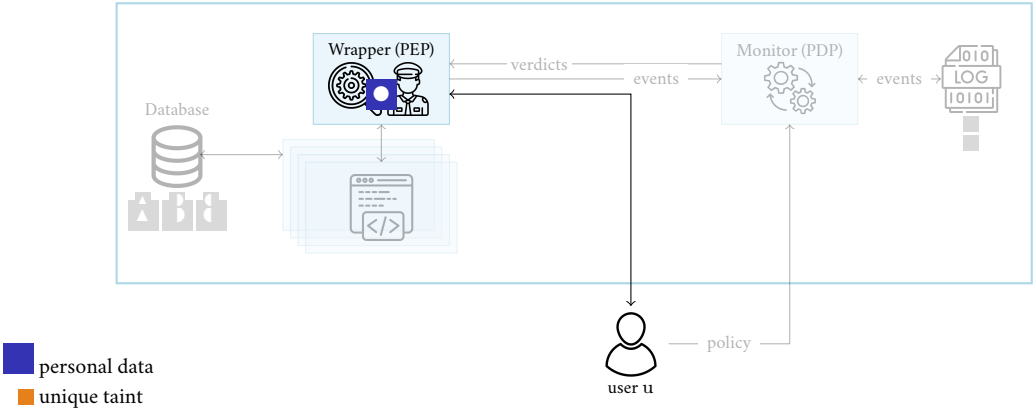

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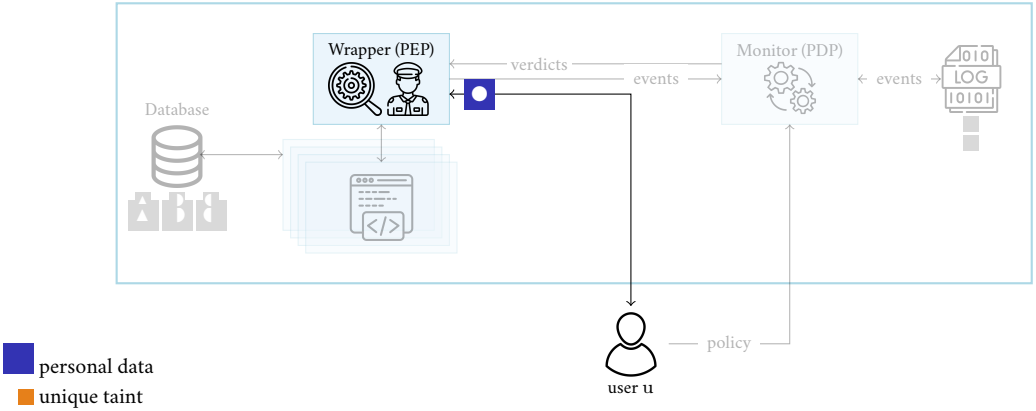

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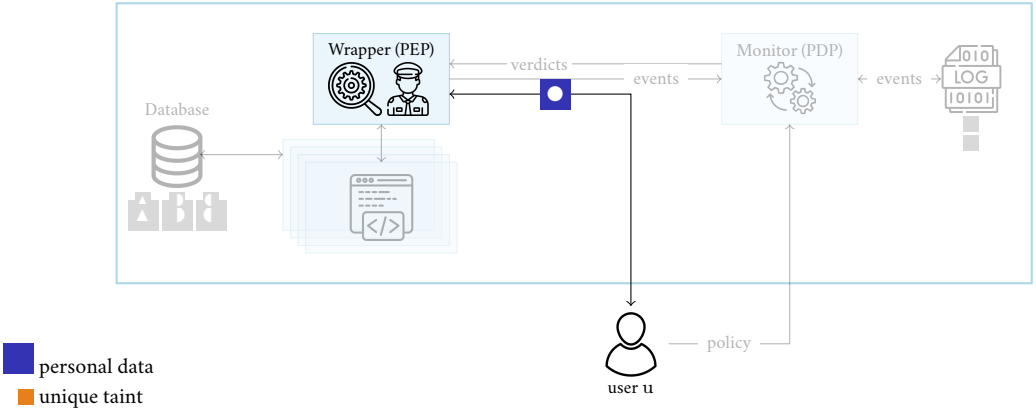

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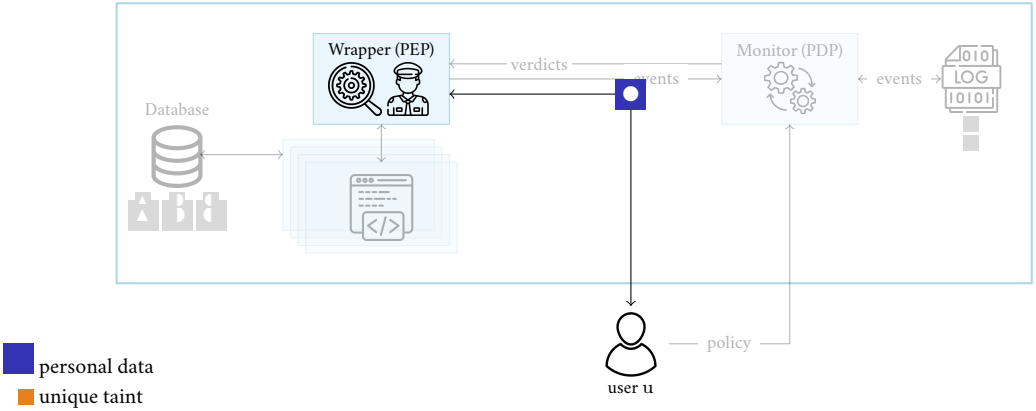

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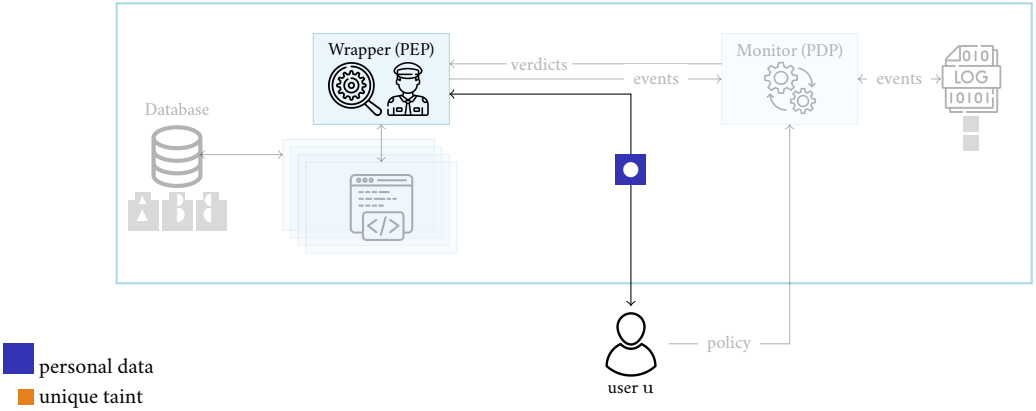

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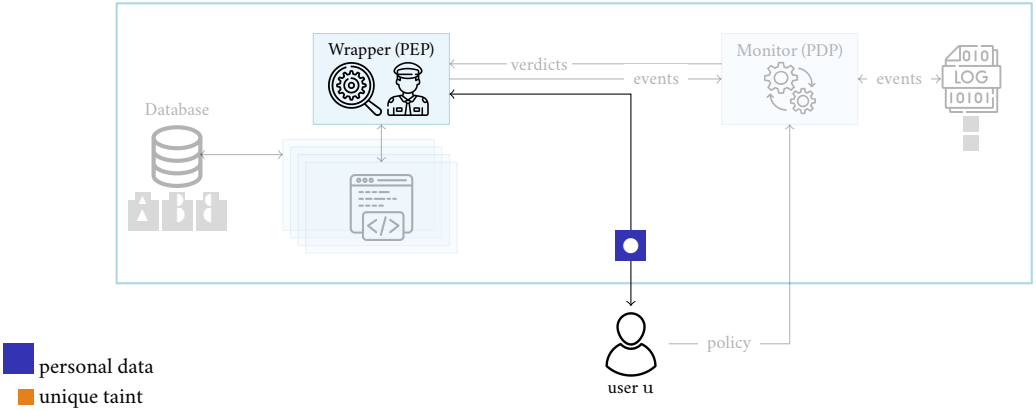

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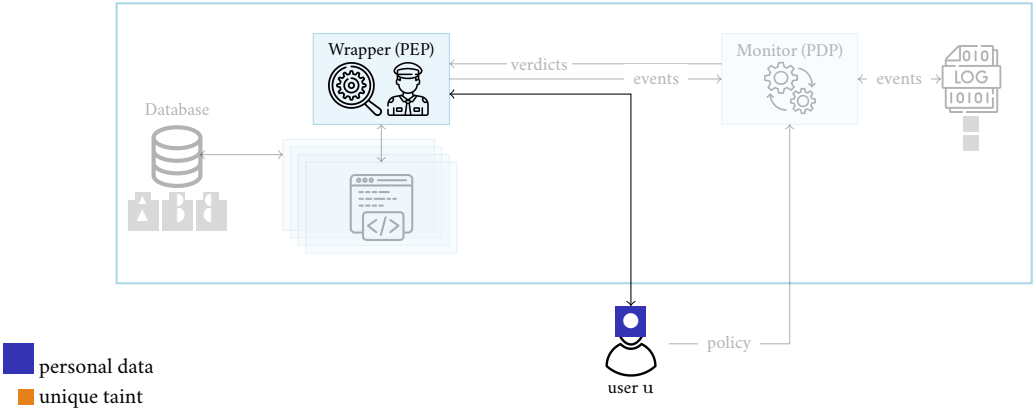

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In both the Taint and Control phases, events are generated, timestamped, and logged:

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Example: Supported policy

$$\Box\big[\forall u, p, o, i.\ \mathsf{Out}(u, p, o) \wedge \mathsf{Itf}(i, o) \Rightarrow \blacklozenge_{[0,\infty)}\ \mathsf{In}(i)$$
$$\Rightarrow\ (p \neq \mathit{"Marketing"}) \wedge (p = \mathit{"Analytics"} \Rightarrow u = \mathit{"trustedanalytics.com"}) \wedge (p = \mathit{"Service"} \Rightarrow \blacklozenge_{[0,1\ \mathtt{week}]}\ \mathsf{In}(i))\big]$$

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Example

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x, y, z = input()
if x == "Hi":
  r = y + z
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```

Variable	Value	UTs
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pc =	⟨	6	,		⟩

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Using Isabelle/HOL, we prove:

Theorem: 4.9

If the monitor is loaded with a policy P *that is enforceable,* ltf*-monotonic, and independent of past outputs*, then any code running in TTC complies with* P.

* see definitions in paper

Artifact and empirical evaluation

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Artifact: Reproduced

- Prototype web programming framework: WebTTC (~ 3500 loc) based on Python
- Three proof-of-concept applications:
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  - Microblogging
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Evaluation

- Successfully ported POC applications from previous work
- Enforcement overhead of 1.5–2× over pure Flask provided that pagination is introduced
- Performance comparable or better than Jacqueline (Yang et al., 2016)

Applications and future work

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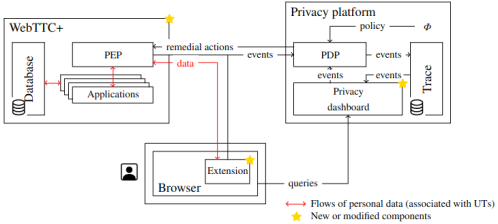
ESORICS'23

Applied WebTTC to enforce 10 GDPR requirements



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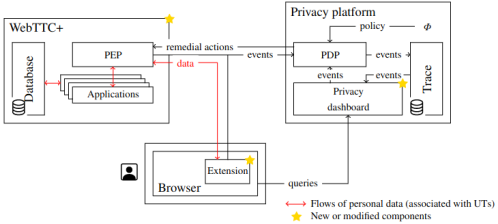

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- Optimizing tracking using static analysis
- TTC in distributed systems
- Anonymization and declassification

Thank you for your attention!

If you are interested in this work, feel free to drop us an e-mail:

François Hublet `francois.hublet@inf.ethz.ch`
David Basin `basin@inf.ethz.ch`
Srđan Krstić `srdan.krstic@inf.ethz.ch`

User-Controlled Privacy: Taint, Track, and Control

François Hublet, ETH Zürich, francois.hublet@inf.ethz.ch
David Basin, ETH Zürich, basin@inf.ethz.ch
Srđan Krstić, ETH Zürich, srdan.krstic@inf.ethz.ch

ABSTRACT

We develop the first language-based, Privacy by Design approach that provides support for a rich class of privacy policies. The policies are user-defined, rather than programmer-defined, and support fine-grained information flow restrictions (considering individual application inputs and outputs) with temporal constraints. Our approach, called Taint, Track, and Control (TTC), combines dynamic information flow control and runtime verification to enforce these policies in the presence of malicious users and developers.

We provide TTC's semantics and proofs of correct enforcement, formalized in the Isabelle/HOL proof assistant. We also implement our approach in a web development framework and port three baseline applications from previous work into this framework for evaluation. Overall, we find that our approach enforces expressive user-defined privacy policies with practical runtime performance.

1 INTRODUCTION

Motivation and Problem Statement. Over the last decade, new legislation, such as the European Union's General Data Protection Regulation (GDPR), has paved the way for a more extensive recognition of individuals' right to privacy. While, from a legal viewpoint, the GDPR has set a de-facto global standard [68], the level of effective privacy enjoyed by users of online applications remains unsatisfactory. Amid reports of widespread non-compliance, the gap between expectations and real-world practice has only become more evident.

Privacy by Design (PbD), the principle of "design[ing] and develop[ing] products with a built-in ability to demonstrate compliance" [76], offers a promising path to improving the status quo. With Privacy by Design, *privacy policies* are specified that define who can use which data, when, and for which purposes. Incentives for practitioners to adopt PbD include developing or maintaining a competitive advantage in privacy-critical markets [51] and avoiding the costs resulting from major privacy breaches and non-compliance [42, 46]. Moreover, Article 25 GDPR makes it obligatory for data controllers to use 'state-of-the-art' techniques to implement data protection principles [14]. Whenever technologies for ensuring compliance are available "at a reasonable price," controllers are legally obliged to use these (or similar) technologies [35].

Privacy policies can be specified by developers (e.g., at the code level) or end-users (e.g., through a policy management interface). An example of a user-specified policy that addresses the key GDPR concern of *purpose* limitation is policy P_1 in Figure 1, which states that *Alice's personal data* shall never be used for marketing. Assuming that *Alice's personal data* is only input by herself, a conservative

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Policy Textual description

- P_1: "Alice's personal data can be used for any purpose"
- P_2: "Alice's personal data shall never be used for marketing purposes"
- P_3: "Alice's posts in the Minitwitter app shall never be used for marketing purposes; after one week, it shall only be used for service purposes; for analytics purposes, it can only be sent to trustedanalytics.com, but not to any other party"
- P_4: "Alice's personal data shall only be shown to herself"

Figure 1: Example privacy policies for Alice

interpretation of this policy is that *Alice's inputs* and any *data derived from those inputs* shall never be used for marketing purposes.

Privacy policies can be enforced using a language-based approach [74]: developers write applications in a specially designed programming language that guarantees the enforcement of policies either statically or dynamically. Language-based PbD can in turn be implemented as an extension of traditional information-flow control (IFC) [55, 74], leveraging the similarity between the two approaches: both PbD and IFC must restrict data flows and guarantee that, by *default*, the protection enjoyed by data *items* extends to any other data derived from them. But despite these similarities, existing IFC designs cannot be directly reused for PbD, since the assumptions made by these designs do not match the requirements of privacy laws. In particular, the following requirements stand out:

[R1] *User-specified policies.* Privacy policies must be specified by individual users, rather than developers. In the GDPR, this reflects that the allowed usage of data depend on end-user consent, which must be freely given [1, Art. 7].

[R2] *Per-input policies.* The policy language must distinguish between different user inputs to support fine-grained restrictions on data usage, e.g., to provide the additional protection enjoyed by special data categories [1, Art. 9]. Users must be able to define different restrictions for each of their inputs.

[R3] *Time-dependent policies.* The policy language must allow users to define restrictions that apply only for a specific time period. For example, the GDPR has the notion of a *storage period* [1, Rec. 85] during which data can be used and retained.

Policy P_3 in Figure 1 exemplifies these requirements: user Alice demands that her posts in a microblogging platform *are never used* for marketing purposes, that only a single trusted third-party can be sent information about the posts for analytics purposes, and that after a week, the messages can only be used for service purposes. These limitations extend to all data derived from her posts. The policy is user-specific (only concerning Alice's inputs), per-input (only applying to Alice's posts), and time-dependent (no additional constraints apply after a week).

State of the Art. Requirements. [R1–3] are out of the scope of most previous work on IFC. Existing approaches usually provide little or no support for time-dependent policies [R3], and define restrictions

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Example: Showing timeline in a microblogging app

```
def filter_check(posts):
  posts2 = []
  for post in posts:
    posts2 += [post] if check("Service", me(), post) else []
  return posts2

@route('/<username>')
def user_timeline(username):
  posts = sql("SELECT * FROM posts WHERE username = ?0", [username])
  posts = filter_check(posts)
  ad    = generate_ad(posts) if check("Marketing", me(), posts) else generate_ad([])
  return render("timeline.html",
                {"posts": ("Service", posts), "ad": ("Marketing", ad)})
```

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1. ▶ x, y, z = input()
2.   if x == "Hi":
3.     r = y + z
4.   else:
5.     r = ""
6.   ...
```

Variable	Value	UTs
x =	⟨	, ⟩
y =	⟨	, ⟩
z =	⟨	, ⟩
r =	⟨	, ⟩
pc =	⟨ 1	, ⟩

Track: Support introspection (cont'd)

- The `check`(`x`, `u`, `p`) function calls the enforcer on the UTs of `x`
- Since the UTs of a variable may depend on personal data, this induces new information flows!
- Solution: Introduce **UT histories** = lists of sets of UTs

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2.   if x == "Hi":
3.     r = y + z
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5.     r = ""
6.   ...
```

Variable	Value	UTs
x =	"Hi"	[X]
y =	"PE"	[Y]
z =	"TS"	[Z]
r =		
pc =	1	

Track: Support introspection (cont'd)

- The `check`(x, u, p) function calls the enforcer on the UTs of x
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5.     r = ""
6.   ...
```

Variable	Value	UTs
x =	"Hi"	[X]
y =	"PE"	[Y]
z =	"TS"	[Z]
r =		
pc =	2	

Track: Support introspection (cont'd)

- The `check`(x, u, p) function calls the enforcer on the UTs of x
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5.     r = ""
6.   ...
```

Variable	Value	UTs
x =	"Hi"	[X]
y =	"PE"	[Y]
z =	"TS"	[Z]
r =		
pc =	2	[X]

Track: Support introspection (cont'd)

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2.    if x == "Hi":
3. ▶    r = y + z
4.    else:
5.      r = ""
6.    ...
```

Variable	Value	UTs
x =	"Hi"	[X]
y =	"PE"	[Y]
z =	"TS"	[Z]
r =		
pc =	3	[X]

Track: Support introspection (cont'd)

- The `check`(x, u, p) function calls the enforcer on the UTs of x
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6.    ...
```

Variable	Value	UTs
x =	"Hi"	[X]
y =	"PE"	[Y]
z =	"TS"	[Z]
r =	"PETS"	[X, Y Z]
pc =	3	[X]

Track: Support introspection (cont'd)

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4.    else:
5.      r = ""
6.    ...
```

Variable	Value	UTs
x =	"Hi"	[X]
y =	"PE"	[Y]
z =	"TS"	[Z]
r =	"PETS"	[X, Y Z]
pc =	3	

Track: Support introspection (cont'd)

- The `check`(`x`, `u`, `p`) function calls the enforcer on the UTs of `x`
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1.    x, y, z = input()
2.    if x == "Hi":
3.      r = y + z
4.    else:
5.      r = ""
6. ▶  ...
```

Variable	Value	UTs
x =	"Hi"	[X]
y =	"PE"	[Y]
z =	"TS"	[Z]
r =	"PETS"	[X, Y Z]
pc =	6	

Track: Support introspection (cont'd)

- The `check`(`x`, `u`, `p`) function calls the enforcer on the UTs of `x`
- Since the UTs of a variable may depend on personal data, this induces new information flows!
- Solution: Introduce **UT histories** = lists of sets of UTs

Example

```
6.  ▶ if check(r, "Alice", "purp"):
7.      s = r
8.    else:
9.      s = ""
10.   ...
```

Variable	Value	UTs
r =	"PETS"	[X, Y, Z]
s =		
pc =	6	

Track: Support introspection (cont'd)

- The `check(x, u, p)` function calls the enforcer on the UTs of `x`
- Since the UTs of a variable may depend on personal data, this induces new information flows!
- Solution: Introduce **UT histories** = lists of sets of UTs

Example

```
6. ▶ if check(r, "Alice", "purp"):
7.     s = r
8.   else:
9.
10.
```

Variable	Value	UTs
`r =`	⟨ `"PETS"` ,	[X, Y Z] ⟩
`s =`	⟨ ,	⟩
		⟩

Can X be output to `"Alice"` for purpose `"purp"`?

Track: Support introspection (cont'd)

- The `check`(`x`, `u`, `p`) function calls the enforcer on the UTs of `x`
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```
6. ▶ if check(r, "Alice", "purp"):
7.     s = r
8.   else:
9.
10.
```

Variable	Value	UTs
`r =`	⟨ `"PETS"` ,	[X , Y Z] ⟩
`s =`	⟨ ,	⟩
		⟩

Can X be output to `"Alice"` for purpose `"purp"`? Monitor: **Yes.**

Track: Support introspection (cont'd)

- The `check(x, u, p)` function calls the enforcer on the UTs of `x`
- Since the UTs of a variable may depend on personal data, this induces new information flows!
- Solution: Introduce **UT histories** = lists of sets of UTs

Example

```
6. ▶ if check(r, "Alice", "purp"):
7.     s = r
8.   else:
9.
10.
```

Variable	Value	UTs
`r =`	⟨ `"PETS"` ,	[X , Y Z] ⟩
`s =`	⟨ ,	⟩
		⟩

Can Y and Z be output to `"Alice"` for purpose `"purp"`?
Already checked UTs = [X]

Track: Support introspection (cont'd)

- The `check`(`x`, `u`, `p`) function calls the enforcer on the UTs of `x`
- Since the UTs of a variable may depend on personal data, this induces new information flows!
- Solution: Introduce **UT histories** = lists of sets of UTs

Example

```
6. ▶ if check(r, "Alice", "purp"):
7.     s = r
8.   else:
9.
10.
```

Variable	Value	UTs
`r` =	⟨ `"PETS"` ,	[X , Y Z] ⟩
`s` =	⟨ ,	⟩
		⟩

Can Y and Z be output to `"Alice"` for purpose `"purp"`? Monitor: **No.**
Already checked UTs = [X]

Track: Support introspection (cont'd)

- The `check`(`x`, `u`, `p`) function calls the enforcer on the UTs of `x`
- Since the UTs of a variable may depend on personal data, this induces new information flows!
- Solution: Introduce **UT histories** = lists of sets of UTs

Example

```
6.  ▶ if check(r, "Alice", "purp"):
7.      s = r
8.    else:
9.
10.
```

Variable	Value	UTs
`r` =	⟨ `"PETS"` ,	[X , Y Z] ⟩
`s` =	⟨ ,	⟩
		⟩

Can Y and Z be output to `"Alice"` for purpose `"purp"`? Monitor: **No.**

Already checked UTs = [X] ⟹ `check(r, "Alice", "purp")` = ⟨`False`, [X]⟩

Track: Support introspection (cont'd)

- The `check`(`x`, `u`, `p`) function calls the enforcer on the UTs of `x`
- Since the UTs of a variable may depend on personal data, this induces new information flows!
- Solution: Introduce **UT histories** = lists of sets of UTs

Example

```
6.    if check(r, "Alice", "purp"):
7.      s = r
8.    else:
9. ▶    s = ""
10.   ...
```

Variable	Value	UTs
r =	⟨ "PETS" ,	[X, Y Z] ⟩
s =	⟨ ,	⟩
pc =	⟨ 9 ,	[X] ⟩

Track: Support introspection (cont'd)

- The `check`(`x`, `u`, `p`) function calls the enforcer on the UTs of `x`
- Since the UTs of a variable may depend on personal data, this induces new information flows!
- Solution: Introduce **UT histories** = lists of sets of UTs

Example

```
6.    if check(r, "Alice", "purp"):
7.      s = r
8.    else:
9. ▶    s = ""
10.   ...
```

Variable	Value	UTs
r =	"PETS"	[X, Y Z]
s =	""	[X]
pc =	9	[X]

Track: Support introspection (cont'd)

- The `check`(x, u, p) function calls the enforcer on the UTs of x
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Example

```
6.    if check(r, "Alice", "purp"):
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10.   ...
```

Variable	Value	UTs
r =	⟨ "PETS" ,	[X, Y Z] ⟩
s =	⟨ "" ,	[X] ⟩
pc =	⟨ 9 ,	⟩

Track: Support introspection (cont'd)

- The `check`(`x`, `u`, `p`) function calls the enforcer on the UTs of `x`
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- Solution: Introduce **UT histories** = lists of sets of UTs

Example

```
6.    if check(r, "Alice", "purp"):
7.      s = r
8.    else:
9.      s = ""
10.▶  ...
```

Variable	Value	UTs
r =	"PETS"	[X, Y Z]
s =	""	[X]
pc =	10	