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Enforcing the GDPR

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Abstract. Violations of data protection laws such as the General Data Protection Regulation (GDPR) are ubiquitous. Currently building IT support to implement such laws is difficult and the alternatives such as manual controls augmented by auditing are limited and scale poorly. This calls for new automated enforcement techniques that can build on, and enforce, a formalization of the law.
In this paper, we present the first enforceable specification of a core set of GDPR provisions, centered on data-subject rights, and describe an architecture that automatically enforces this specification in web applications. We evaluate our architecture by implementing three case studies and show that our approach incurs only modest development and runtime overhead, while covering the most relevant privacy-related aspects of GDPR that can be enforced at runtime.

1 Introduction

Since 2018, nearly €3 billion in fines were imposed on organizations violating the EU's General Data Protection Regulation (GDPR).[1] Despite these fines, GDPR violations are still ubiquitous [10, 32]. In a world where data processing permeates most aspects of life, it appears unlikely that ex-post auditing and fines can bring about compliance at scale. In this context, an ex-ante, automated approach to privacy is needed.

Runtime verification (RV) [5] provides both a theoretical and practical framework for monitoring and enforcing complex properties of computer systems at runtime. In RV, system actions are represented as time-stamped events. System execution then consitutes a trace of events that is checked for compliance with a specification, i.e., a trace property describing the system's desired executions. In particular, online RV tools can check compliance in real-time, with violations being either reported (in the case of *runtime monitoring* [23]) or prevented (in the case of *runtime enforcement* [39]).

The challenge of using RV techniques for automated enforcement of privacy laws is threefold. First, legal provisions must be *faithfully translated* into a formal specification: relevant actions by both software systems and individuals must be encoded as events, and legal provisions turned into a formal specification. Second, the resulting specification must be *enforceable* by an automatic process, also called an enforcer (Section 2.1): one must identify which actions can be suppressed or caused to prevent violations, and then check that all potential violations of the specification can be prevented by such suppression or causation. Third and finally, applications must be *instrumented* so that they emit appropriate events and can suppress or cause relevant actions. In particular, a core requirement of privacy laws is for applications to track information flows in order to

[1] July 2018–May 2023. Source: www.enforcementtracker.com.

faithfully determine where and how personal data is used. A dynamic information-flow control mechanisms can be used to deduce data ownership during execution (Section 2.2).

In this paper, we propose the first comprehensive approach to privacy enforcement that jointly addresses all of the above challenges for a core set of GDPR provisions. More specifically, we leverage an RV approach that uses a logical specification language supporting first-order quantification and (metric) temporal operators, providing both a high degree of expressiveness and real-time enforcement support [24]. The provided expressiveness is crucial for a faithful formalization of GDPR provisions.

We first formalize a core set of GDPR provisions as an enforceable specification (Section 3). Our specification builds on previous work [2] on formalizing and *monitoring* parts of the GDPR using Metric First-Order Temporal Logic (MFOTL) [8, 13]. However, in contrast to this prior work, we show how GDPR provisions can be *enforced* rather than just monitored. Specifically, we extend the previous work to cover a larger fragment of GDPR provisions, and then use the theory of MFOTL enforcement [24] to show the enforceability of our specifications. We cover purpose and consent-based data usage, as well as the rights to access, rectify, erase, restrict, and object to data processing.

We then build an architecture that enforces this specification in web applications (Section 4). Our architecture consists of three components: data subjects' *browsers*, the *WebTTC+ execution environment* where data controllers deploy their applications, and a *privacy platform* to which data subjects delegate the enforcement of their privacy preferences. WebTTC+ is an extension of the recently introduced WebTTC environment (TTC stands for Taint, Track, and Control) for enforcing information-flow policies using taint tracking [25]. WebTTC+ ensures that the applications' behavior complies with privacy laws by interacting with an enforcer deployed at the privacy platform. WebTTC+ reports relevant events to the enforcer, which in turn responds with remedial actions (i.e., sets of events to cause or suppress) that WebTTC+ must execute to ensure compliance. Additionally, the data subjects can directly interact with the privacy platform to manage their consent and exercise their rights. The platform sends events representing data subject queries (e.g., requests for data access or erasure) to the enforcer.

We evaluate our architecture by implementing three web applications as case studies. These are a microblogging app, a conference management system, and a health record manager. Our evaluation shows that our architecture can enforce a relevant core fragment of GDPR provisions while preserving the application's functionality and introducing only a modest performance and development overhead (Section 5).

In summary, we make the following contributions:

- We propose the first enforceable specification for core GDPR provisions in MFOTL.
- We develop an architecture for enforcing this specification in web applications and show how to instrument relevant actions to obtain appropriate events.
- We evaluate a prototype implementation of our architecture on three case studies. Our evaluation shows that our approach incurs only modest development and runtime overhead, while covering the most relevant privacy-related aspects of the GDPR that can be enforced at runtime.

Our analysis of related work (Section 6) shows that this is the first approach that comprehensively enforces a core set of GDPR provisions. The companion repository [26] contains all artifacts.

2 Background

We first introduce Metric First-Order Temporal Logic (MFOTL) and runtime enforcement. We then present the WebTTC environment that extracts the traces for enforcement.

2.1 Runtime enforcement with Metric First-Order Temporal Logic

Given a specification describing intended system execution, runtime enforcement [39] is the process whereby the system execution is observed by a so-called *enforcer* that detects attempted violations and reacts to *prevent* them. In this paper, we use MFOTL [8] as the specification language and the EnfPoly tool [24] as the enforcer.

Let $\Sigma = (\mathbb{D}, \mathbb{E}, a)$ be a first-order signature, containing an infinite set $\mathbb{D}$ of constant symbols, a finite set of *event names* $\mathbb{E}$, and an arity function $a : \mathbb{E} \to \mathbb{N}$. An *event* is a pair $e(d_1, \ldots, d_{a(e)}) \in \mathbb{E} \times \mathbb{D}^{a(e)}$ of an event name e with arity $a(e)$, and $a(e)$ parameters.

Events represent system actions *observable* by the enforcer. Some observable events can be suppressed or caused by the enforcer, while others can only be observed. Hence, $\mathbb{E}$ can be partitioned into sets of suppressable (Sup), causable (Cau), and only-observable (Obs) event names. Given a signature Σ, a *trace* is a sequence of pairs $\sigma = ((\tau_i, D_i))_i$, where the $\tau_i \in \mathbb{N}$ are nondecreasing timestamps and $D_i \in \mathbb{DB}$ is a finite set of events. The empty trace is denoted by ε, the set of traces by $\mathbb{T}$, and a *(trace) property* is any set $P \subseteq \mathbb{T}$. For two traces σ, σ' with σ finite, $\sigma \cdot \sigma'$ is their concatenation, and $|\sigma'|$ is the length of σ'.

Let $\mathbb{I}$ be the set of (possibly infinite) intervals over $\mathbb{N}$ and let $\mathbb{V}$ be for a countable set of variables. MFOTL formulae over a signature Σ are defined by the grammar

$$\varphi ::= \; r(t_1, \ldots, t_{a(r)}) \mid \neg\varphi \mid \varphi \vee \varphi \mid \exists x.\, \varphi \mid \bullet_I \varphi \mid \bigcirc_I \varphi \mid \varphi \, \mathsf{S}_I \, \varphi \mid \varphi \, \mathsf{U}_I \, \varphi,$$

where $x \in \mathbb{V}$, $t_1, \ldots, t_{a(r)} \in \mathbb{V} \cup \mathbb{D}$, $r \in \mathbb{E}$, and $I \in \mathbb{I}$. We further derive Boolean $\top := p \vee \neg p$, $\bot := \neg\top$, $\varphi \wedge \psi := \neg(\neg\varphi \vee \neg\psi)$, $\varphi \Rightarrow \psi := \neg\varphi \vee \psi$, and temporal operators "once" ($\blacklozenge_I \varphi := \top \, \mathsf{S}_I \, \varphi$) and "always" ($\Box_I \varphi := \neg(\top \, \mathsf{U}_I \, \neg\varphi)$).We also define a shorthand for the "inclusive since" operator as $\varphi \, \hat{\mathsf{S}}_I \, \psi := \varphi \, \mathsf{S}_I \, (\varphi \wedge \psi)$. Temporal operators with no interval explicitly given have the interval $[0, \infty)$ instead. Predicates are formulae of the form $r(t_1, \ldots, t_{a(r)})$. A formula that contains no future temporal operators is called a *past-only* formula. We use $\mathsf{fv}(\varphi)$ for the set of φ's free variables.

A *valuation* is any function $v : \mathbb{V} \cup \mathbb{D} \to \mathbb{D}$ such that $v(d) = d$ for all $d \in \mathbb{D}$. We write $v[x \mapsto d]$ for the function equal to v, except for $v(x) = d$. Given a trace $\sigma = ((\tau_i, D_i))_i$, a timepoint $1 \leq i \leq |\sigma|$, a valuation v, and a formula φ, the satisfaction relation $\models$ is defined in Figure 1. We write $v \models_\sigma \varphi$ for $v, 1 \models_\sigma \varphi$ and $\{\sigma \mid \exists v.\ v \models_\sigma \varphi\}$ for the trace property P_φ defined by the formula φ. Without the loss of generality, we focus on closed MFOTL formulae, which are formulae φ where $\mathsf{fv}(\varphi) = \emptyset$.

Trace properties may be defined in terms of infinite traces, whereas enforcers can only observe a finite (prefix of a) trace. Intuitively, a trace must be checked 'prefix-wise', i.e., by evaluating its prefixes in increasing order. A trace complies with a property iff an enforcer for this property accepts all of its prefixes.

An enforceable property must contain the empty trace, i.e., the system must initially comply with the property. Additionally, for any extension $\sigma \cdot (\tau, D)$ of a (non-violating) prefix σ, the enforcer must have enough information to *decide* on its compliance with the property. In MFOTL, this means that the formula should not depend on future

$$\begin{array}{lll|lll}
v,i \models_\sigma r(t_1,...,t_n) & \text{iff } r(v(t_1),...,v(t_n)) \in D_i & & v,i \models_\sigma \neg\varphi & \text{iff } v,i \not\models_\sigma \varphi \\
v,i \models_\sigma \exists x.\,\varphi & \text{iff } v[x \mapsto d],i \models_\sigma \varphi \text{ for } d \in \mathbb{D} & & v,i \models_\sigma \varphi \vee \psi & \text{iff } v,i \models_\sigma \varphi \text{ or } v,i \models_\sigma \psi
\end{array}$$

$$\begin{array}{ll}
v,i \models_\sigma \bullet_I \varphi & \text{iff } i > 1 \text{ and } v,i-1 \models_\sigma \varphi \text{ and } \tau_i - \tau_{i-1} \in I \quad | \;\; v,i \models_\varepsilon \varphi \\
v,i \models_\sigma \bigcirc_I \varphi & \text{iff } i+1 \leq |\sigma| \text{ and } v,i+1 \models_\sigma \varphi \text{, and } \tau_{i+1} - \tau_i \in I \\
v,i \models_\sigma \varphi \, \mathsf{S}_I \, \psi & \text{iff } v,j \models_\sigma \psi \text{ for some } j \leq i, \tau_i - \tau_j \in I, \text{ and } v,k \models_\sigma \varphi \text{ for all } k,\ j < k \leq i \\
v,i \models_\sigma \varphi \, \mathsf{U}_I \, \psi & \text{iff } v,j \models_\sigma \psi \text{ for some } |\sigma| \geq j \geq i, \tau_j - \tau_i \in I, \text{ and } v,k \models_\sigma \varphi \text{ for all } k,\ j > k \geq i
\end{array}$$

Fig. 1: MFOTL semantics

information in the trace, for example, it can be a past-only formula. Furthermore, there must exist finite sets D^- and D^+ of suppressable and causable events respectively that the enforcer can respectively suppress and cause to ensure satisfaction of the property at the new time point, i.e., $\sigma \cdot (\tau, D \setminus D^- \cup D^+)$ satisfies the property. In general, the problem of checking whether an MFOTL formula defines an enforceable property is undecidable [24]. Instead, we consider a syntactic fragment, called *guarded* MFOTL (GMFOTL), where each formula is guaranteed to define an enforceable property:

$$\psi ::= \bot \mid s(t_1,\ldots,t_n) \mid \neg c(t_1,\ldots,t_n) \mid \psi \wedge \varphi \mid \psi \vee \psi \mid \exists x.\,\psi.$$

Here, $s \in \mathsf{Sup}, c \in \mathsf{Cau}$, and φ is any MFOTL formula. When $\mathsf{Sup} \cap \mathsf{Cau} = \emptyset$, GMFOTL is expressively complete [24], i.e., any MFOTL formula that defines an enforceable property can be rewritten to an equivalent GMFOTL formula. Formally:

Theorem 1. *Assume that* $\mathsf{Sup} \cap \mathsf{Cau} = \emptyset$*. Given a past-only closed* MFOTL *formula* φ*, property* $P_{\Box\varphi}$ *is enforceable iff there exists a* GMFOTL *formula* ψ *and* $\Box\varphi \equiv \Box\neg\psi$*.*

EnfPoly [24] is an implementation of an MFOTL enforcer. It takes as input an GMFOTL formula and a trace, which it incrementally processes. At each processing step it reports sets of events to be suppressed or caused such that the formula is satisfied.

2.2 The WebTTC execution environment

WebTTC is an execution environment for web applications that can enforce information-flow policies specified as MFOTL formulae [25]. Such formulae are expressed over *information-flow traces* whose events capture inputs, outputs, and the influence of inputs on outputs. For example, the policy "Alice's inputs shall never influence any output performed to any user for marketing purposes" is formalized in WebTTC as

$$\Box\, [\forall o, ds.\ \mathtt{Out}(ds, \text{Marketing}, o) \Rightarrow \neg(\exists i.\ \mathtt{Itf}(i,o) \wedge (\blacklozenge\, \mathtt{In}(\text{Alice}, i)))]\,.$$

Here, $\mathtt{Out}(u, \text{Marketing}, o)$ reads "the output with identifier o is performed to user ds for marketing purposes", $\mathtt{In}(\text{Alice}, i)$ reads "Alice inputs the input with identifier i", and $\mathtt{Itf}(i,o)$ states "the input with identifier *i interferes* with the output with identifier o." The `Itf` event captures a standard notion of (non-)interference between inputs and outputs, from the information-flow control (IFC) literature [22].

To enforce such information-flow policies, WebTTC follows a dynamic approach that uses a policy enforcement point (PEP) that supervises application execution together with a policy decision point (PDP) implemented by EnfPoly (see Figure 2). Applications written in a Python-like programming language with IFC semantics [25] are deployed by

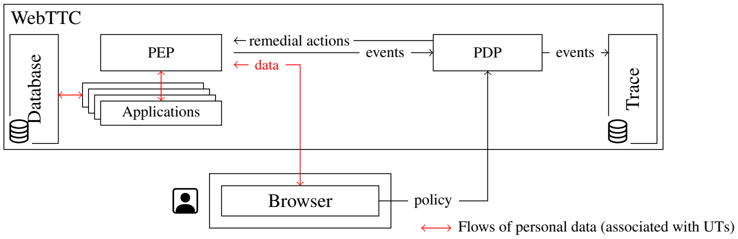


Fig. 2: WebTTC architecture

developers inside WebTTC where they interact with a database. All inputs and outputs are observable by the PDP, which can suppress outputs to ensure compliance with a user-specified information-flow policy. User inputs to applications are processed in three steps:

TAINT: A new input from a user u goes through the PEP, which tags it with a fresh input identifier, called a *unique taint* (UT), and sends an event $\mathtt{In}(u,ut)$ to the PDP, which stores it in the trace. The input and its UT are forwarded to the application.

TRACK: The semantics of the programming language in which applications are written propagates UTs during execution. At any time, each data item in memory or in the database is tagged with the UTs of all inputs that interfered with its current value.

CONTROL: WebTTC requires that every application output be labeled with a purpose. When an application attemps to perform an output to a user u for some purpose p, the PEP generates a fresh output identifier o as well as events $\mathtt{Out}(u,p,o)$ and $\mathtt{Itf}(ut,o)$ for each UT ut tagging the output value. It then sends these events to the PDP, which can instruct the PEP to suppress the output if it would cause a policy violation. If the output is not suppressed, the trace is updated.

To summarize, WebTTC uses the following first-order signature Σ_{TTC}:

Event	**Description**	**Type**
$\mathtt{In}(u,ut)$	Data subject ds inputs a value with UT ut	
$\mathtt{Out}(u,p,ut)$	Value with UT ut is output to data subject ds for purpose p	Ⓢ
$\mathtt{Itf}(ut,o)$	Input with UT ut interferes with output o	

Ⓢ = Suppressable; unmarked events are only-observable

We refer the reader to the paper presenting TTC [25] for additional details.

3 Formalizing GDPR provisions

We now review the core GDPR provisions (Section 3.1), present an appropriate first-order signature (Section 3.2), and an MFOTL formula formalizing the core GDPR provisions (Section 3.3). Finally, we show that the formula is enforceable (Section 3.4).

3.1 Core GDPR provisions

We focus on the provisions laid out in Chapters 2 and 3 of the GDPR, which define the *principles* of data processing and the *rights* of the data subject:

- **Purpose and consent-based usage** [Art. 5(1)(b), 6(1), 7(1,3), 9(1,2)]. The processing of personal data is lawful only if the data subject has consented to processing *for one or more specific purposes*, unless the data controller can claim a specific legal ground. Data subjects can revoke consent at any time. Specific legal grounds are applicable in the case of sensitive data (*special data categories*, Art. 9).

- **Right to access** and **right to data portability** [Art. 15(1), 20(1)]. Data subjects have the right to access any personal data relating to them. They have the right to obtain a copy of this data in a machine-readable format.
- **Right to rectification** [Art. 5(1)(d), Art. 16]. Data subjects have the right to rectify any inaccurate personal data relating to them.
- **Right to erasure ("right to be forgotten")** [Art. 17(1,2)]. Data subjects have the right to obtain the erasure of any personal data relating to them. Other controllers with whom the data has been shared shall be notified about the erasure.
- **Right to restriction of processing** [Art. 18(1)]. Data subjects have the right to restrict the processing of any personal data relating to them.
- **Right to object** [Art. 21(1)]. Data subjects have the right to object to the processing of data relating to them based on specific legal grounds.

For simplicity, we focus on the case where data subjects interact with applications, each managed by a single data controller. We then formalize the above provisions for each individual application, rather than for each data controller.

3.2 First-order signature for core GDPR concepts

We encode key GDPR concepts as a first-order signature representing observable system actions. The signature (Table 1a) consists of two sets of events. The first set represents actions triggered by the data subjects (DS): consent (`DSConsent`) and revocation (`DSRevoke`) thereof; requests for accessing (`DSAccess`), deleting (`DSErase`), rectifying (`DSRectify`), or restricting the use of data (`DSRestrict`); repealing restrictions (`DSRepeal`); and objections to processing (`DSObject`). Each event in this set has a name prefixed with `DS`. The second set represents actions triggered by the application: collection (`Collect`), usage (`Use`), and sharing of data (`ShareWith`); granting access to (`GrantAccess`), erasure (`Erase`), and rectification of data (`Rectify`); notifications of data deletion to third-party controllers (`NotifyErase`); and claims of legal grounds to process data (`LegalGround`). All predicates refer to single data items by their unique taints (UTs). The predicate `Collect` (resp. `LegalGrounds`) has a Boolean parameter *sp* that is `true` if and only if the data collection (resp. the claim of legal grounds) involves (resp. applies to) 'special' data. We call *sp* the *special-data flag* of the data or claim.

Data-subject-triggered actions are not controlled by the enforcer, and hence the corresponding events are only-observable. The collection of data, sharing, and claims for legal grounds, which are not constrained by any core GDPR provision, are also only-observable. In contrast, the usage of data (`Use`) is subject to restrictions and must therefore be suppressable (🅢). Finally, `GrantAccess`, `Erase`, `Rectify` and `NotifyErase` events, which data subjects must be able to request, must be causable (🅒).

3.3 MFOTL formula formalizing core GDPR provisions

The core GDPR provisions are formalized by the formula given in Table 1b. The formula

Table 1: MFOTL formalization of core GDPR provisions

(a) MFOTL signature

Predicate	**Description**	**Type**
	The data subject ds:	
$\texttt{DSConsent}(ds, prp, ut)$	gives consent to use data with UT ut for purpose prp	
$\texttt{DSRevoke}(ds, prp, ut)$	revokes consent given to use data with UT ut for purpose prp	
$\texttt{DSAccess}(ds, ut)$	requests access to data with UT ut	
$\texttt{DSErase}(ds, ut)$	requests erasure of data with UT ut	
$\texttt{DSRectify}(ds, ut, val)$	requests rectification of data with UT ut to new value val	
$\texttt{DSRestrict}(ds, ut)$	requests restriction of data with UT ut	
$\texttt{DSRepeal}(ds, ut)$	repeals restriction of data usage for data with UT ut	
$\texttt{DSObject}(ds, ut)$	objects to usage of data with UT ut by application	
	The application:	
$\texttt{Collect}(ds, ut, sp)$	collects data with UT ut of data subject ds^*	
$\texttt{Use}(prp, ut)$	uses data with UT ut for purpose prp	Ⓢ
$\texttt{ShareWith}(ctr, ut)$	shares data with UT ut with third-party controller ctr	
$\texttt{GrantAccess}(ds, ut)$	gives data subject access to data with UT ut	Ⓒ
$\texttt{Erase}(ut)$	erases data with UT ut	Ⓒ
$\texttt{Rectify}(ut, val)$	rectifies data with UT ut to new value val	Ⓒ
$\texttt{NotifyErase}(ctr, ut)$	notifies controller ctr about erasure of data with UT ut	Ⓒ
$\texttt{LegalGround}(grd, ut, sp)$	claims legal ground grd for using data with UT ut^*	

Ⓒ = Causable; Ⓢ = Suppressable; unmarked events are only-observable

$^*sp$ is a *special-data* Boolean flag that is true iff the data belongs to a special category

(b) MFOTL formula

Description	**Formula**
Overall formula	$\varPhi = \Box\neg\big(\varphi_{\text{Purp}} \vee \varphi_{\text{Acc}} \vee \varphi_{\text{Rect}} \vee \varphi_{\text{Er}} \vee \varphi_{\text{Restr}} \vee \varphi_{\text{Obj}}\big)$
Purpose-based usage	$\varphi_{\text{Purp}} = \exists prp, ut, ds, sp.\ \texttt{Use}(prp, ut) \wedge \blacklozenge\texttt{Collect}(ds, ut, sp)$ $\wedge\neg\big(\big(\neg\texttt{DSRevoke}(ds, prp, ut)\ \hat{\mathsf{S}}\ \texttt{DSConsent}(ds, prp, ut)\big)$ $\vee(\exists grd.\ \blacklozenge\texttt{LegalGround}(grd, ut, sp)))$
Right to access	$\varphi_{\text{Acc}} = \exists ds, ut, sp.\ \big(\neg\texttt{GrantAccess}(ds, ut)\ \hat{\mathsf{S}}_I\ \texttt{DSAccess}(ds, ut)\big)$ $\wedge\blacklozenge\texttt{Collect}(ds, ut, sp) \wedge \neg\texttt{GrantAccess}(ds, ut)$ $\underline{or}\ \exists ds, ut, sp.\ \texttt{DSAccess}(ds, ut)$ $\wedge\blacklozenge\texttt{Collect}(ds, ut) \wedge \neg\texttt{GrantAccess}(ds, ut)$
Right to rectification	$\varphi_{\text{Rect}} = \exists ds, ut, val, sp.\ \big(\neg\texttt{Rectify}(ds, ut, val)\ \hat{\mathsf{S}}_I\ \texttt{DSRectify}(ds, ut, val)\big)$ $\wedge\blacklozenge\texttt{Collect}(ds, ut, sp) \wedge \neg\texttt{Rectify}(ds, ut, val)$ $\underline{or}\ \exists ds, ut, sp.\ \texttt{Rectify}(ds, ut, val)$ $\wedge\ \blacklozenge\texttt{Collect}(ds, ut, sp) \wedge \neg\texttt{Rectify}(ds, ut, val)$
Right to erasure (1)	$\varphi_{\text{Er1}} = \exists ds, ut, sp.\ \big(\neg\texttt{Erase}(ut)\ \hat{\mathsf{S}}_I\ \texttt{DSErase}(ds, ut)\big)$ $\wedge\blacklozenge\texttt{Collect}(ds, ut, sp) \wedge \neg\texttt{Erase}(ut)$ $\underline{or}\ \exists ds, ut, sp.\ \texttt{DSErase}(ds, ut)$ $\wedge\blacklozenge\texttt{Collect}(ds, ut, sp) \wedge \neg\texttt{Erase}(ut)$
Right to erasure (2)	$\varphi_{\text{Er2}} = \exists ctr, ut.\ \texttt{Erase}(ut)$ $\wedge\ \blacklozenge\texttt{ShareWith}(ctr, ut) \wedge\ \neg\texttt{NotifyErase}(ctr, ut)$
Right to restriction	$\varphi_{\text{Restr}} = \exists prp, ut, ds, sp.\ \texttt{Use}(prp, ut) \wedge \blacklozenge\texttt{Collect}(ds, ut, sp)$ $\wedge\big(\neg\texttt{DSRepeal}(ds, ut)\ \hat{\mathsf{S}}\ \texttt{DSRestrict}(ds, ut)\big)$
Right to object	$\varphi_{\text{Obj}} = \exists prp, ut, ds, sp.\ \texttt{Use}(prp, ut) \wedge \blacklozenge\texttt{Collect}(ds, ut, sp)$ $\wedge\blacklozenge(\texttt{DSObject}(ds, ut) \wedge \blacklozenge(\exists grd.\ \texttt{LegalGround}(grd, ut, sp)))$

I denotes any interval $[i \text{ days}, \infty)$ with $i \leq 30$.

$\varPhi$ is a past-only MFOTL formula of the form $\Box\neg(\varphi_{\text{Purp}} \vee \cdots \vee \varphi_{\text{Obj}})$. The disjunction contains seven subformulae that describe the *violations* of the provisions in Section 3.1.

Provisions restricting data usage. The formulae $\varphi_{\text{Purp}}, \varphi_{\text{Restr}}$, and φ_{Obj} respectively capture violations of purpose-based usage, the right to restrict processing, and the right to object. Purpose-based usage is violated when each of the following hold:

1. The data with UT *ut* is used for purpose *prp*, which is exactly $\mathtt{Use}(prp, ut)$;
2. The data with UT *ut* was collected from data subject *ds* with the special-data flag *sp*, which is $\blacklozenge\,\mathtt{Collect}(ds, ut, sp)$;
3. (a) Neither the data subject *ds* has given consent to process data with UT *ut* for purpose *prp* and has not revoked that consent since then, which is exactly $\neg\mathtt{DSRevoke}(ds, prp, ut)\,\hat{\mathsf{S}}\,\mathtt{DSConsent}(ds, prp, ut)$,
   (b) nor has the application claimed a legal ground *grd* to use data with UT *ut* with the special-data flag *sp*, i.e., $\exists grd.\ \blacklozenge\,\mathtt{LegalGround}(grd, ut, sp)$.

The corresponding formula φ_{Purp} is shown in Table 1b. The formula φ_{Restr} is similar, but does not allow claims of legal grounds. The formula φ_{Obj} formalizes the right to object. This right is violated when all of the following hold:

1. The data with UT *ut* is used for purpose *prp*;
2. The data with UT *ut* was collected from data subject *ds*;
3. At some time in the past:
   (a) the application has claimed legal ground *grd* to use data with UT *ut*,
   (b) and meanwhile, the data subject *ds* has objected to the use of data with UT *ut*.

We formalize 3. as $\blacklozenge\,(\mathtt{DSObject}(ds, ut) \wedge \blacklozenge\,(\exists grd, sp.\ \mathtt{LegalGround}(grd, ut, sp)))$.

Provisions regulating data-subject requests. The formulae φ_{Acc}, φ_{Rect} φ_{Er1}, and φ_{Er2} respectively capture the rights to access, rectification, and (two types of) erasure. Formulae φ_{Acc}, φ_{Rect}, and φ_{Er1} share a similar structure, which requires that the application performs some action in a timely manner when the data subject requests it (a so-called *response pattern* [17]). We describe erasure in detail, with the other cases being analogous.

According to Art. 12(3) GDPR, erasure must be performed "*without undue delay and in any event within one month of receipt of the request.*" To ensure compliance with such a provision, it suffices that an appropriate `Erase` event is always caused within 30 days after each `DSErase` event. In particular, both the 'zealous' approach that causes `Erase` immediately after `DSErase` and the 'lazy' approach that causes it $i \leq 30$ days after `DSErase` are acceptable. These approaches translate into the GMFOTL formulae

$$\varphi_{\mathrm{Er1,zealous}} = \Box\neg\left(\exists ds, ut.\ \neg\mathtt{Erase}(ut) \wedge \mathtt{DSErase}(ds, ut)\right)$$

$$\varphi_{\mathrm{Er1,lazy},i} = \Box\neg\left(\exists ds, ut.\ \neg\mathtt{Erase}(ut)\,\hat{\mathsf{S}}_{[i,\infty)}\,\mathtt{DSErase}(ds, ut)\right) \qquad \forall i \leq 30.$$

The phrase "*without undue delay*" used in Article 12(3) suggests that the 'zealous' variant may be closest to the spirit of the law. However, since this aspect remains open to interpretation, we report both in Table 1b. We obtain similar variants for φ_{Rect} and φ_{Acc}.

According to Art. 17(2), erasure of any data item should be accompanied by notifying all controllers with whom this data item was shared. This is formalized by the formula φ_{Er2} in Table 1b. It is violated when some data with UT *ut* has been shared with a controller at some point in the past ($\blacklozenge\,\mathtt{ShareWith}(pro, ut)$), this data is erased ($\mathtt{Erase}(ut)$), and no notification has been issued ($\neg\mathtt{NotifyErase}(pro, ut)$).

3.4 Enforceability

To use EnfPoly, we must show that formula Φ defines an enforceable property P_{Φ}.

Lemma 1. *The formula* $\Psi = \varphi_{\mathrm{Purp}} \vee \varphi_{\mathrm{Acc}} \vee \varphi_{\mathrm{Rect}} \vee \varphi_{\mathrm{Er}} \vee \varphi_{\mathrm{Restr}} \vee \varphi_{\mathrm{Obj}}$ *is in GMFOTL.*

Proof. Each disjunct is a GMFOTL formula. The subformulae φ_{Purp}, φ_{Restr}, and φ_{Obj} are all of the form $\exists x_1 \ldots x_k.\ \texttt{Uses}(\ldots) \wedge \psi$ with ψ past-only, which is a GMFOTL formula since `Uses` is suppressable. The subformulae φ_{Acc}, φ_{Rect}, φ_{Er1}, and φ_{Er2} are all of the form $\exists x_1 \ldots x_k.\ \neg \texttt{X}(\ldots) \wedge \psi$ or $\exists x_1 \ldots x_k.\ \psi \wedge \neg \texttt{X}(\ldots)$ where ψ is past-only and `X` is a causable event (`GrantAccess`, `Rectify`, `Erase`, or `NotifyErase`), and is therefore also a GMFOTL formula. Hence, formula Ψ is a disjunction of GMFOTL formulae, and itself a GMFOTL formula.

Since $\Phi = \Box \neg \Psi$ a closed past-only formula, we use Theorem 1 to obtain as a corrollary:

Lemma 2. P_{Φ} *is enforceable.*

Since Φ is also monitorable [8], we can use EnfPoly to enforce it. EnfPoly's algorithm guarantees compliance with the negated disjunction by preventing the violation of each of its disjuncts. The violations of φ_{Purp}, φ_{Restr}, and φ_{Obj} will be prevented by suppressing the involved `Use` event (i.e., preventing data usage), while violations of φ_{Acc}, φ_{Rect}, φ_{Er1}, and φ_{Er2} will be prevented by causing `GrantAccess`, `Rectify`, `Erase`, and `NotifyErase`.

4 Enforcement architecture

Figure 3 depicts our enforcement architecture. Data subjects interact with applications through their *web browser*, equipped with a browser extension. The extension helps data subjects view purposes and set their consent preferences, and sends the corresponding consent events to the PDP. It also allows data subjects to declare some inputs as containing special data or personal data of another data subject. Additionally, data subjects can access the platform's privacy dashboard to see how their data has been used.

A controller deploys their applications in the *WebTTC+ execution environment*, which extends WebTTC with support for deletion, rectification, data subject access, and notification of other controllers. As in WebTTC, applications' inputs and outputs are controlled by a PEP, which reports critical operations to the PDP and can suppress or cause actions at the PDP's request. However, unlike in WebTTC, the PDP is no longer located inside of WebTTC+, but deployed on a *privacy platform*.

The privacy platform consists of three main components: a PDP (as in WebTTC) instantiated with the policy formalized by the MFOTL formula Φ (Section 3.3); a trace (as in WebTTC) storing events of the current compliant application execution; and a *privacy dashboard* [9,35,36] used by data subjects to query and review events related to their data, and exercise their privacy-related rights. The dashboard can read past events from the trace and emit new ones (the `DS`-prefixed events in Table 1a) on behalf of data subjects.

We now explain how the actions corresponding to the events introduced in Section 3.2 are instrumented. We first consider purpose-based usage, the right to restriction, and the right to object, which are enforced through the suppression of `Use` (Section 4.1). Next, we discuss erasure and rectification, whose enforcement requires causation (Section 4.2). Finally, we consider the right to access personal data (Section 4.3).

4.1 Instrumenting purpose and consent-based usage, restriction, and objection

Data collection and consent are captured by the events `Collect` and`DSConsent`, which

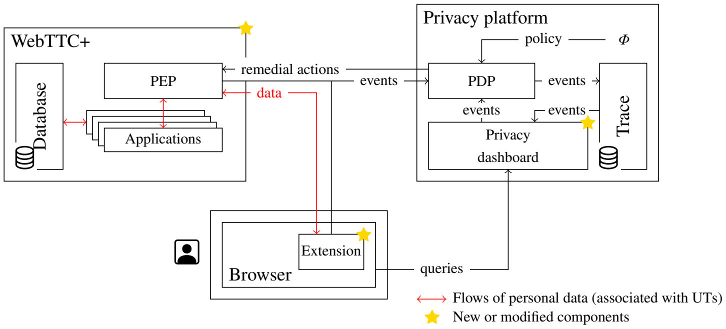


Fig. 3: GDPR enforcement architecture

are only-observable. The browser extension plays a key role in the data and consent collection process. Recall that it allows data subjects to set their privacy preferences (i.e., which of their data can be processed for which purposes), to declare if some data belongs to a special category, and to declare *whose* personal data they input. An example of the latter is when a physician enters patient data into a software system; the physician would use the extension to declare the patient's identity. Formally, the extension keeps three maps M_{purposes}, M_{owners}, and M_{special} each associating pairs (url, arg) of an URL and argument name to, respectively, a set of purposes, a set of data subjects, and a special-data flag. Any value sent as argument arg to the URL url is considered to belong to $M_{\mathsf{owners}}[(url, arg)]$ data subjects, to contain special data if $M_{\mathsf{special}}[(url, arg)]$, and it can be used for $M_{\mathsf{purposes}}[(url, arg)]$ purposes.

Data collection consists of three steps. First, a data subject attempts to make a request to an application's URL; the extension retrieves the data subject's preferences and immediately logs the relevant consent events to the PDP. Then, the extension modifies the request to add fresh UTs for each input. Finally, the application receives the request and logs `Collect` events for each input. More formally:

1. The data subject ds queries the URL url deployed on a WebTTC+ server with arguments a_i and values v_i, for $1 \leq i \leq k$. The extension intercepts the request and associates fresh UTs $(ut_i)_{1 \leq i \leq k}$ to the new inputs. It then sends $\texttt{DSConsent}(ds, prp, ut_i)$ to the PDP for all $1 \leq i \leq k$ and $prp \in M_{\mathsf{purposes}}[(url, a_i)]$.
2. The extension sends to the application the original request together with the UTs ut_i, the owners $M_{\mathsf{owners}}[(url, a_i)]$, and the special-data flags $M_{\mathsf{special}}[(url, a_i)]$.
3. Finally, after it receives the new inputs and their UTs, WebTTC+ logs an event $\texttt{Collect}(ds', app, ut_i, sp_i)$ for each $1 \leq i \leq k$, $ds' \in M_{\mathsf{owners}}[(url, a_i)]$, and $sp_i = M_{\mathsf{special}}[(url, a_i)]$, and waits for the PDP to acknowledge the logging of all events. Only then can the collected data be processed.

Data usage is captured by the predicate `Use`. Purpose-based usage, the right to restriction, and the right to object are all enforced through the suppression of `Use` events.

WebTTC+ emits $\texttt{Use}(prp, ut)$ whenever WebTTC would emit both $\texttt{Out}(ds, prp, o)$ and $\texttt{Itf}(ut, o)$. Thus, $\texttt{Use}(prp, ut)$ holds whenever the application performs an output for the purpose prp whose value is influenced by input ut. Any `Use` event can be suppressed by suppressing the corresponding output. Being based on non-interference, our definition captures not only the usage of the original data-subjects inputs, but also the usage of any data *derived from data-subject inputs*. Extending the notion of personal data to data derived from user inputs is in line with the GDPR. Namely, the GDPR defines personal data as "*any information relating to an identified or identifiable natural person*" [Art. 4(1)], a definition that generally encompasses both raw and derived data.

At first glance, controlling data usage only at outputs may appear to depart from the GDPR's definition of processing as "*any operation or set of operations which is performed on personal data or on sets of personal data*" [Art. 4(2)]. However, we claim that this approach does not restrict the violations that we can prevent. First, the notion of *purpose* is best understood as an attribute of *business processes* [7] that rely on interactions between computer systems and human agents. Such interactions necessarily involve outputs. Moreover, according to the GDPR, data must be "*limited to what is necessary in relation to the purposes for which they are processed*" ('data minimization', Art. 5(1)(c)). The principle of data minimization is inherently unmonitorable [2], and is therefore not amenable to runtime enforcement. Now, data which has no influence on outputs can hardly be considered 'necessary' in relation to the purposes of the business process, since interaction with humans is what business processes are designed for. Hence, any violation of purpose-based usage that cannot be captured by observing outputs is also a violation of data minimization, and can therefore not be prevented using runtime enforcement.

Legal grounds can be claimed by WebTTC+ applications by using a special instruction $\texttt{claim\_legal\_ground}(grd, sp, x)$. This claims a legal ground grd to use the data contained in some term x with special-data flag sp. When this instruction is executed by an application app, WebTTC+ logs a $\texttt{LegalGround}(grd, ut, sp)$ event for each UT ut associated with the value that term x is evaluates to. Note that it is not the system's responsability to ensure that these legal claims are *valid* as such a check cannot be automated. The system only logs the events, which can be objected to later on.

Data-subject requests can be sent by data subjects for each of their inputs collected by the applications by interacting with the privacy dashboard. Recall that these requests are captured by `DSRevoke`, `DSRestrict`, `DSRepeal`, and `DSObject` events that are sent to the PDP by the privacy dashboard. Note that in addition to using the extension, users can also provide consent manually (i.e., emit `DSConsent` events) through the dashboard.

4.2 Erasure and rectification

Erasure and rectification can be requested by users through the privacy dashboard, which emits `DSErase` and `DSRectify` events on their behalf.

WebTTC+ extends WebTTC's with two functions $\texttt{erase}(ut)$ and $\texttt{rectify}(ut, v)$ that can be caused by the PDP to handle the erasure (resp. the rectification) of data stored in the database. Additionally, WebTTC+ allows applications to declare *handler functions* that can be used to restore a consistent application state when data is erased. Assuming a relational database, the algorithm implemented by $\texttt{erasure}(ut)$ proceeds as follows:

1. Identify all tables, rows, and fields tagged with ut;
2. Perform erasure by deleting the identified table content or rows or setting the identified fields to a default value;

3. For each erased table, row, or field, call the handling function, if it exists;
4. Emit $\texttt{Erase}(ut)$.

The case of rectification is slightly more complex. Namely, rectification should behave differently for raw data and derived data. For raw data, the old input value can be immediately replaced with the new input value. Derived data can only be set to a default, after which the application can provide a way for it to be re-computed using the new input value. The algorithm for $\texttt{rectify}(ut, v)$ is as follows:

1. Identify all tables, rows, and fields tagged with *ut*;
2. Erase the content of any identified tables or rows;
3. For any identified field, if it contains raw data, replace its value by v,
   otherwise, set it to a default value;
4. For each identified table, row, or field, call the handling function, if it exists;
5. Emit $\texttt{Rectify}(ut, v)$.

Integrity tags To distinguish raw data from derived data, we extend TTC's memory model with *integrity tags*. Instead of pairs $\langle v,\alpha\rangle$ of a value v and a set of UTs α, our memory model now relies on triples $\langle v,\alpha,\beta\rangle$, where β is either the constant $\mathsf{Derived}$ or an object $\mathsf{Raw}(ut)$, where *ut* is a UT. Whenever a data item in memory is equal to $\langle v,\alpha,\mathsf{Raw}(ut)\rangle$, its value v must be equal to the original value of the input with UT *ut*. When it is equal to $\langle v,\alpha,\mathsf{Derived}\rangle$, its value may not be equal to the value of any input.

After erasure, the formula φ_{Er2} triggers notification of all controllers with whom the erased data has been previously shared. WebTTC+ triggers a $\texttt{ShareWith}(pro, ut)$ event on each output influenced by *ut* whose recipient is a third-party controller, rather than a data subject. The causable event $\texttt{NotifyErase}$ is instrumented by exposing a function $\texttt{notify}(ut, ctr)$ that can be triggered by the PDP. This function notifies the third-party controller *ctr* about the erasure of *ut*.

4.3 Access to data

Data subjects request access to data through the privacy dashboard, which emits $\texttt{DSAccess}$ events. On receiving a $\texttt{DSAccess}$ event, the PDP instructs the PEP to cause a corresponding $\texttt{GrantAccess}$ event. The PEP then calls a function $\texttt{access}(ds, ut)$ exposed by WebTTC+, which has the following behavior:

1. Identify all tables, rows, and fields tagged with *ut*;
2. Copy the content of all identified tables, rows, and fields into a specific $\texttt{access}$ table.
3. Provide the data subject with a link to an interface that supports browsing, and downloading, a machine-readable dump of the data (for data portability).
4. Emit $\texttt{GrantAccess}(ds, ut)$.
5. In the interface, use the standard WebTTC+ mechanism to show *ds only the data that can be shown without violating other data subjects' consent*.

The last step resolves the tension that arises between the right to access and other rights when data aggregates different users' inputs. When a data item d has been produced by combining inputs from two users A and B, granting A access to d might violate purpose-based usage from B's point of view, hamper B's capacity to erase or rectify d, and interfere with B's right to restrict the processing of d (see [29] for a discussion of the GDPR's ambiguity in matters of shared data ownership). We take a conservative

Application	WebTTC+			Python/Flask	
	Functionality	Privacy	Template	Functionality	Template
Minitwit^{+}	140	16	100	121	119
Conf	312	47	502	284	508
HIPAA	142	25	852	136	846

Table 2: Lines of code of the WebTTC+ and the baseline implementations

approach that prioritizes consent-based usage over access, subjecting the extracted data to the same enforcement procedures as any data stored by applications.

5 Evaluation

We now evaluate a prototype implementation of our enforcement architecture with regard to its development and runtime overhead and its coverage of GDPR provisions. Our prototype includes the WebTTC+ environment, the privacy platform, and a Firefox extension. Overall it has 5.5k lines of code (LoC) in Python with 2.7k LoC reused from the WebTTC environment from previous work [25]. The WebTTC+ environment and the privacy dashboard use the Flask web framework and SQLite databases. The PDP is based on EnfPoly [24], with additional Python code ensuring synchronization with a QuestDB time-series database storing the log. Appendix B shows screen captures of the privacy dashboard, the browser extension, and one of the deployed case study applications. Our evaluation aims to answer the following research questions:

RQ1: Can realistic web applications be developed in WebTTC+? If yes, how do the additional privacy requirements impact the size of their code base?

RQ2: How much runtime overhead does WebTTC+ incur compared to a baseline application without support for automated privacy enforcement?

RQ3: What share of the GDPR's provisions does our implementation effectively enforce? What aspects are not covered?

To answer the above questions, we port the following applications to our architecture:

- **Minitwit**$^{+}$, a clone of the microblogging **Minitwit** application [46];
- **Conf**, a conference management system [49]; and
- **HIPAA**, a health record management system [49].

These applications have been previously used to evaluate the performance of various IFC frameworks [25, 30, 34, 46, 49]. Here, we use the variants of these applications presented in Hublet et al. [25], where every output is labeled with a GDPR-style purpose from {`Service`,`Analytics`,`Marketing`}, and we compare our WebTTC+ implementation to a baseline implementation in Python using only Flask with the same database backend.

RQ1: Development effort. We have implemented all three applications in our framework, preserving their original functionality. Most of the code from the baseline implementation has been reused with only minor changes. This makes porting Flask applications to WebTTC+ straightforward. Privacy-specific code (e.g., the handling functions) accounts for less than 10% of all application code in the WebTTC+ implementations. We show examples of this privacy-specific code in **Minitwit**$^{+}$ in Appendix A. Table 2 shows the number of LoC for each case study application.

RQ2: Performance overhead. We compare the runtime performance of WebTTC+ implementations with a Python/Flask implementation. Since the Python/Flask baseline does not enforce privacy, this yields an upper bound on the overhead of GDPR enforcement for web apps. We measure the latency of executing the following representative workloads:

- In **Minitwit**$^{+}$, we show 30 messages in its TIMELINE and post a NEW MESSAGE;
- In **Conf**, we show ALL PAPERS and ONE PAPER, and SUBMIT a paper;
- In **HIPAA**, we show ONE PATIENT and ALL PATIENTS.

The ALL PAPERS and ALL PATIENTS workloads constitute stress tests [49] used to measure the runtime behavior of applications in the presence of large outputs. In real production scenarios, showing all entities stored in a system is generally avoided and pagination is used to improve runtime performance.

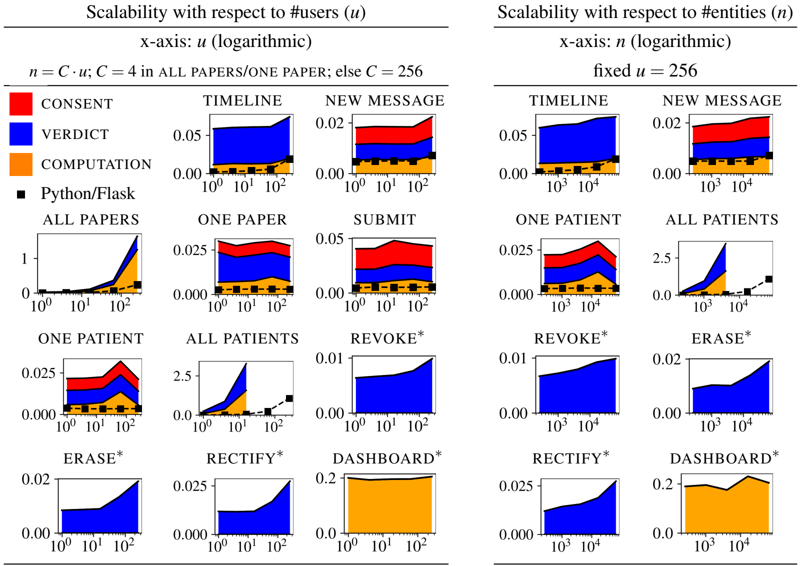
For each workload, we measure the time spent on (1) registering CONSENT at the PDP, (2) waiting for the PDP's VERDICTs, and (3) COMPUTATION within WebTTC+. Additionally, for each application, we measure the latency of revoking consent (REVOKE), erasing an input (ERASE) or rectifying it (RECTIFY), and opening the privacy DASHBOARD. We perform the measurements on a high-end laptop (Intel Core i5-1135G7, 32 GB RAM) over $N = 100$ repetitions, while varying the number u of users and the number n of entities (messages for **Minitwit**$^{+}$, papers for **Conf**, and patients for **HIPAA**) in the database. The results are shown in Figure 4.

For all workloads displaying a constant number of entities (i.e., TIMELINE, NEW MESSAGE, ONE PAPER, SUBMIT, ONE PATIENT, REVOKE, ERASE, and RECTIFY), our architecture incurs an overhead of at most one order of magnitude with respect to the Flask/Python baseline. The part of the execution occurring within the WebTTC+ environment (i.e., the COMPUTATION part) adds at most 10 ms of extra latency with respect to the baseline. The PDP is the main performance bottleneck: WebTTC+ spends 70%–90% of its running time waiting for PDP verdicts. The PDP's latency grows logarithmically. The total latency however remains below 75 ms, allowing for the seemless usage of the applications. For the stress-test workloads displaying a number of entities linear in n (ALL PAPERS and ALL PATIENTS), runtime performance remains within one order of magnitude of the Flask/Python, with logarithmic growth. Comparable runtime performance was measured in previous studies that used the same applications [25,49].

RQ3: GDPR coverage. Beyond articles 5(1)(b,d), 6(1), 7(1,3), 9(1,2), 13(1), 15(1), 20(1), 16, 17(1,2), 18(1), and 21(1), our implementation provides at least a technical starting point for enforcing the following provisions:

- **Lawfulness** [Art. 5(1)(a)];
- **Transparency** [Art 12(1,3)]. Any information requested by data subjects shall be provided in transparent form, without undue delay and within at most one month;
- **Right to information** [Art. 13(1), 15(1)]. Data subjects have a right to be informed when their personal data is collected and processed;
- **Privacy by design** [Art. 25(1)]. Appropriate technical measures shall be implemented to provide privacy by design;
- **Record of processing activities** [Art. 30(1)]. Data controllers shall keep a record of all processing activities conducted under their responsability.

Together, articles 5(1)(a,b,d), 6-7, 9, 12-13, 15-18, 21, 25, and 30 appear in 66% of the violations reported on `www.enforcementtracker.com` as of May 2023. While this



*Figures computed with the system loaded with **Minitwit**$^+$ data

Fig. 4: Latency of workloads (y-axis: seconds per request, avg. over $N = 100$ requests)

figure only provides a rough estimate of the (maximal) coverage that can be expected from our approach, it also clearly underlines the potential of runtime enforcement techniques. The following provisions not covered by our approach are cited in at least 5% of the cases each: Art. 32 (security of processing, 22%); Art. 5(1)(c) (data minimization, 10%), and Art. 5(1)(f) (storage limitation, 9%). Security is a concern orthogonal to ours, whereas data minimization and storage limitation are generally unmonitorable [2].

6 Related work

GDPR formalization. Our formalization of a core of GDPR is closest to Arfelt et al.'s work on monitoring the GDPR [2]. It extends their formalization by introducing UTs as input identifiers and covering special data categories and the right to erasure. Additionally, it fixes two inaccuracies. First, Arfelt et al.'s specification lacked $\blacklozenge\, \texttt{Collect}(ds, ut, sp)$ conjuncts, allowing consent given by *any user* to justify data usage. Second, the third condition of the right to object ("there has been an objection since legal grounds have been claimed") was specified as $\exists \ldots \neg(\neg\texttt{DSObject}(\ldots)\,\mathsf{S}\,\texttt{LegalGround}(\ldots))$, allowing an application to reclaim the same legal grounds to override any objection.

Robaldo et al. have formalized a large part of the GDPR using reified Input/Output logic [37, 38], and have validated their formalization with legal experts [6]. Their work focuses on accurately encoding the law, but it does support enforcement. Smaller fragments of the GDPR have been represented in other formalisms providing some support for automated reasoning, such as deontic logic [1, 31], LegalRuleML [33], OCL [44], OWL2 [11], and Prolog [16]. In a different line of research, several policy languages were designed explicitly with GDPR provisions in mind [3, 20, 41, 47, 48].

						Right to...						
		Consent	Purpose	Legal grounds	Special data	access	rectification	erasure	restriction	object	Derived data	Implementation
Language-based	This work	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Ferrara & Spoto [18]	✓	✓								✓	
	Ferreira et al. [19]	✓	✓								✓	✓
	Hublet et al. [25]	✓	✓								✓	✓
	Karami et al. [28]	✓	✓					✓				
	Tokas et al. [43]	✓	✓			✓					✓	
	Wang et al. [47,48]	✓	✓								✓	✓

						Right to...						
		Consent	Purpose	Legal grounds	Special data	access	rectification	erasure	restriction	object	Derived data	Implementation
Data-store-based	Barati et al. [4]	*	✓									✓
	Chhetri et al. [12]	*	✓									
	Dauden et al. [14]	*	✓			*	*	*	*	*		✓
	Davari & Bertino [15]	*	✓									
	Gjermundrød et al. [21]	*	✓				*					✓
	Schwarzkopf et al. [40]	✓	✓			✓		✓		✓	✓	
	Truong et al. [45]	*				*	*	*	*			✓

* Provision is covered, but data leaving the data store is not protected.

Fig. 5: GDPR compliance by design: coverage of the provisions in Section 3.1

GDPR compliance by design. Many approaches enforce a specific GDPR provision in software systems. To the best of our knowledge, none of these works relies on an explicit logical formalization of the GDPR. Figure 5 shows existing approaches based on their GDPR coverage: *consent*-based usage, *purpose*-based usage, *legal grounds*, *special data* categories; coverage of the *rights to access*, *rectification*, *erasure*, *restriction*, and *objection*; protection of *derived data*; and availability of an *implementation*.

Existing work can be classified into two categories: language-based approaches [42], which include TTC [25], and data-store-based approaches [27]. In language-based approaches, a programming language is instrumented to ensure privacy compliance either statically [18,19,43,46,47] or at runtime [19,25,28]. Language-based approaches typically can protect derived data. However, they have not been widely applied so far beyond consent-based usage. In data-store-based approaches, personal data is stored in protected database containers (*data stores*) that can be queried by controllers through an API. Access-control mechanisms ensure data is only accessed with user consent. Within data stores, most GDPR rights can be exercised seemlessly [14,45]. Data processing, however, happens mainly outside of the data stores; as a result, data that leaves the database – and in particular, derived data – is no longer protected. The only work discussing the protection of derived data with such an approach [40] provides just a high-level roadmap without a concrete implementation.

7 Conclusion

We have presented the first enforceable specification of core GDPR provisions that comes together with an enforcement architecture for web applications. To the best of our knowledge, this work is the first to enforce a core set of GDPR provisions and protect derived data by tracking information flows.

We envision three main directions for future work. First, our coverage of legal provisions can be extended beyond the current fragment by relying on a more comprehensive but still enforceable formalization of the GDPR, which we plan to develop. Second, we will further investigate the performance of our enforcement mechanism under very large data volumes and number of users and study optimizations that may ease its deployment in real-world settings. Finally, we plan to extend our architecture by incorporating complementary techniques that allow for the coverage of those aspects of the GDPR (e.g., data and storage minimization) not readily amenable to monitoring techniques.

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A Privacy code in Minitwit

In **Minitwit**$^{+}$, the additional code can be summarized as follows:

- In the functions displaying user messages, we use a function filter_check to select only those messages for which the data subjects have given consent for purpose `Service`. The function filter_check is defined as follows:

  ```
  def filter_check(messages):
      messages2 = []
      checks = check_all('Service', messages)
      for i in range(0, len(messages)):
          if checks[i]:
              messages2.append(messages[i])
      return messages2
  ```

  The function **check_all** is provided by WebTTC+. It takes a purpose p and a list of pairs of values and sets of UTs $[\langle v_1, \alpha_1 \rangle, \ldots, \langle v_k, \alpha_k \rangle]$, and returns a list of Booleans $[b_1, \ldots, b_k]$ such that each b_i is true iff v_i can be used with purpose p. To obtain the b_i, WebTTC+ communicates with the PDP [25].
- We define handlers to support the deletion and rectification of messages and friendship relationships. Deleting the text of the message or the ID of the friend should trigger the deletion of the entire message or relation, e.g.,

  ```
  @handle_field_deletion('message', 'text')
  def handle_message_text_deletion(i):
      sql("DELETE␣FROM␣message␣WHERE␣id␣=␣?0", [i])
      return None
  ```

  In the case of rectification, we remove the previous message and create a new message that we mark as `[edited]`. The code is as follows:

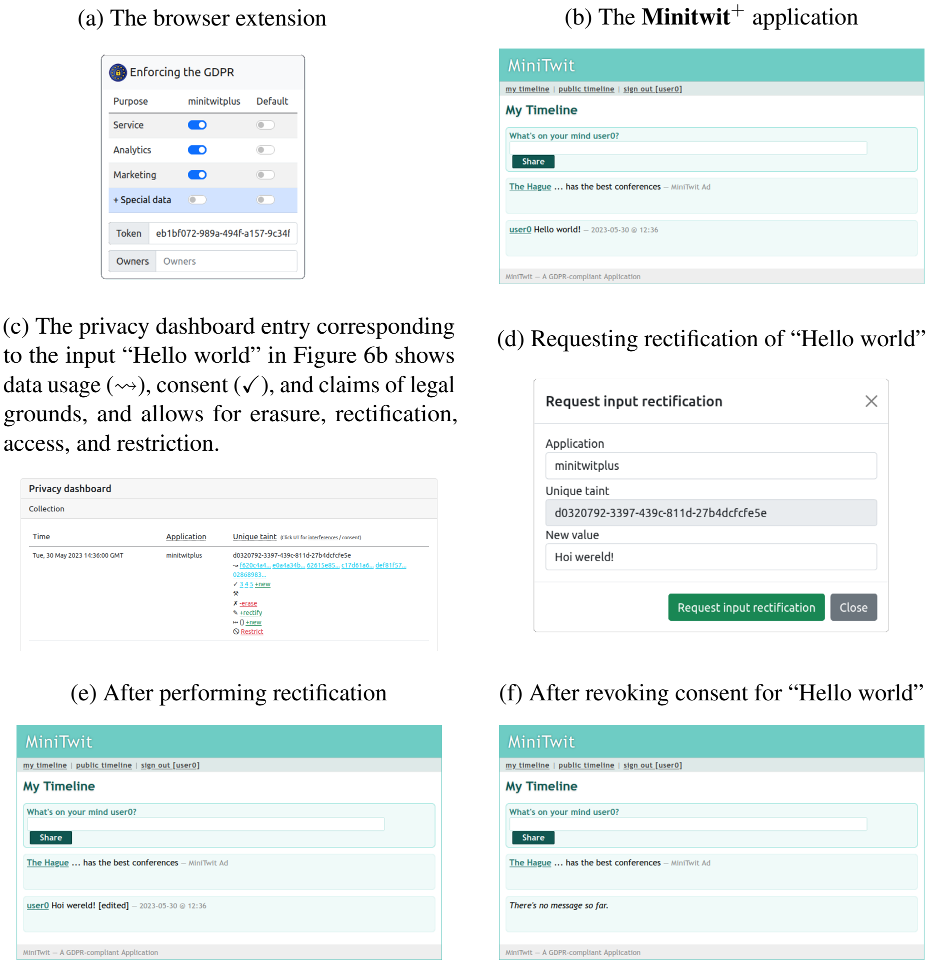
  ```
  @handle_field_rectification('message', 'text')
  def handle_message_text_rectification(i, new_text):
      row = sql("""SELECT author_id, text, pub_date
                   FROM message WHERE id = ?0""", [i])[0]
      sql("""INSERT INTO message (author_id, text, pub_date)
  ```

```
            VALUES (?0, ?1, ?2)""",
        [row[0], new_text + "␣[edited]", row[2]])
    sql("DELETE␣FROM␣message␣WHERE␣id␣=␣?0", [i])
    return None
```

The functions **handle_field_deletion** and **handle_field_rectification** are provided by WebTTC+, and allow programmers to define handler functions for the deletion of specific fields.

B User interface

Fig. 6: Screen captures of the prototype's user interface



(a) The browser extension

Enforcing the GDPR

Purpose	minitwitplus	Default
Service	●	○
Analytics	●	○
Marketing	●	○
+ Special data	○	○

Token eb1bf072-989a-494f-a157-9c34f

Owners Owners

(b) The **Minitwit**$^{+}$ application

MiniTwit

my timeline | public timeline | sign out [user0]

My Timeline

What's on your mind user0?

Share

The Hague … has the best conferences — MiniTwit Ad

user0 Hello world! — 2023-05-30 @ 12:36

MiniTwit — A GDPR-compliant Application

(c) The privacy dashboard entry corresponding to the input "Hello world" in Figure 6b shows data usage (⇝), consent (✓), and claims of legal grounds, and allows for erasure, rectification, access, and restriction.

Privacy dashboard

Collection

Time	Application	Unique taint (Click UT for interferences / consent)
Tue, 30 May 2023 14:36:00 GMT	minitwitplus	d0320792-3397-439c-811d-27b4dcfcfe5e ⇝ f620c4a4… e0a4a34b… 62615e85… c17d61a6… def81f57… 02868983… ✓ 3 4 5 +new ⚒ ✗ -erase ✎ +rectify ↦ () +new ⃠ Restrict

(d) Requesting rectification of "Hello world"

Request input rectification

Application: minitwitplus

Unique taint: d0320792-3397-439c-811d-27b4dcfcfe5e

New value: Hoi wereld!

(e) After performing rectification

MiniTwit

my timeline | public timeline | sign out [user0]

My Timeline

What's on your mind user0?

Share

The Hague … has the best conferences — MiniTwit Ad

user0 Hoi wereld! [edited] — 2023-05-30 @ 12:36

MiniTwit — A GDPR-compliant Application

(f) After revoking consent for "Hello world"

MiniTwit

my timeline | public timeline | sign out [user0]

My Timeline

What's on your mind user0?

Share

The Hague … has the best conferences — MiniTwit Ad

There's no message so far.

MiniTwit — A GDPR-compliant Application