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# Tutorial: Trusted Execution Environments and Intel SGX - a few basic notions and usages

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*Inria*



RESSI

*Neuvy-sur-Barangeon, 10 mai 2023*

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Saclay/UVSQ)

# Trusted Execution Environments and Intel SGX

*a few basic notions and usages*



# Overview

## PART I – Introduction to Trusted Execution Environments (TEE)

Historical view of TEEs

Promises and architecture of TEEs

Intel Software Guard eXtensions (SGX)

Efficient data processing with SGX

Limitations of TEEs and attacks on TEEs (SGX)

## PART II – Tutorial introducing SGX

Federated Learning scheme using SGX

## PART III – Use-case

Secure and Extensive Personal Data Management Systems with SGX

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# From Secure Elements to Trusted Execution Environments (TEEs)

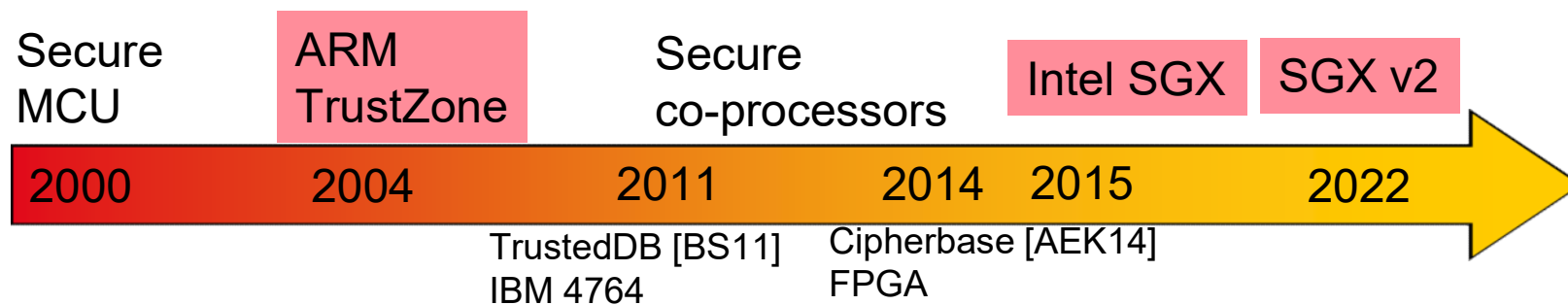
From secure elements, TPM, HSM, etc. [ANS14]

Smart cards or TPM (in smartphones, PCs, home boxes)

... to: Trusted Execution Environments (TEEs) [ABP+19]

Specialized HW: ARM TrustZone, Intel SGX, AMD platform security, etc.

Everywhere : Smartphones & PCs



## Promise: HW level isolation and attestation

Isolation:

- Code executed within a TEE safe from external observation/tampering (OS, user)

Attestation:

- Ability to give a certificate that result produced by a specific piece of code running within TEE

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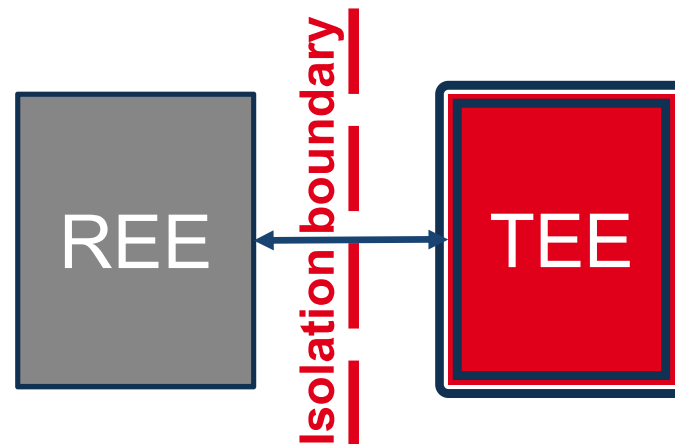
Federated Learning scheme using SGX

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# Secure data management in TEEs

Common general architecture (for existing basic TEEs, secure co-CPU/FPGAs, recent TEEs-Intel SGX): trusted vs. untrusted memory space



## What to look for in details?

**HW architecture:** inherent limitations of the HW (e.g., SCPU clock, size of the secure RAM, bandwidth between secure/unsecure worlds...)

**SW architecture:** which modules run inside the secure HW => Objective: minimize the Trusted Computing Base (TCB) vs. efficiency (REE/TEE context switching)

**Security guarantees:** access pattern leak vs. oblivious query processing

## Adversary: untrusted, curious and controls the system

**Assumption:** TEE isolation cannot be bypassed by an attacker controlling the system

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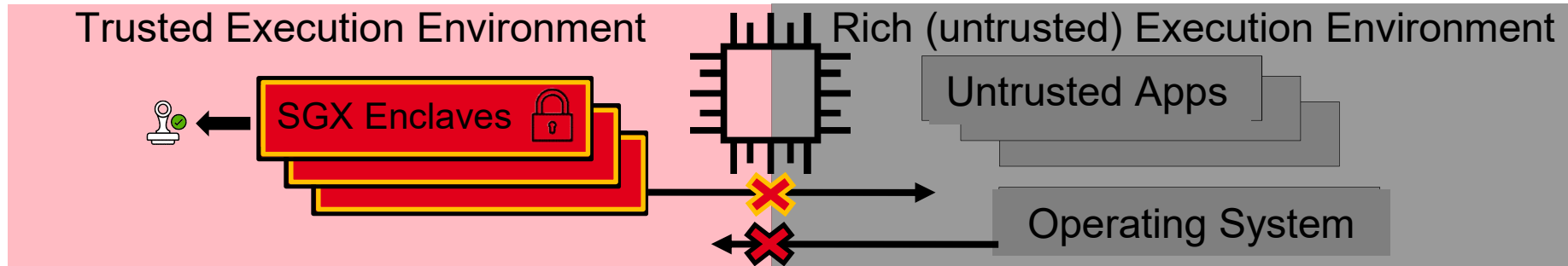
Federated Learning scheme using SGX





## PART III – Use-case

Secure and Extensive Personal Data Management Systems with SGX



# Intel Software Guard eXtensions (SGX)



- **Enclaving** 
  - **Attestation** 
  - **Confidentiality** 
- } Insured by SGX
- + Recent works with **Sandboxing** 

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## Efficient data processing with TEEs

**Modern HW, e.g. Intel SGX, democratize the access to trusted execution technologies**

**Main CPU chip offers TEE capabilities through enclaves (special CPU mode enabled via new instructions) => ubiquitous access to TEE and strong (HW) integration between REE/TEE**

**Yet, performance considerations remain critical for minimizing the enclave related overheads**

**Main overhead sources with SGX enclaves [WAK18] [PVC18]**

**Memory encryption and integrity checking: unavoidable but low overhead**

**Enclave transitions (ECALL/OCALL): high overhead**

**Enclave paging (related to a limited enclave size): high overhead**

**It requires carefully redesigning (data-oriented) apps**

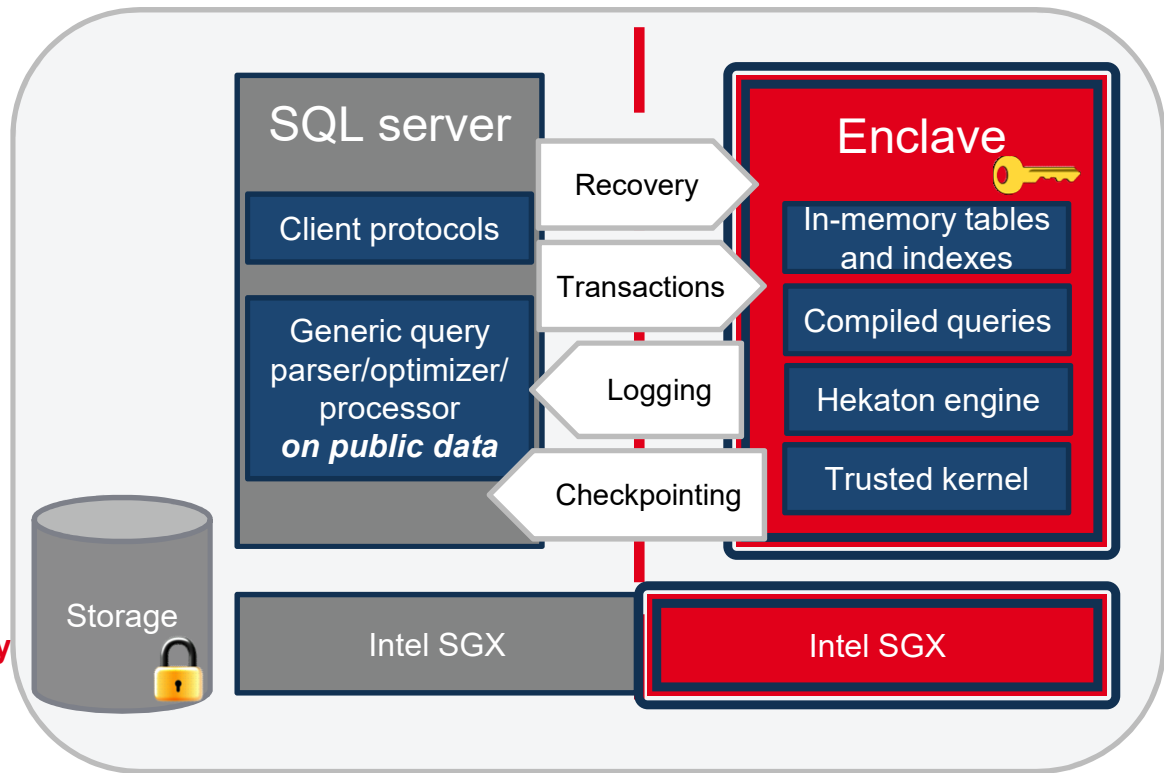
# Efficient data processing with TEEs – EnclaveDB [PVC18]

High performance DB engine...  
with security using Intel SGX

Important assumption: all sensitive data loaded in enclave memory

- No need for expensive SW encryption/integrity checks
- In-memory enclave data minimizes the leakage of sensitive information
- Also minimizes the number of costly IN/OUT enclave transitions
- Smaller TCB (Hekaton engine) using precompiled procedures

- Focus on secure and efficient DB logging and recovery
  - Efficient protocol for checking integrity and freshness of the DB log
  - Low overhead (~40%) compared with classical industry in-memory DBs



## Efficient data processing with TEEs – Indexing/KVS

### HardIDX [FBB+18]: secure and efficient B-tree indexing using SGX

Leverage SGX enclaves to secure outsourced data searches while maintaining high query performance

Several order of magnitude lower query processing time than with traditional compared with the best known searchable encryption schemes...

... with similar level of confidentiality protection

### eLSM [TCL+19]: authenticated KVS with TEE enclaves

Focuses on optimizing update-oriented workloads...

... and ensuring query authenticity: integrity, completeness and freshness

Modifies the classical LSM-tree to cope with SGX enclave constraints

Both HardIDX and eLSM leak the access patterns

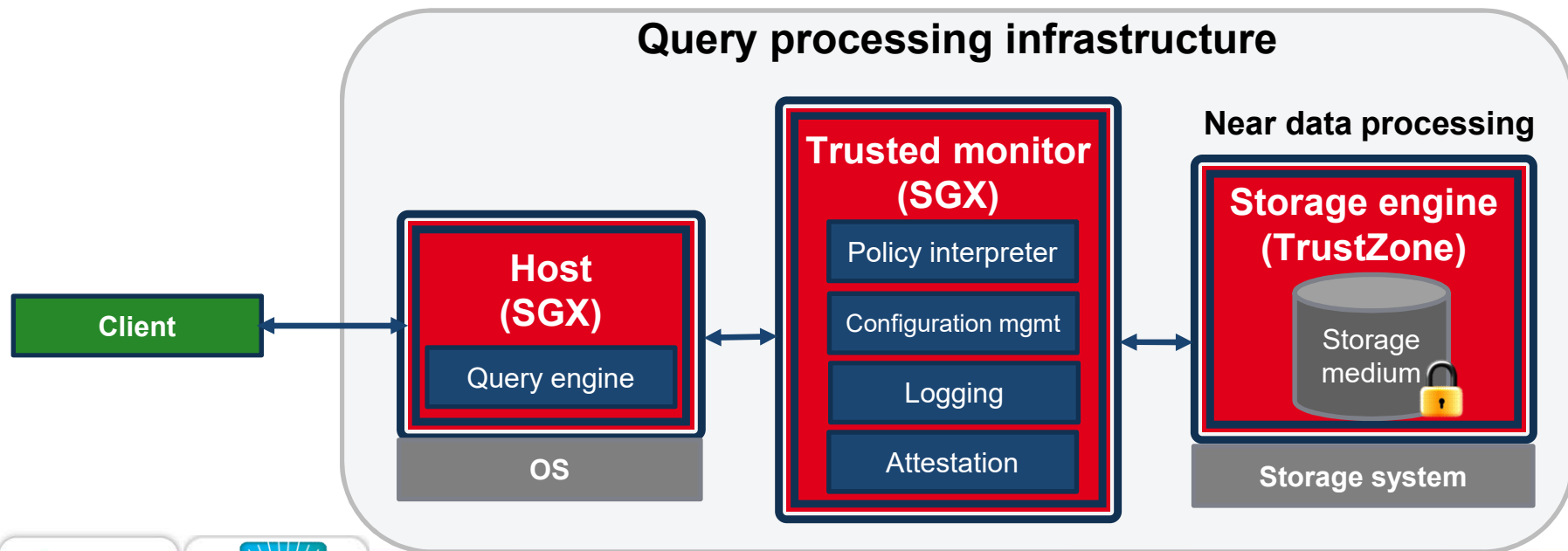
# IronSafe [UCB+22]

## IronSafe computing storage architecture (CSA)

Efficient data-oriented query processing leveraging near data processing  
TEE-based policy enforcement and compliance

## Heterogeneous TEEs for host (Intel SGX) and storage (ARM TrustZone)

Combine execution across TEEs  
Offload computations closer to data (TrustZone-based storage) for performance gains  
Trusted monitor (SGX enclave) to ensure the integrity/authenticity of all components through attestation



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## Security limitations of TEEs

**TEEs do not protect accesses outside the secure enclave**

**Loading everything inside the enclave is not always an option**

**Known side channel attacks with Intel SGX: OS can observe the enclave data accesses at the granularity of pages**

**Access patterns in the workflow can reveal information (e.g., order, frequency distribution) for disk/memory resident data**

Example:

1. Query Alice's age
2. Query average age of people who voted for X
3. If record retrieved in 1 is also retrieved in 2, Alice voted for X



## Oblivious query processing

**Objective: make sure memory access patterns are data independent (except for query input/output size) [AK13]**

Ensures that the only leakage from a query is the size of input/output, even if the adversary observes memory

*i.e., semantic security for queries*

Relevant here: adversary is assumed to control all memory external to secure hardware

ORAM (Opaque [ZDB+17]), OblIDB [EZ17], Oblix [MPC18], Path ORAM[HH21]...

# What if enclaved code cannot be trusted?

Problem: TEEs do not ensure that malicious code cannot voluntarily leak data

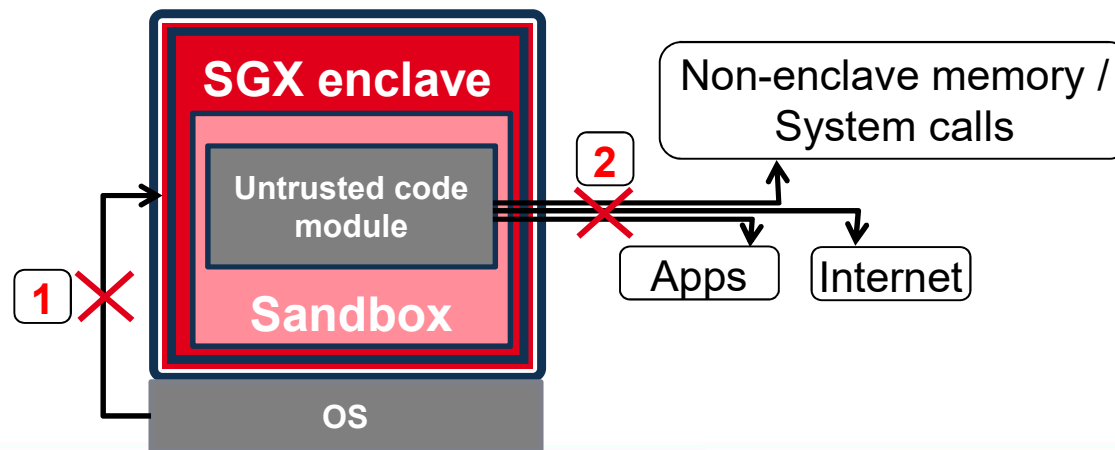
## Confining untrusted code through double isolation

1. Execute code inside of an enclave □ untrusted platform cannot access private enclave-memory data
2. Restrict accessible memory of the untrusted module execution with a sandbox □ module cannot copy secrets to non-enclave memory

## Ryoan [HZX18] sandboxing

Based on Google's Native Client: can only address module memory, intercepts syscalls...

Similar alternative sandboxing solutions: SGXJail [WSG19], SGX-LKL [PML+19], DBT [CSS+22]

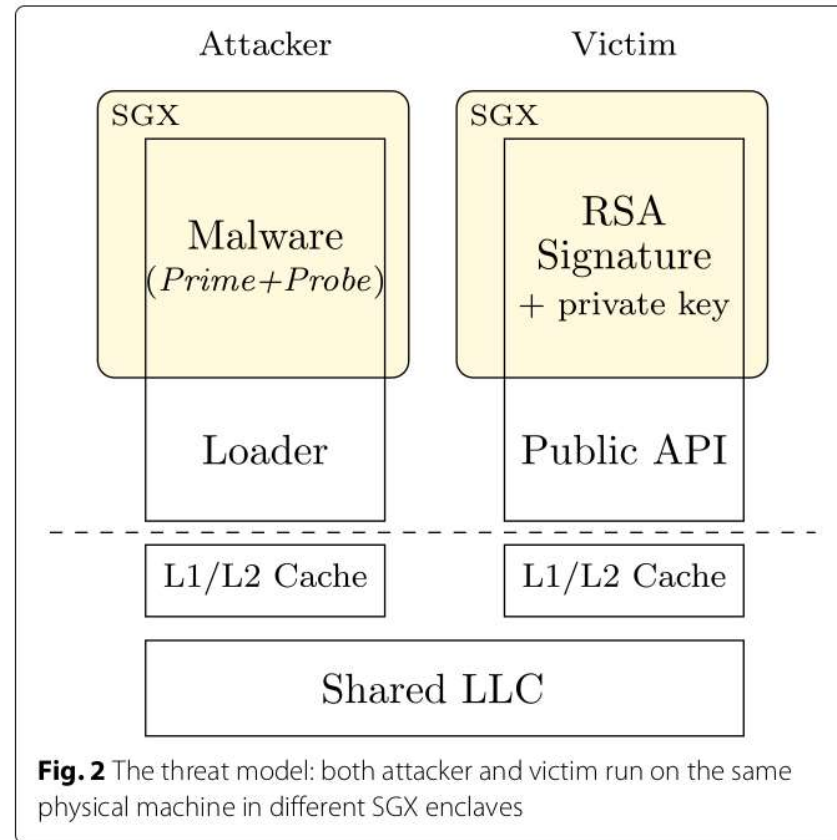
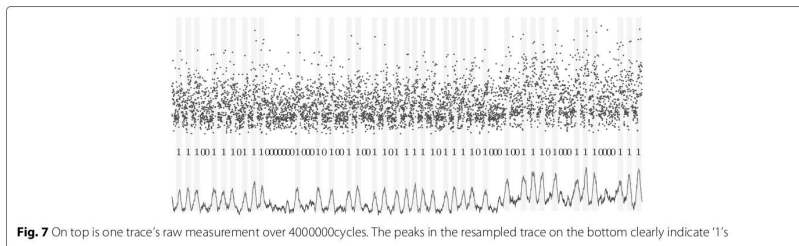
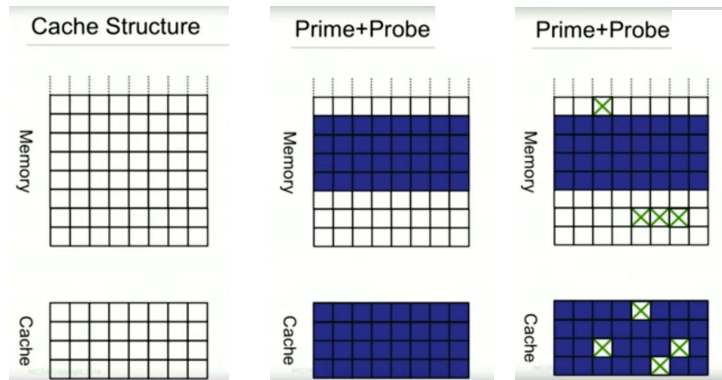


# Side-channel attacks on SGX

## Malware Guard Extension: abusing Intel SGX to conceal cache attacks

M Schwarz, S Weiser, D Gruss, C Maurice, S Mangard

Cybersecurity 3 (1), 2



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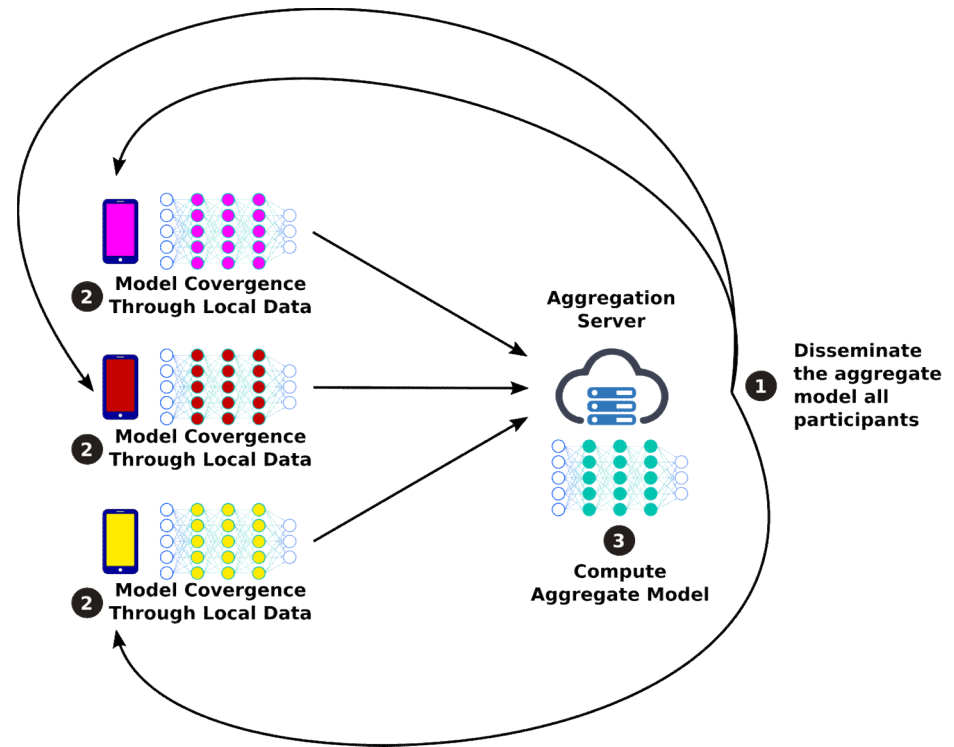
Federated Learning scheme using SGX

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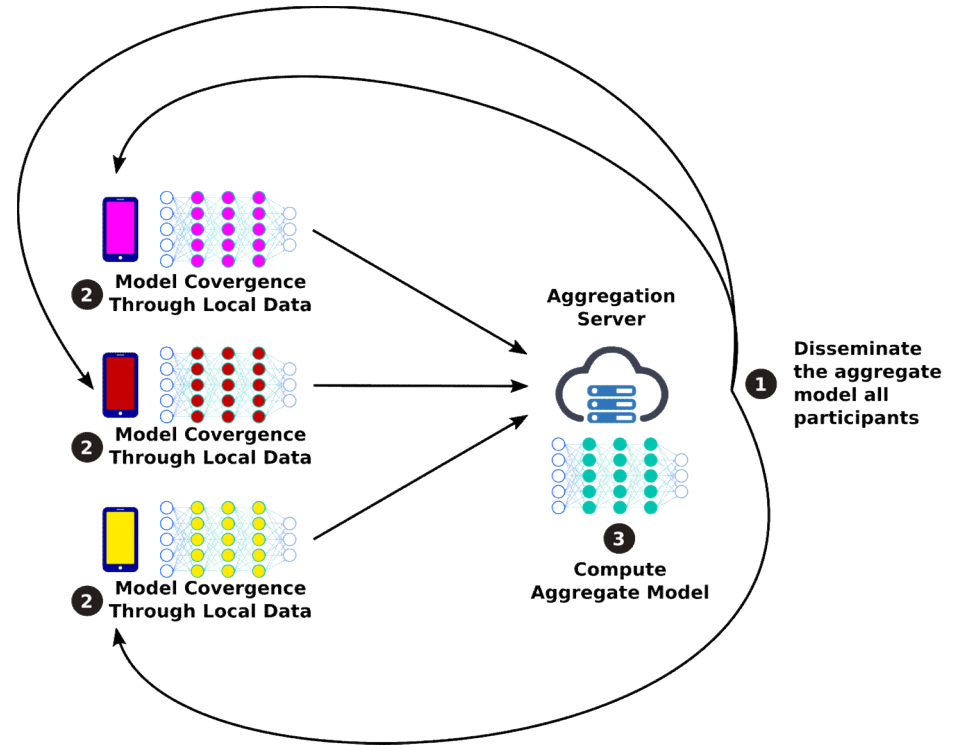
# Tutorial introducing SGX

## Federated Learning



# Tutorial introducing SGX

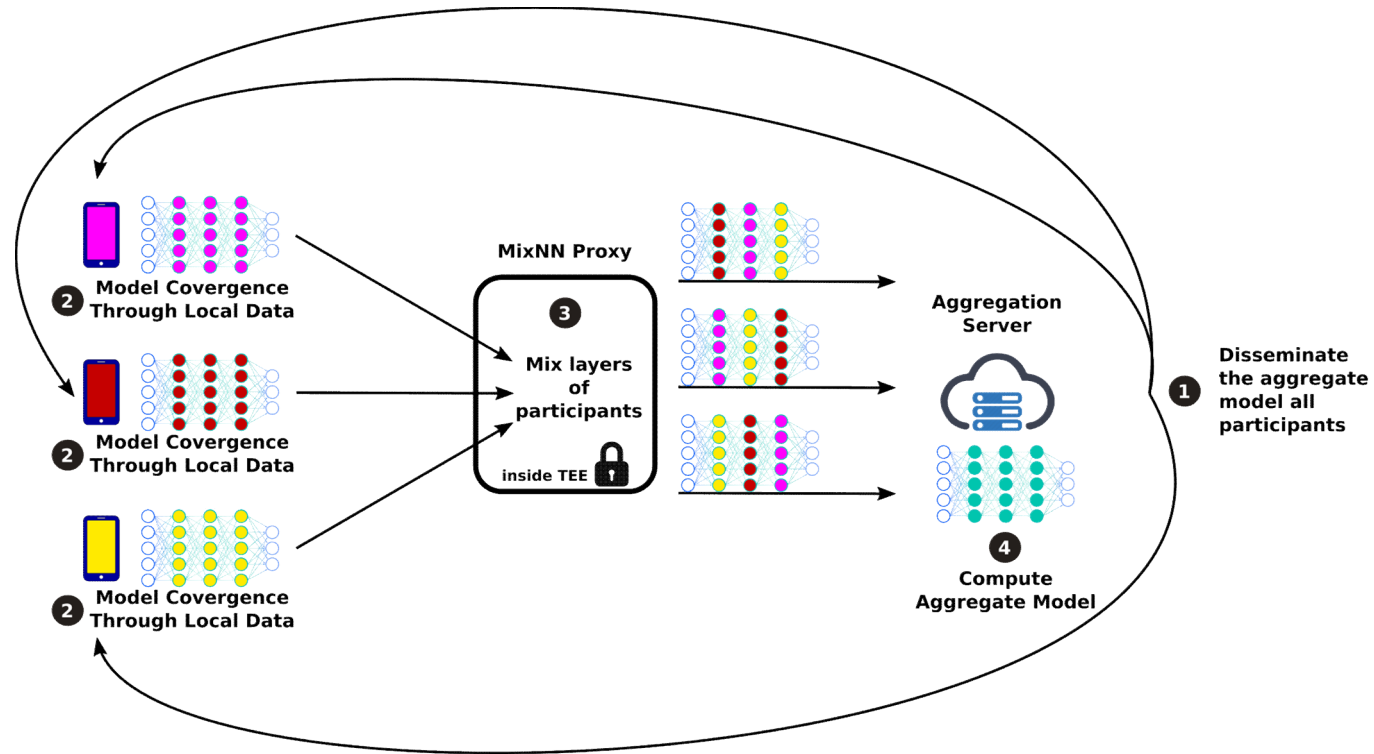
## Federated Learning



- Limitations
- Countermeasures
  - Perturbation (e.g., Differential Privacy [1] )  
→ Drastically reduces accuracy
  - Crypto (e.g., Secure Aggregation [2] )  
→ Overhead

# Tutorial introducing SGX

## Federated Learning scheme using SGX: MixNN [1]



→ Improve the privacy (at low cost) without compromising the utility

[1] MixNN : protection of federated learning against inference attacks by mixing neural network layers, T Lebrun et al., Middleware 2022

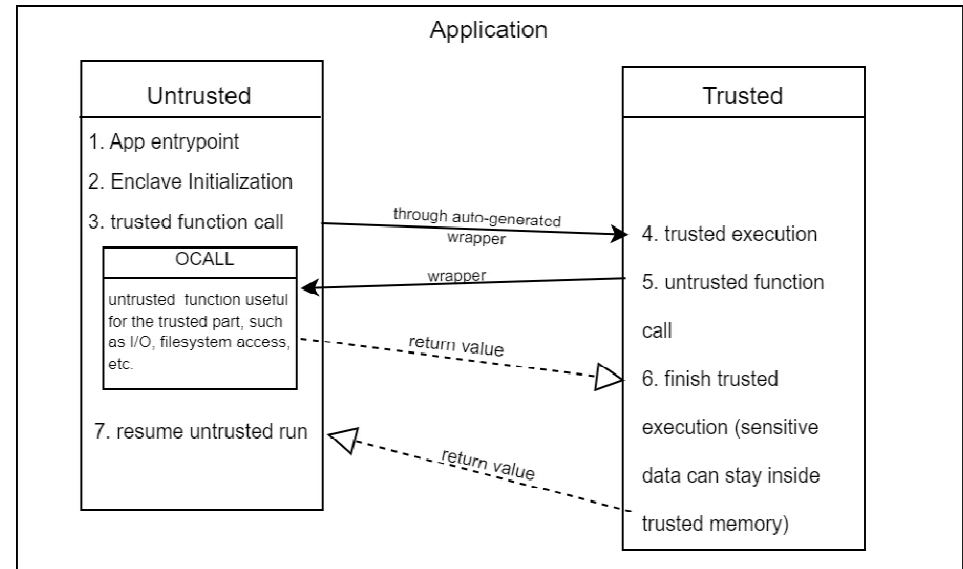
# Tutorial introducing SGX

## Installation

- Guide à travers l'installation des drivers & SDK  
SGX + OpenSSL SGX

## Bases

- Architecture de base d'un projet SGX
- Initialisation d'une enclave
- Principe OCALL & ECALL : permet de faire un "context-switch" entre la partie trusté & non-trusté
- Comment faire transiter des données & stockage de données sécurisé pour l'enclave





# Tutorial introducing SGX

## Crypto

- Utilisation de la librairie de crypto OpenSSL : génération d'une paire de clés RSA et l'implémentation d'un chiffrement / déchiffrement basique
- Principe de "Sealing", chiffrement d'une données qui peut être enregistrée sur disque afin d'être réutilisée entre plusieurs run d'une enclave, ici chiffrement de la clé privée

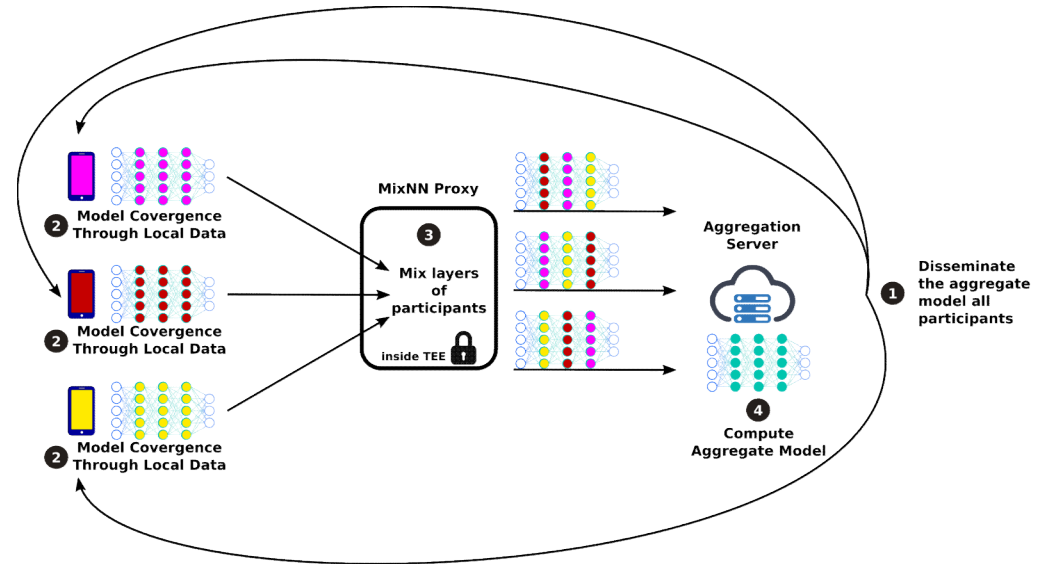
## Multi Threading

- Mise en place du multi-threading à l'intérieur de l'enclave
- Synchronisation entre les différents threads

# Tutorial introducing SGX

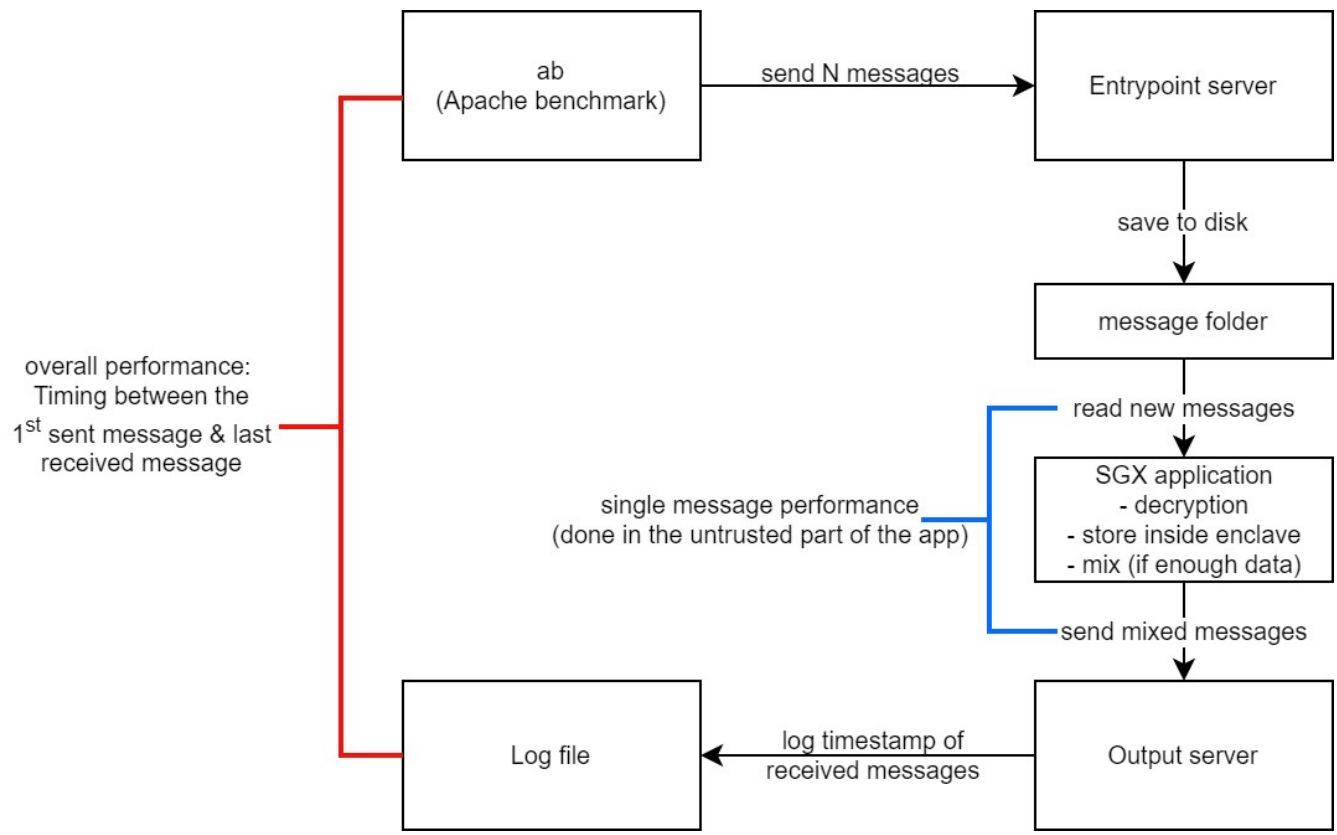
## Implémentation MixNN

- Génération d'une paire de clés et partage de la clé publique
- Déchiffrent des messages en entrée et stockage de leur contenu à l'intérieur de l'enclave
- Une fois un seuil de message atteint, mixage du contenu des messages et sortie de l'enclave avec transmission des messages mixés au serveur
- Les messages sont simplement des tableaux d'entiers, ce qui simplifie le stockage dans l'enclave et les structures de données avec lesquels le mixage doit être fait



# Tutorial introducing SGX

## Évaluation des performances



# Tutorial introducing SGX

<https://gitlab.inria.fr/abaud/sgx-basics>

The screenshot displays the GitLab web interface for the 'sgx-basics' project. The top navigation bar includes a search bar and various utility icons. The left sidebar lists project management options such as 'Project information', 'Repository', 'Issues', 'Merge requests', 'Security & Compliance', 'Deployments', 'Packages and registries', 'Infrastructure', 'Monitor', 'Analytics', 'Wiki', 'Snippets', and 'Settings'. The main content area shows the project name 'sgx-basics' with its ID (40034) and a 'Leave project' link. It also displays statistics: 13 Commits, 1 Branch, 0 Tags, and 348 KB Project Storage. A commit titled 'crypto in untrusted part' by Adrien Baud is highlighted. Below this, there are buttons for 'Find file', 'Web IDE', and 'Clone'. A row of utility buttons includes 'README', 'Add LICENSE', 'Add CHANGELOG', 'Add CONTRIBUTING', 'Set up CI/CD', and 'Configure Integrations'. At the bottom, a table lists the project's files and their commit history.

Name	Last commit	Last update
App	adding a cast to silence a warning uint8_t ~>...	3 months ago
Enclave	changes requested by Robin	3 months ago
include	add perftest utility + curlpp & directory watc...	5 months ago
server	add perftest utility + curlpp & directory watc...	5 months ago
.gitignore	update tutorial	7 months ago
Makefile	crypto in untrusted part	3 months ago

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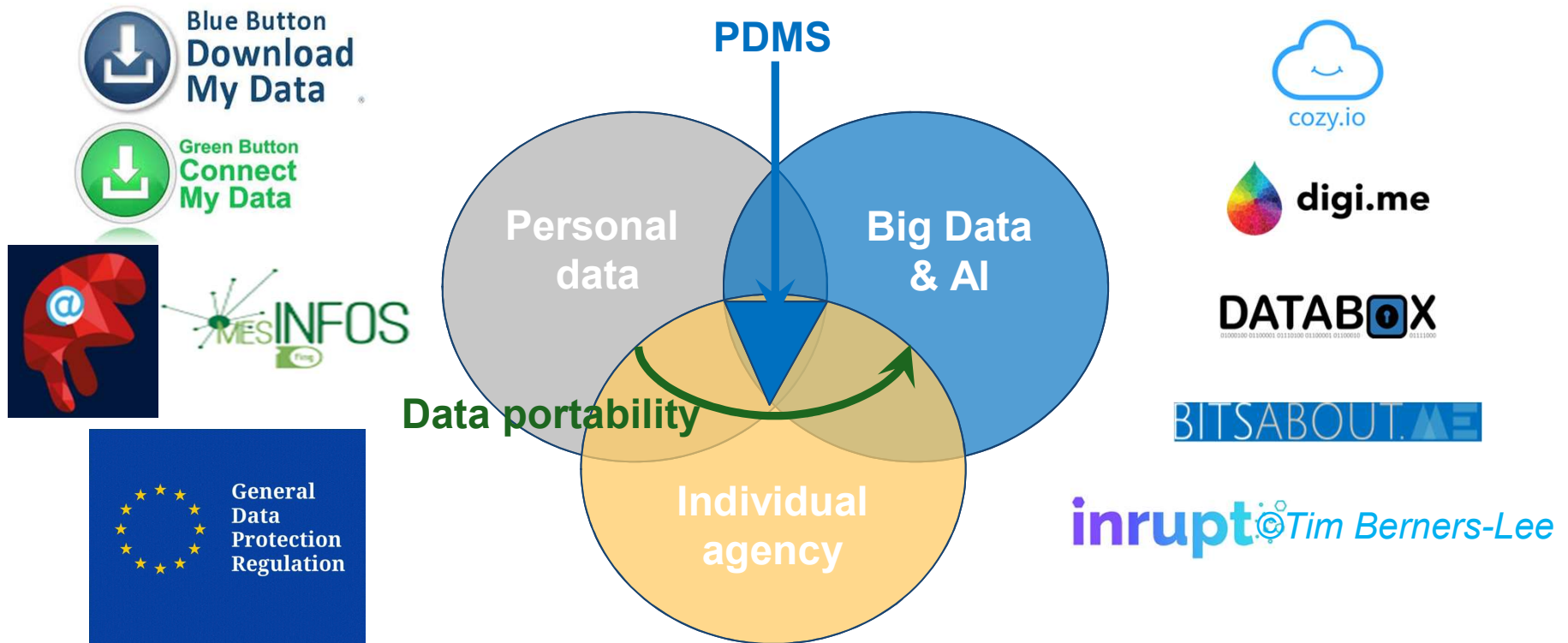
## PART III – Use-case

Secure and Extensive Personal Data Management Systems with SGX

# Current trend: return personal data to the individuals to enable individual agency

**Act I: the right to Data portability**  
... the right to retrieve its own data

**Act II: Personal Data Mg<sup>t</sup> Systems (PDMS)**  
... the tool to manage its own data



# Personal Data Management Systems

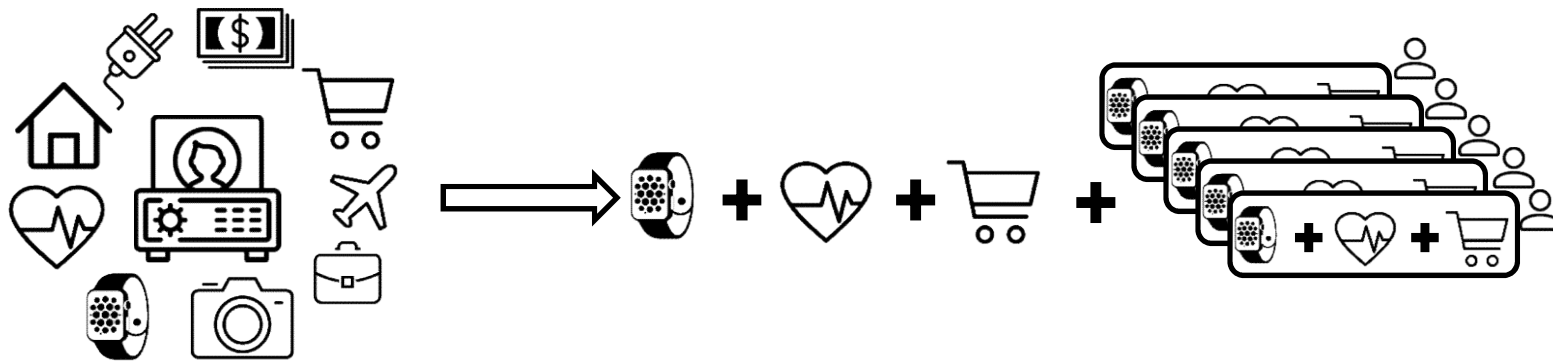
Solutions to gather the digital life of an individual

More and more solutions available (Cozy Cloud, Digi.me, Personal Infomediarities . . . )

Boosted by regulations such as Data Portability (GDPR)

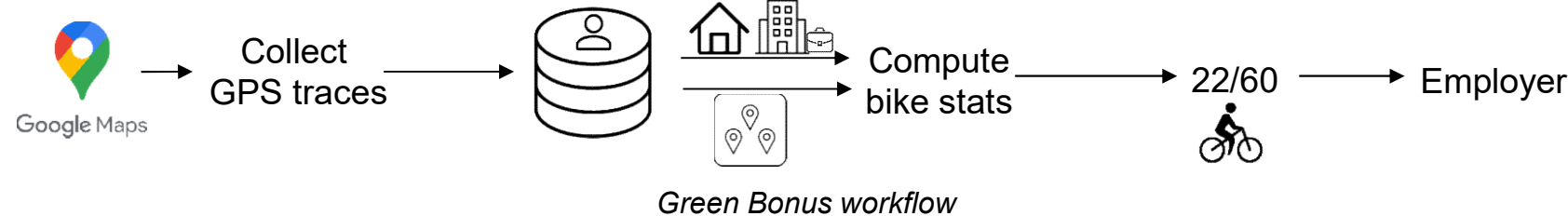
Crosses data from multiple data sources and/or multiple users

Promising paradigm : computation comes to data

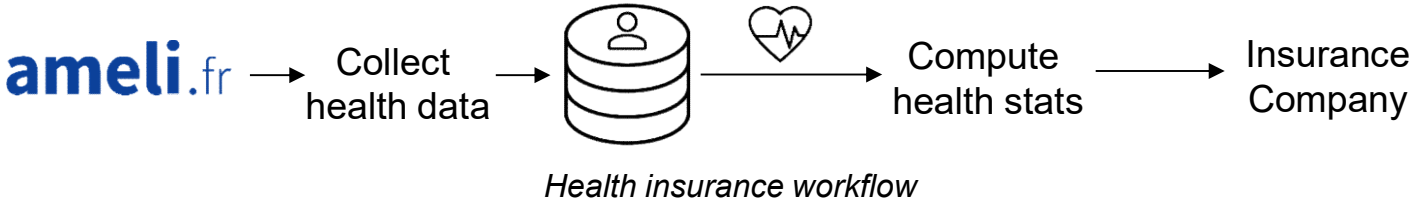


# Examples of PDMS related use-cases

## Companies want to reward employees commuting by bike



## Citizens wants to get a quotation from a new health insurance company

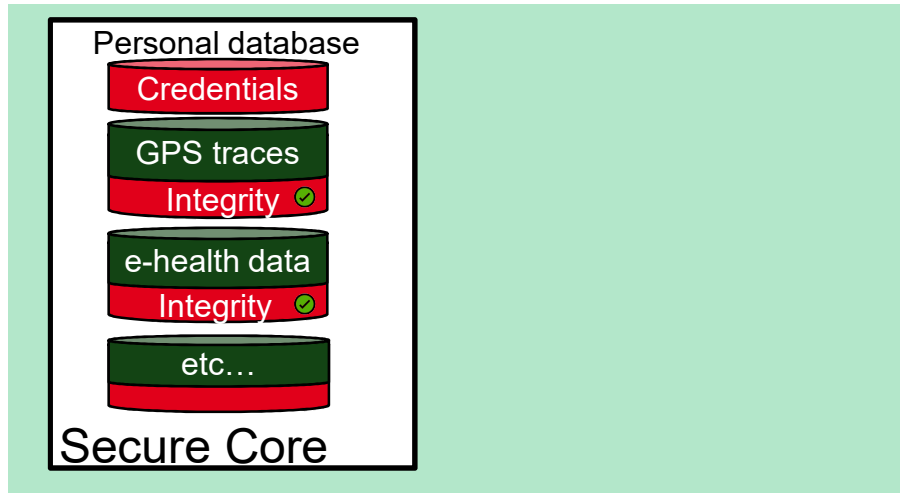


### Such use-cases require

- Privacy
- Verifiability
- Extensibility



# PDMS architecture leveraging SGX enclaves

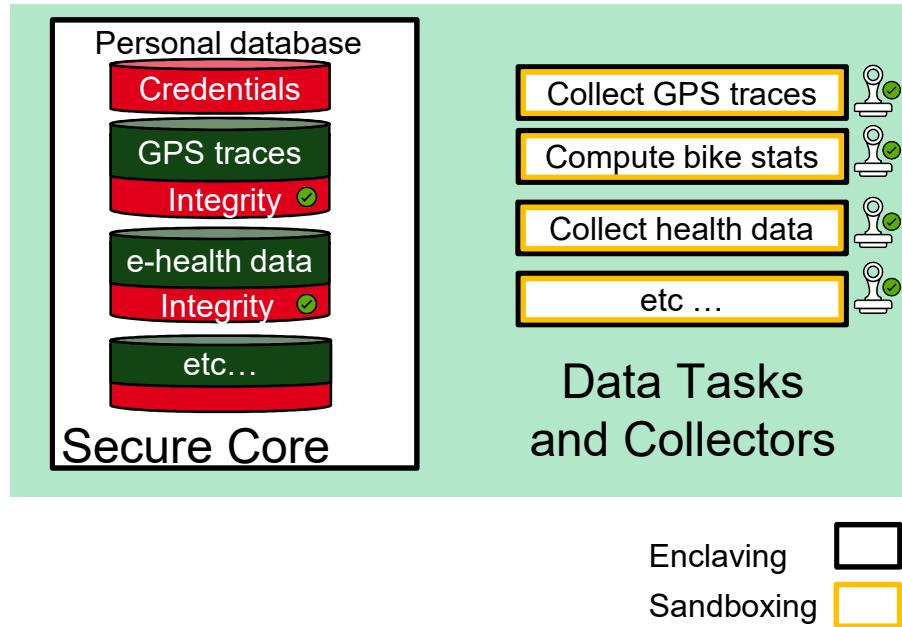


## Elements & Properties

- **one Secure Core**
  - Trusted Computing Base
  - Minimal and Inextensible
  - Enclaved

Enclaving

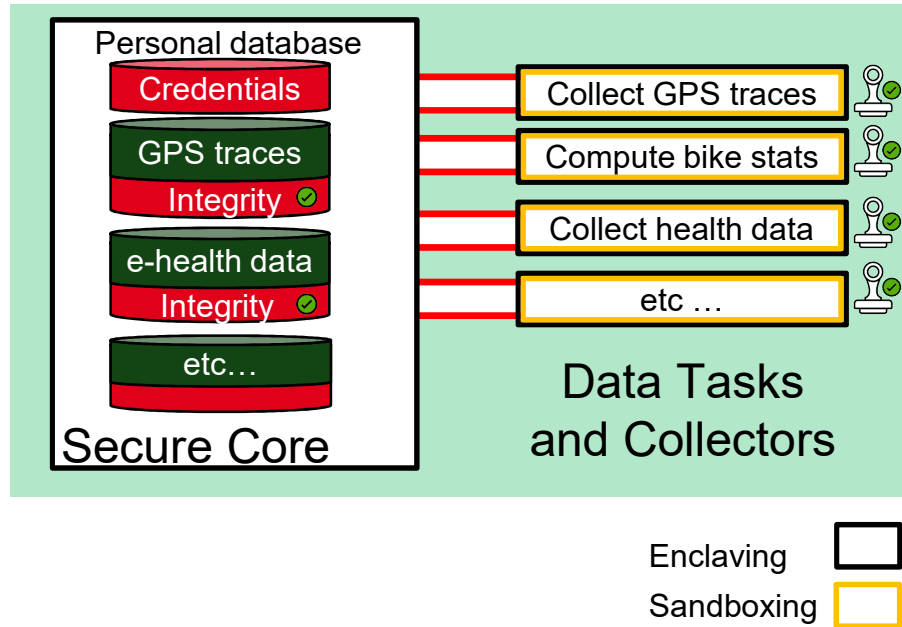
# PDMS architecture leveraging SGX enclaves



## Elements & Properties

- **one Secure Core**
  - Trusted Computing Base
  - Minimal and Inextensible
  - Enclaved
- **and Data Tasks/Collectors**
  - Code extensions
  - Enclaved
  - Sandboxed

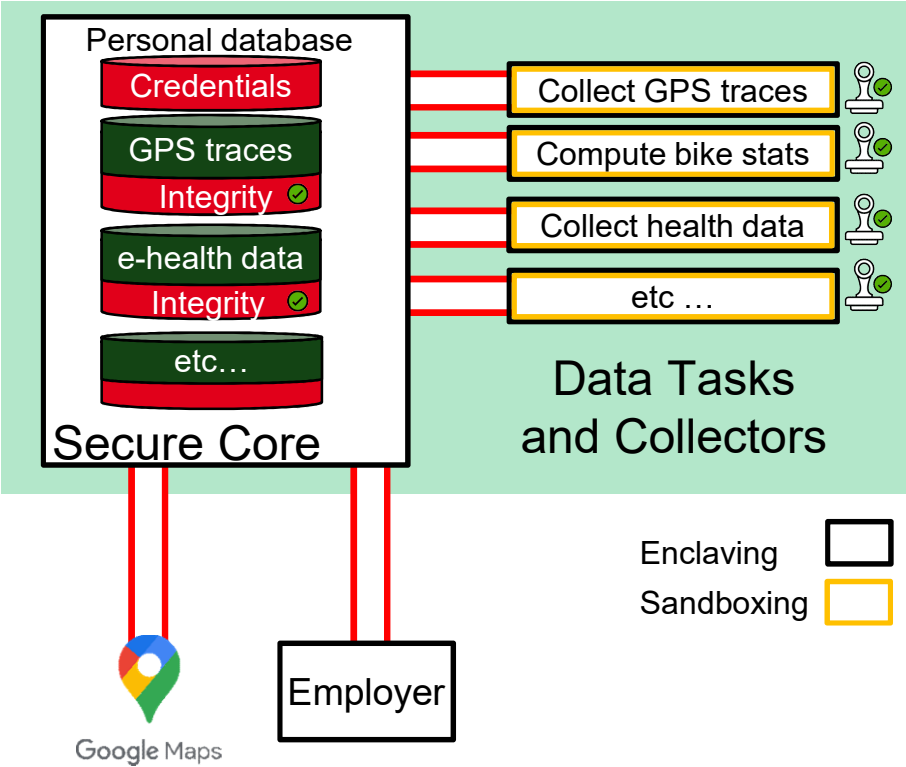
# PDMS architecture leveraging SGX enclaves



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  - Sandboxed
- **Secure communications**

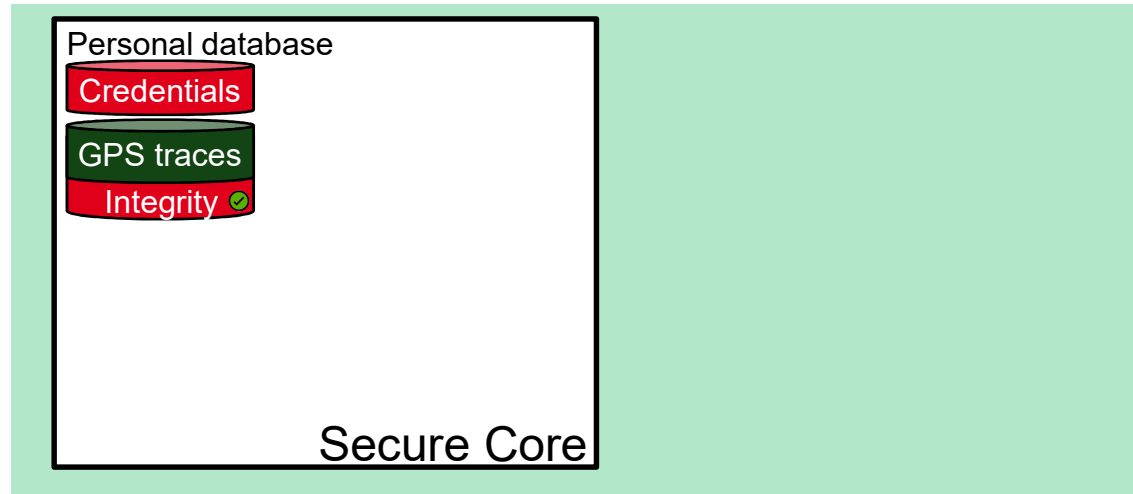
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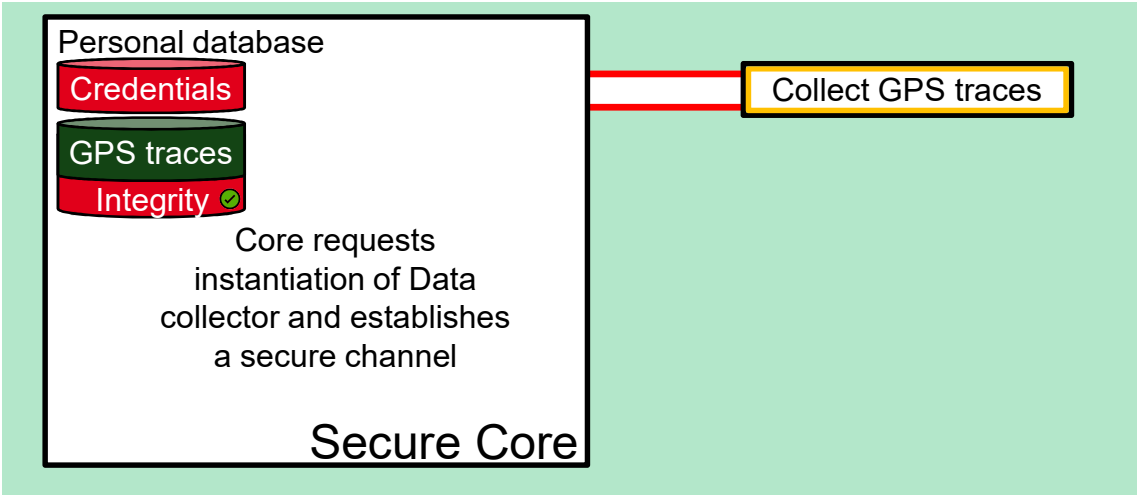
## Elements & Properties

- **one Secure Core**
  - Trusted Computing Base
  - Minimal and Inextensible
  - Enclaved
- **and Data Tasks/Collectors**
  - Code extensions
  - Enclaved
  - Sandboxed
- **Secure communications**
- **Core as proxy**

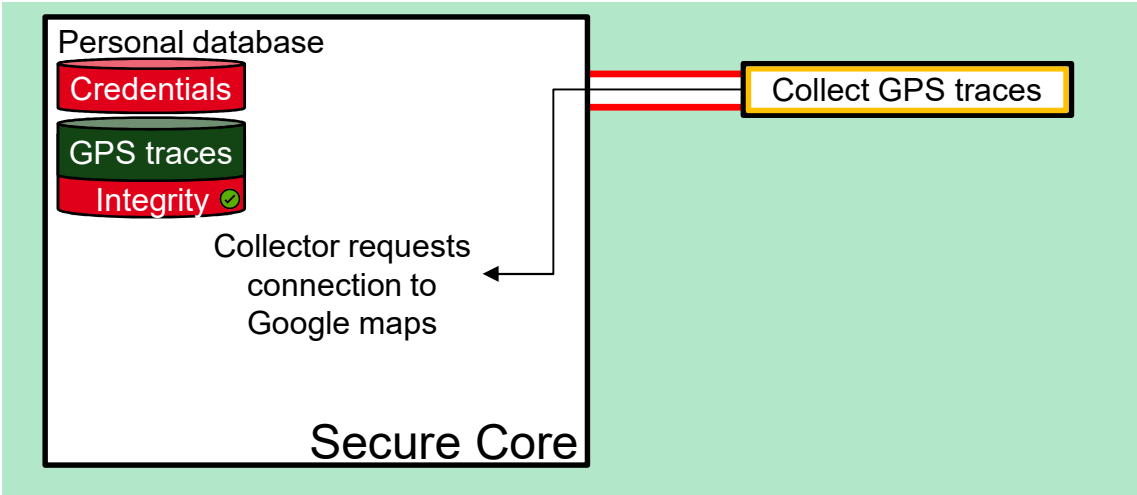
# Data collection



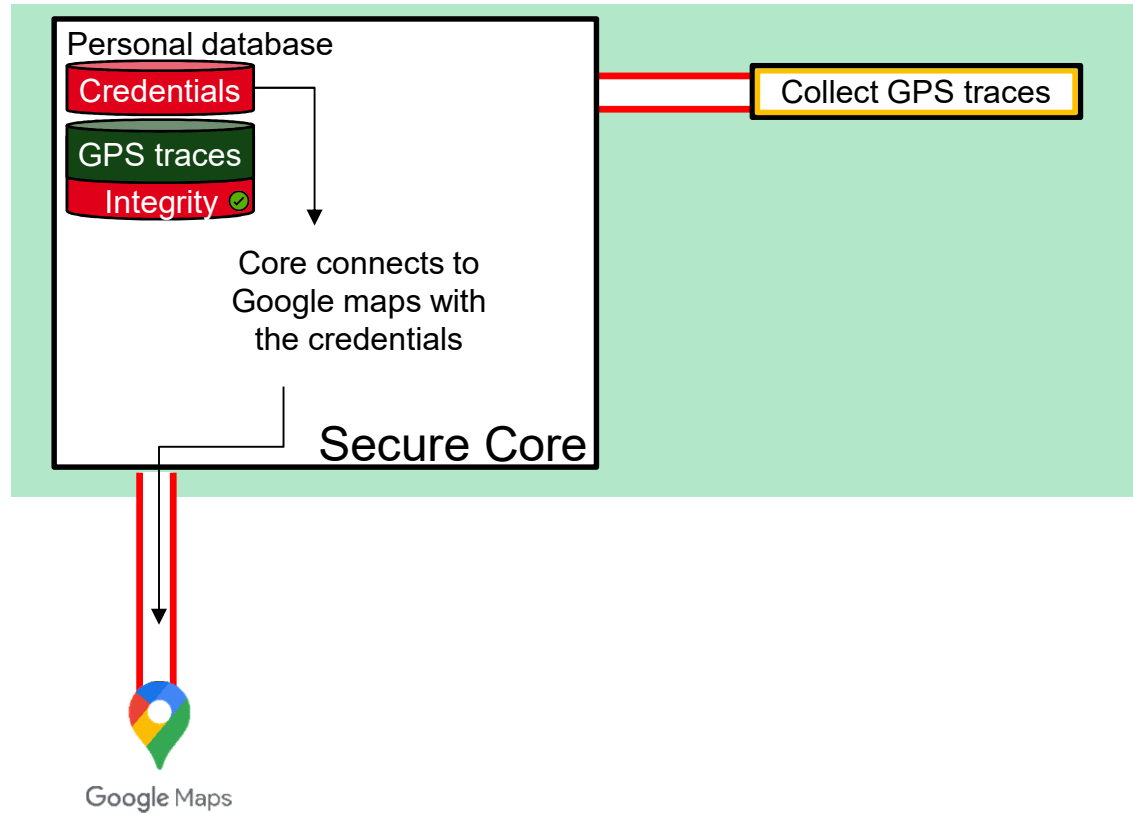
# Data collection



# Data collection

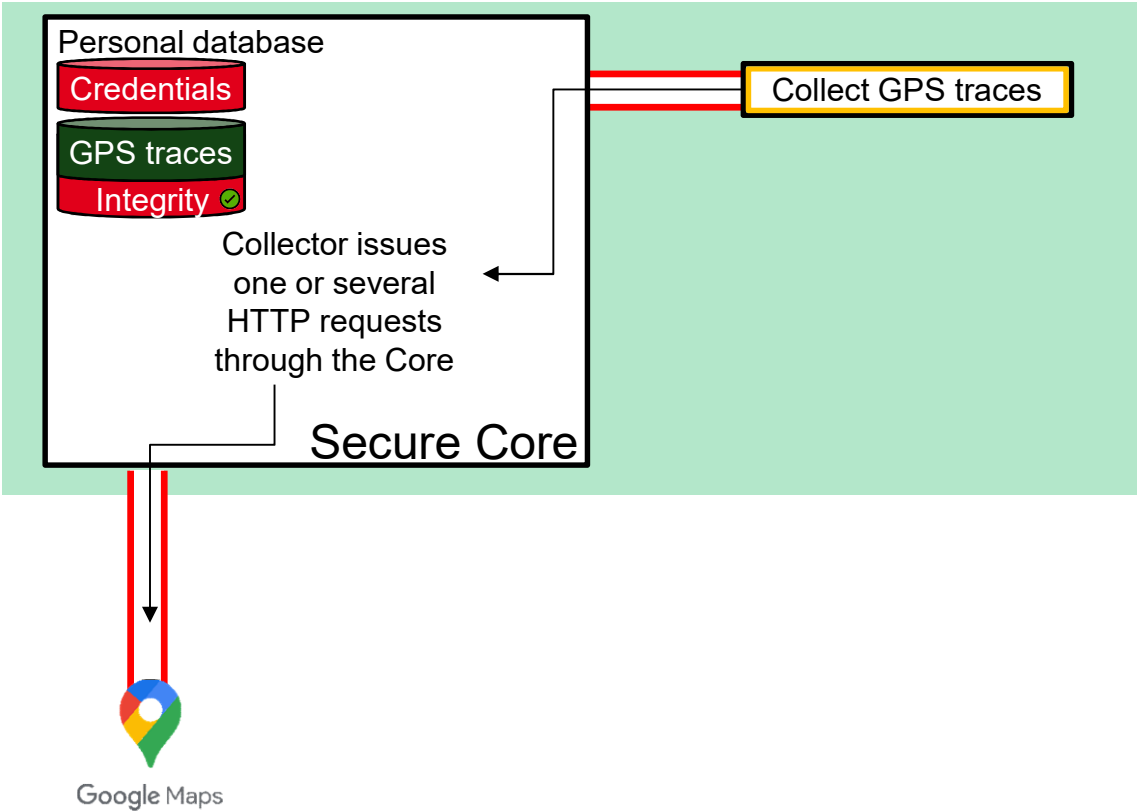


# Data collection

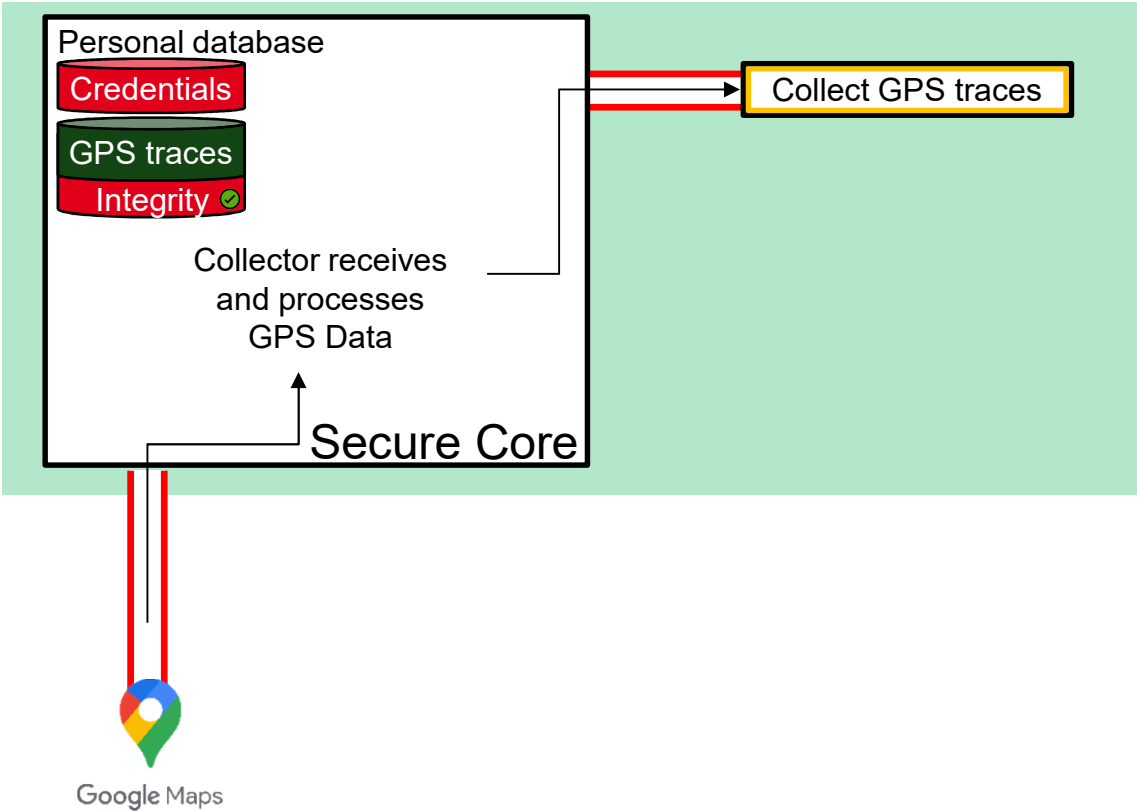




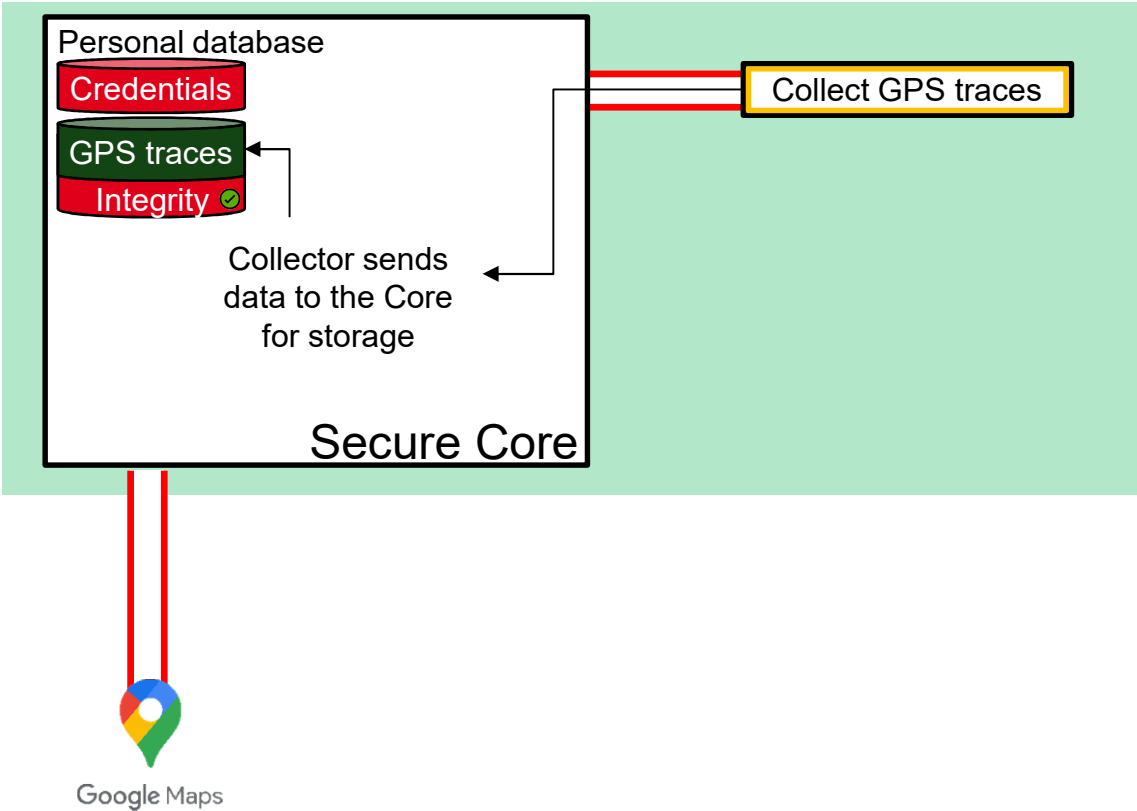
# Data collection



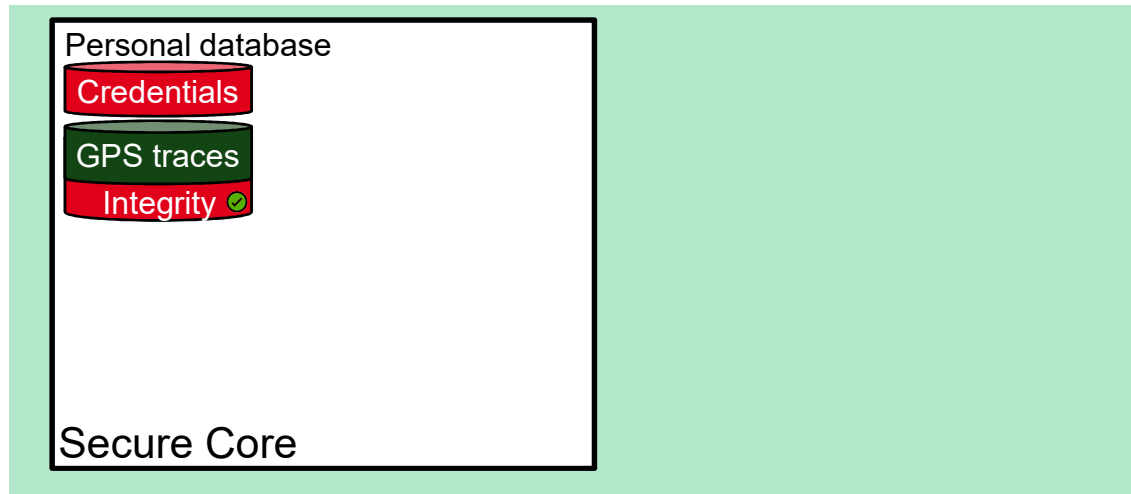
# Data collection



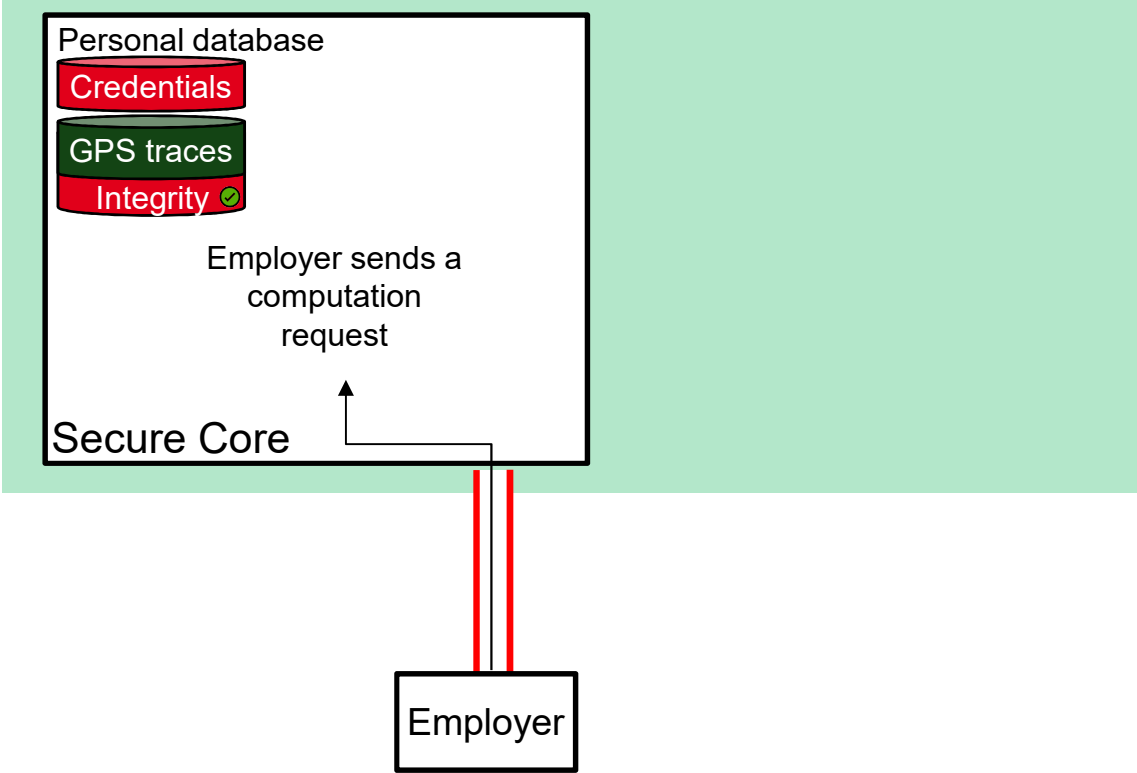
# Data collection



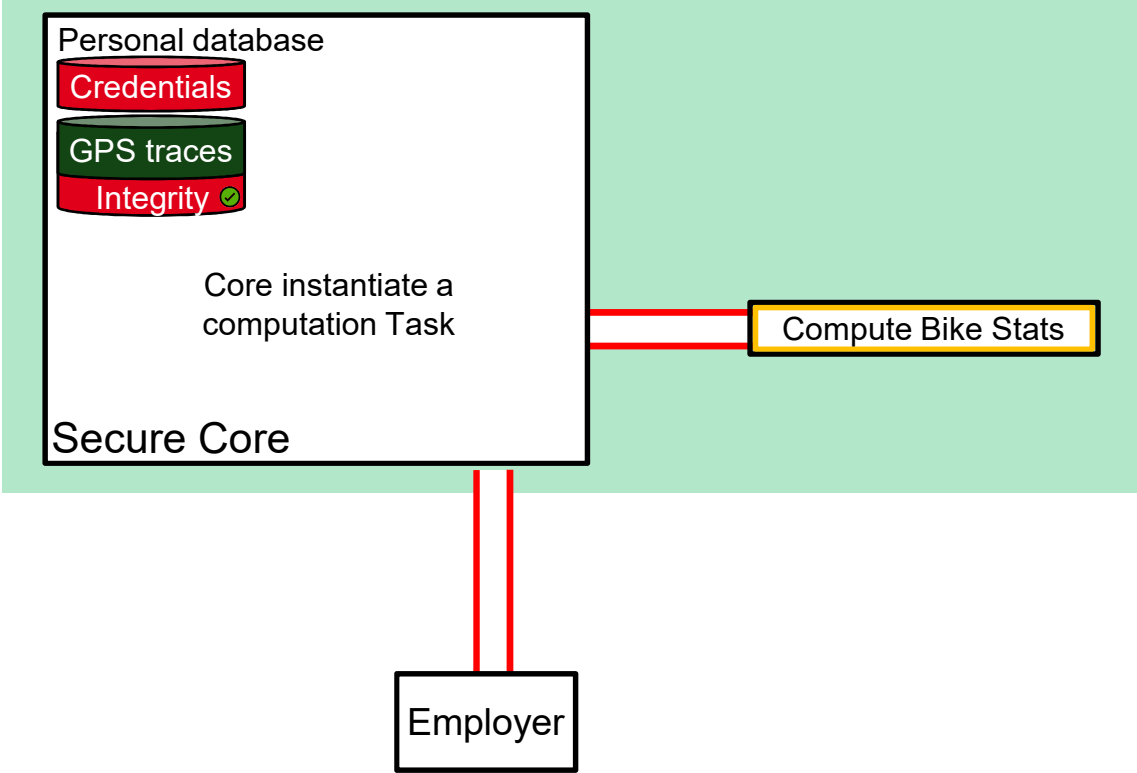
# Data computation



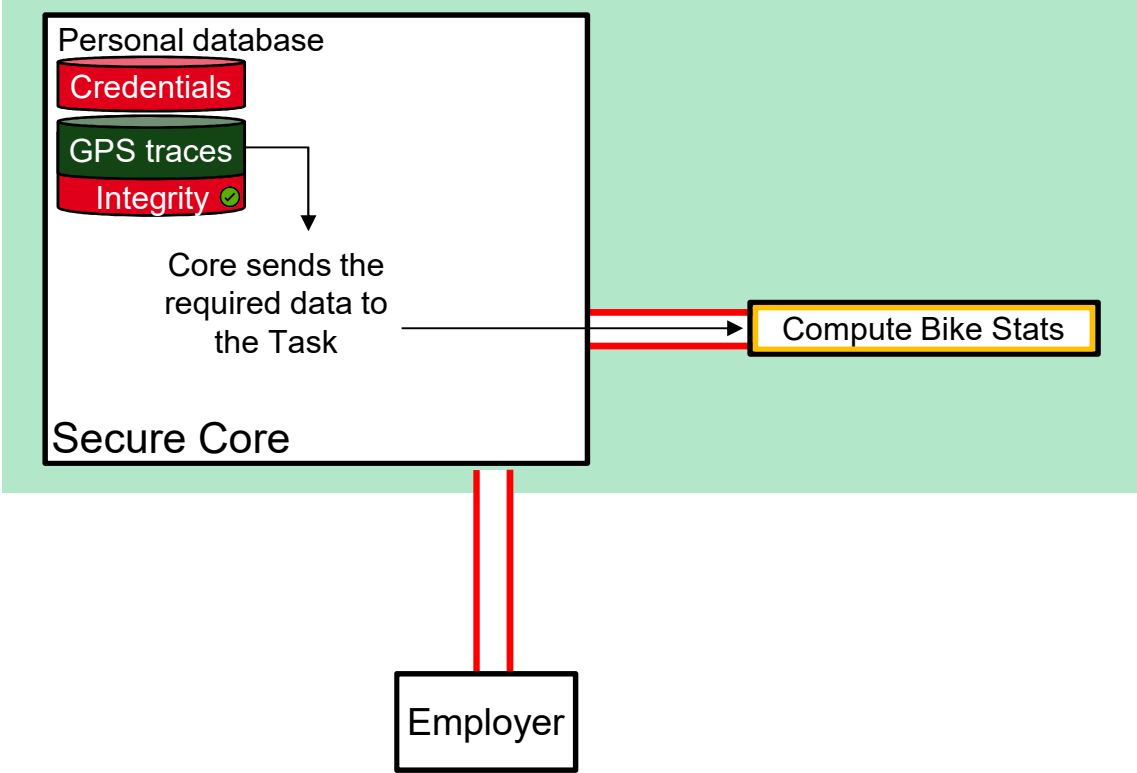
# Data computation



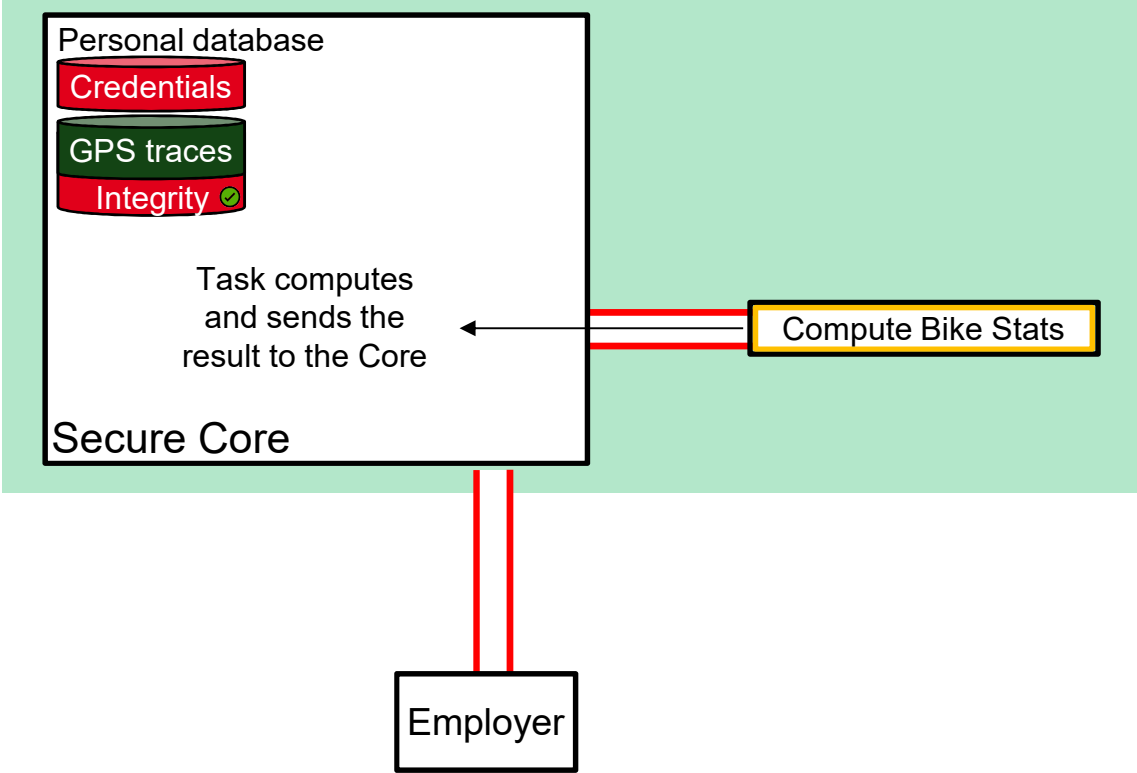
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# Data computation

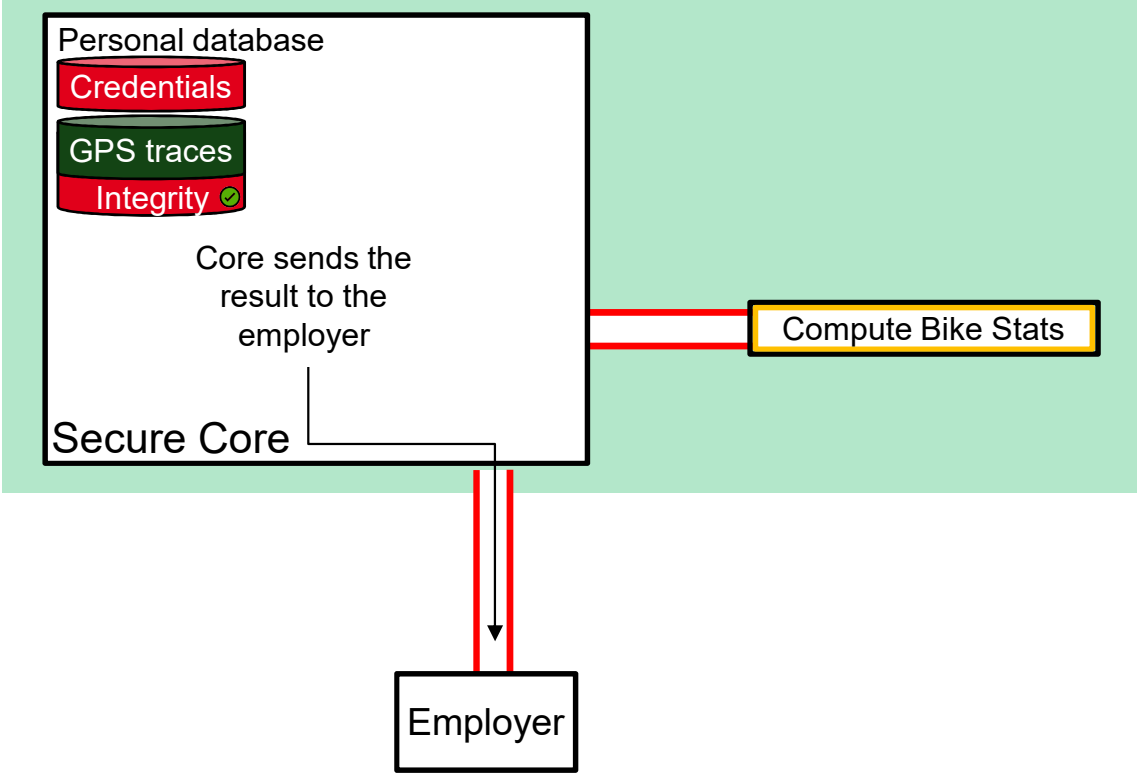


# Data computation





# Data computation



# Prototype PDMS on SGX [project.inria.fr/espdms](http://project.inria.fr/espdms)

The screenshot shows a web interface for managing the ES-PDMS platform. At the top, there are navigation tabs: "SGX-ES-PDMS", "Administration" (which is selected), and "Scenarios". On the left side, there is a sidebar with "ES-PDMS Controls" and "Admin Platform". The main content area is titled "ES-PDMS Controls" and includes the instruction "Manage the platform.". It features two main control panels. The first panel, "ES-PDMS State Machine", contains two green status bars: "Host is running" and "Core is running". Below these bars are three buttons: "Initialize host", "Start Core", and "Stop". The second panel, "Http Server", contains a single green status bar: "Http server is running", with a mouse cursor hovering over it. Below this bar are two buttons: "Start" and "Stop".

# Prototype PDMS on SGX [project.inria.fr/espdms](http://project.inria.fr/espdms)

The screenshot shows the 'User Data' page in the SGX-ES-PDMS application. The page has a navigation menu on the left with options: 'User Data', 'Run a scenario', 'Data Collection', 'Data Computation', and 'Complex Scenarios'. The main content area is titled 'User Data' and contains the text 'This data is stored on the HTTP server'. Below this text is a scrollable text box containing a JSON array of data points. Each data point is an object with fields for 'timestamp', 'latitude', 'longitude', and 'altitude'. The data points are as follows:

```
[{"timestamp": 1210392837, "latitude": 39.969459, "longitude": 116.307284, "altitude": 71}, {"timestamp": 1210392842, "latitude": 39.969512, "longitude": 116.30724, "altitude": -29}, {"timestamp": 1210392847, "latitude": 39.969508, "longitude": 116.307252, "altitude": 2}, {"timestamp": 1210392852, "latitude": 39.969481, "longitude": 116.307247, "altitude": 19}, {"timestamp": 1210392855, "latitude": 39.969481, "longitude": 116.307247, "altitude": 19}
```

# Prototype PDMS on SGX [project.inria.fr/espdms](http://project.inria.fr/espdms)

The screenshot displays the 'Administration' section of the 'Scenarios' tab in the 'SGX-ES-PDMS' application. On the left, a sidebar contains 'User Data' and a 'Run a scenario' button. The main area is divided into three sections: 'CORE' (red background), 'DATA COLLECTOR' (yellow background), and 'HTTP SERVER' (grey background). Each section has a log of events and a set of control buttons.

**CORE**

- Establishing TLS connection to localhost:4433
- TLS connection established, connected to localhost:4433
- Preparing user credentials for localhost:4433
- Incoming data from CollectGPS
- Incoming request from CollectGPS collector data task
- Https request from data collector transmitted to localhost:4433
- Incoming data from localhost:4433
- Transmitting received data to the CollectGPS collector
- Incoming data from localhost:4433
- Transmitting received data to the CollectGPS collector

**DATA COLLECTOR**

- Collector's collector data task is up and running : ready to collect...
- Start data collection
- Sending Core connection request to localhost:4433
- Connection established : ready to collect
- Https request "POST / HTTP/1.1 Connection: keep-alive Content-Length: 45 {"file":"location\_history.json","data":"all"}" transmitted to Core
- Incoming data from Core...
- 24 bytes received
- Incoming data from Core...
- 9445 bytes received

**HTTP SERVER**

- TLS connection established for user Demo
- Https request received from Demo: b'{"file":"location\_history.json","data":"all"}'
- Sending requested json file(s) to Demo

**Control Buttons:**

- CORE:** TLS communication, Policy enforcement, Data storage, Keys, Credentials, Policies, Manifests
- DATA COLLECTOR:** TLS communication, Https/data query, Integrity check, Processing data, Insert to Core

# Prototype PDMS on SGX [project.inria.fr/espdms](http://project.inria.fr/espdms)

EXTENSIVE AND SECURE PERSONAL DATA MANAGEMENT SYSTEM

HOME GAMES VIDEOS PUBLICATIONS RESOURCES MEMBERS

### GAME1

#### PDMS version

- The core controls user accesses: **YES**
- The PDMS produces cascading attestations: **YES**

Enter your guesses on the right ⇒⇒⇒

Run attack script!

— waiting for input —

Number of computed bike trips:  
 22/60  
 60/60  
 other

Ecological bonus considered:  
 0 bike trips  
 22 bike trips  
 60 bike trips  
 other

Check your guess!

#### PDMS version

- The core controls user accesses: **NO**
- The PDMS produces cascading attestations: **YES**

Enter your guesses on the right ⇒⇒⇒

Run attack script!

— waiting for input —

Number of computed bike trips:  
 22/60  
 60/60  
 other

Ecological bonus considered:  
 0 bike trips  
 22 bike trips  
 60 bike trips  
 other

Check your guess!

— waiting for input —

Number of computed bike trips:

# Prototype PDMS on SGX [project.inria.fr/espdms](http://project.inria.fr/espdms)

## EXTENSIVE AND SECURE PERSONAL DATA MANAGEMENT SYSTEM

HOME GAMES VIDEOS PUBLICATIONS RESOURCES MEMBERS

### GAME3

#### PDMS version

- The core enforces stateless data tasks: **NO**
- The core enforces deterministic data tasks: **NO**
- The result size is limited to: **6 bits**

**Note that:**

- A POI is encoded on two 24 bits numbers
- POIs are highly sensitive since they can reveal the PDMS owner habits, religion or sexual preferences.

The goal, here, is to explain the malicious data tasks logic and their differences.

Run data task 1    Run: 00    Nb of retrieved POIs: 00

First POI retrieved at run:

Run data task 2    Run: 00    Nb of retrieved POIs: 00

First POI retrieved at run:

Thanks !

Questions ?



*Inria*

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