



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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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)

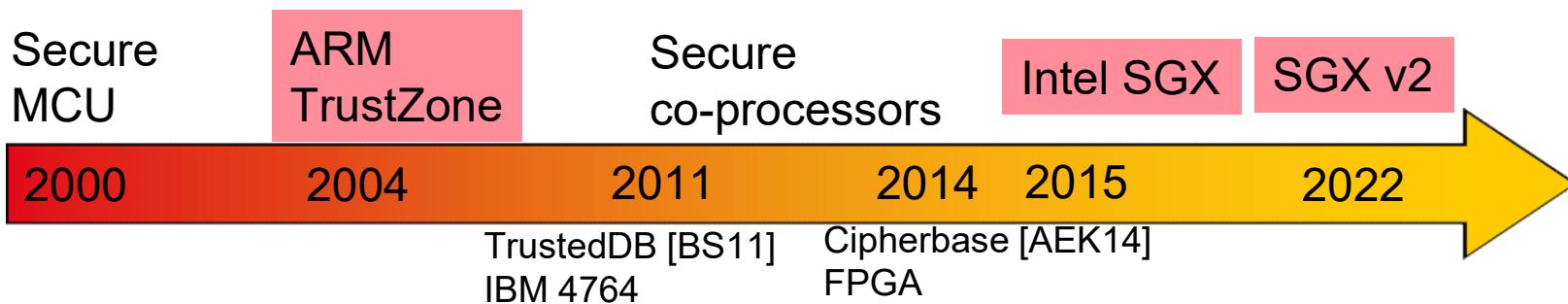
From secure elements, TPM, HSM, etc. [ANS14]

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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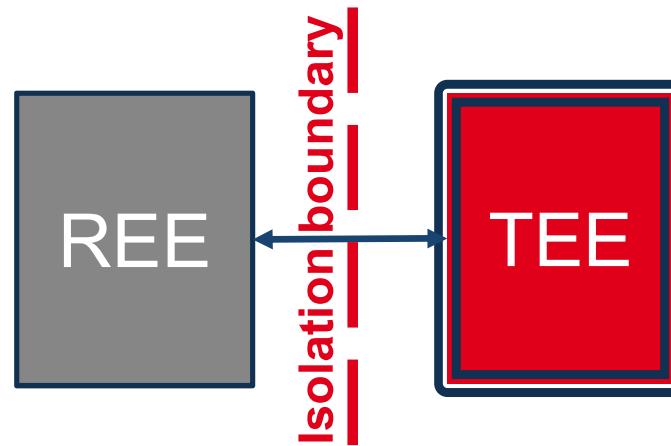
Federated Learning scheme using SGX

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Secure and Extensive Personal Data Management Systems with SGX

Secure data management in TEEs

Common general architecture (for existing basic TEEs, secure co-CPUs/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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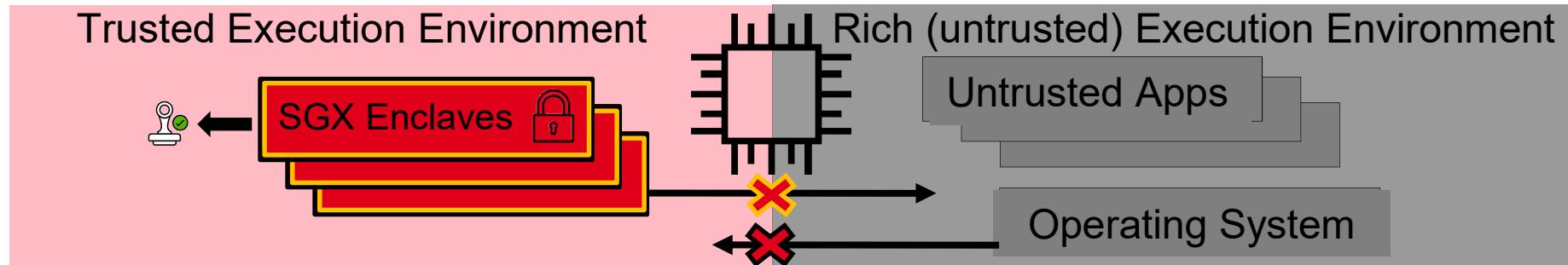
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Secure and Extensive Personal Data Management Systems with SGX

Intel Software Guard eXtensions (SGX)



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

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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

PROGRAMME ET EQUIPEMENTS
PRIORITAIRES DE RECHERCHE
CYBERSECURITE

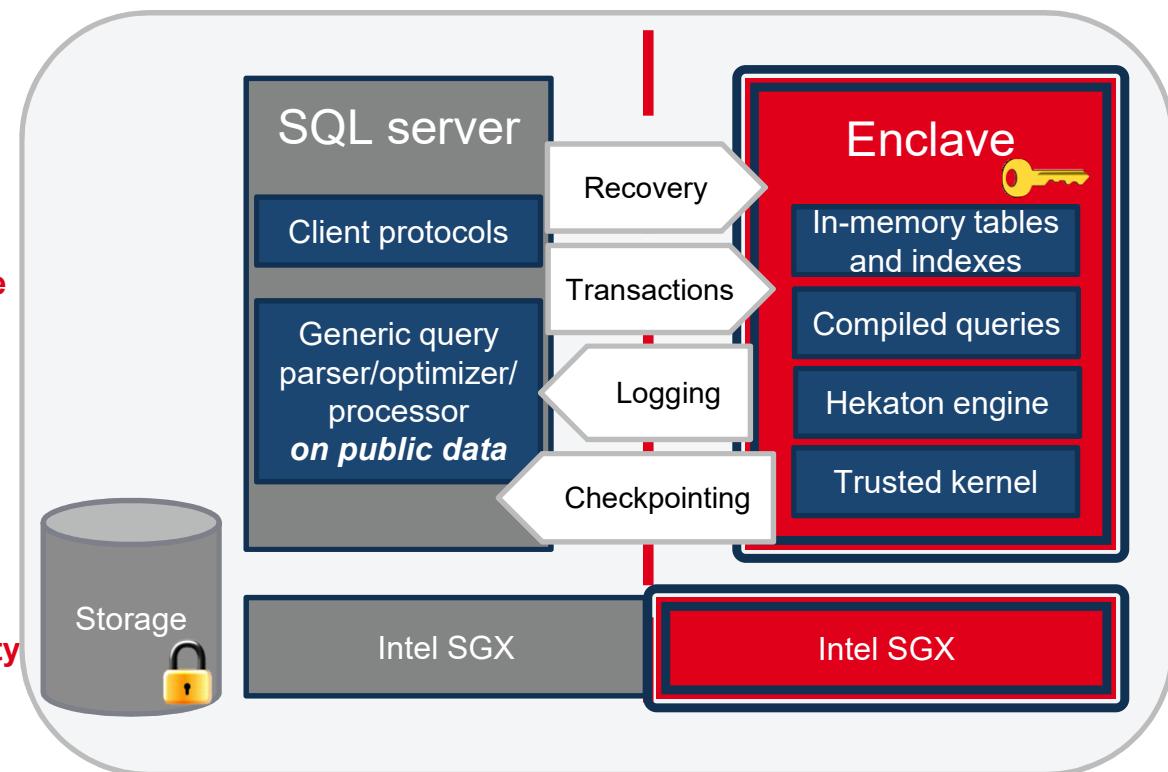
Efficient data processing with TEEs – EnclaveDB [PVC18]

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 (Heckaton 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 orders 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

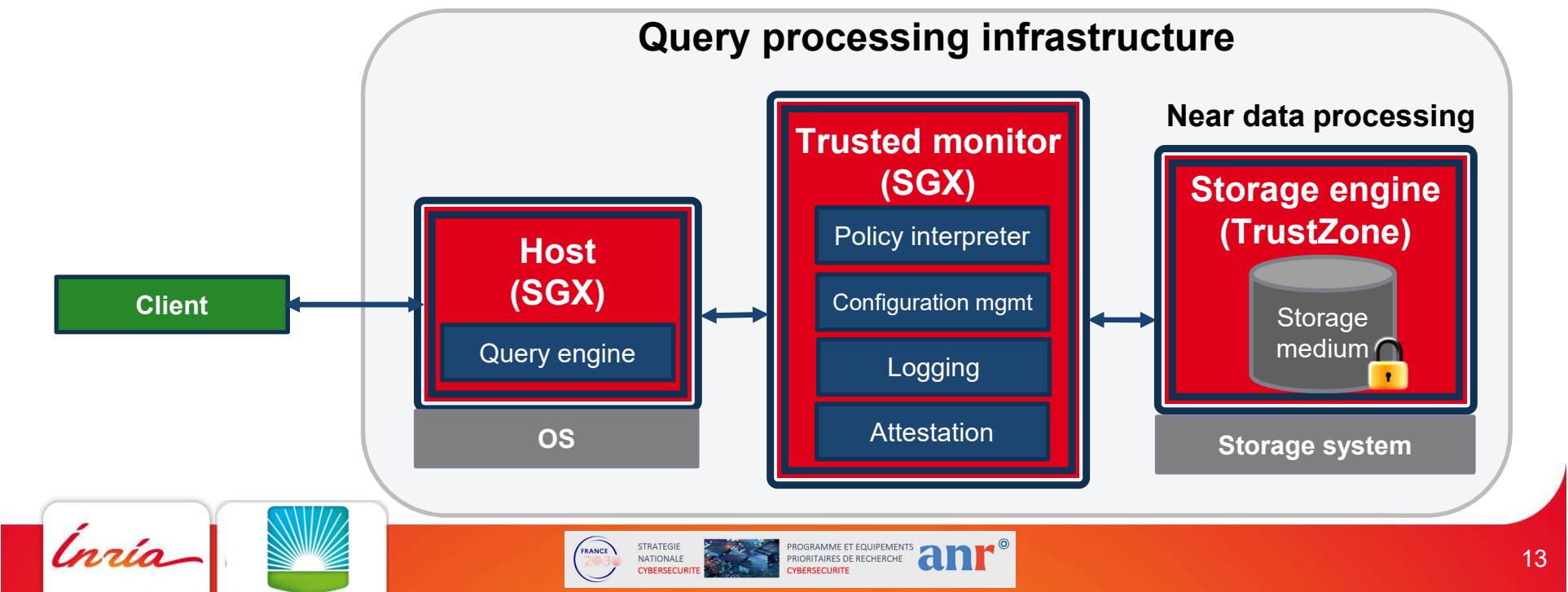
IronSafe [UCB+22]

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

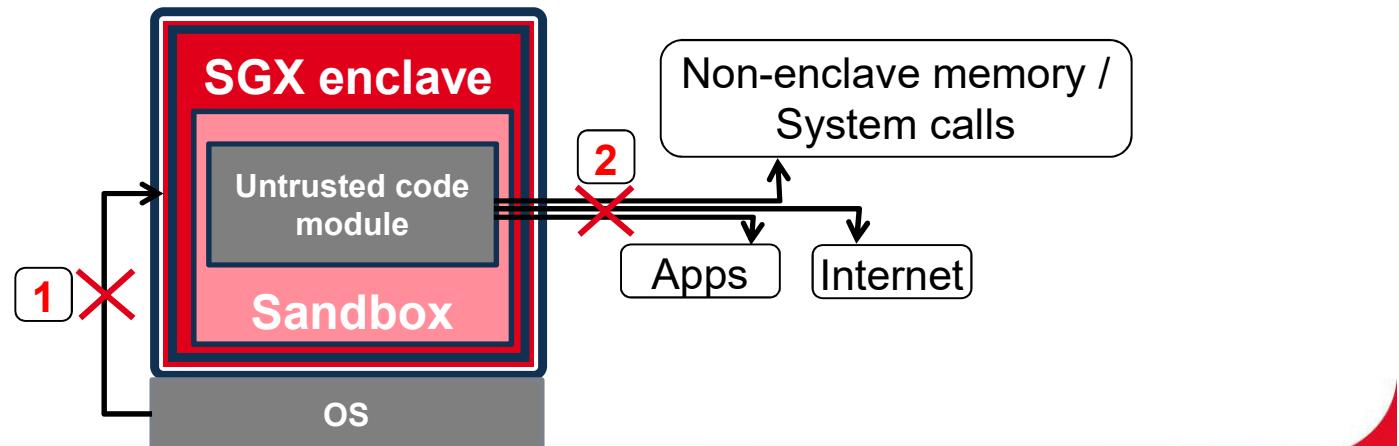
Confining untrusted code through double isolation

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

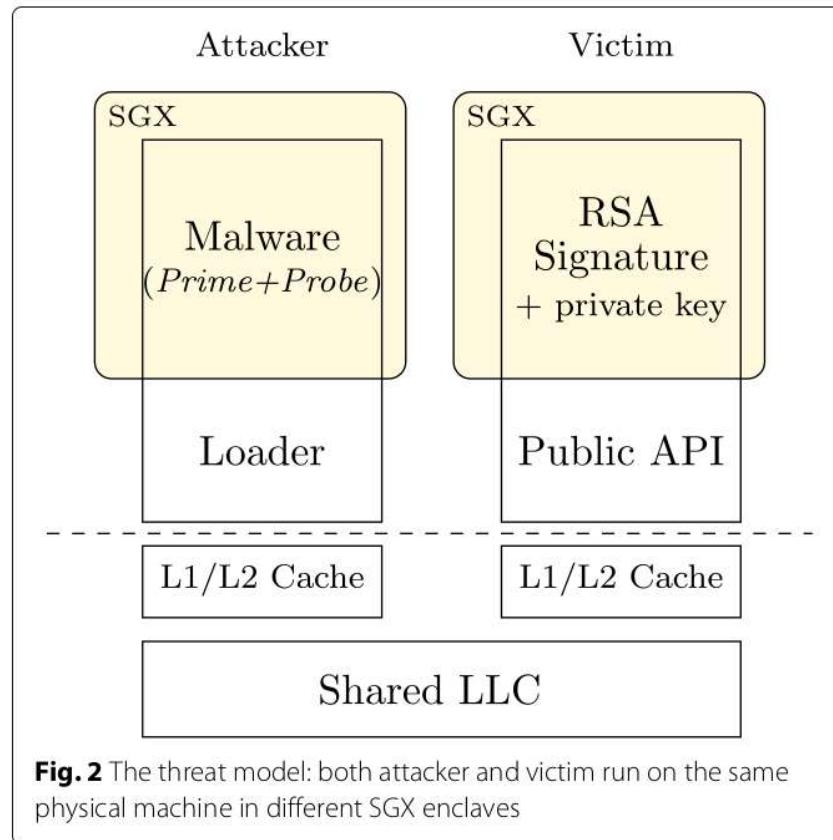
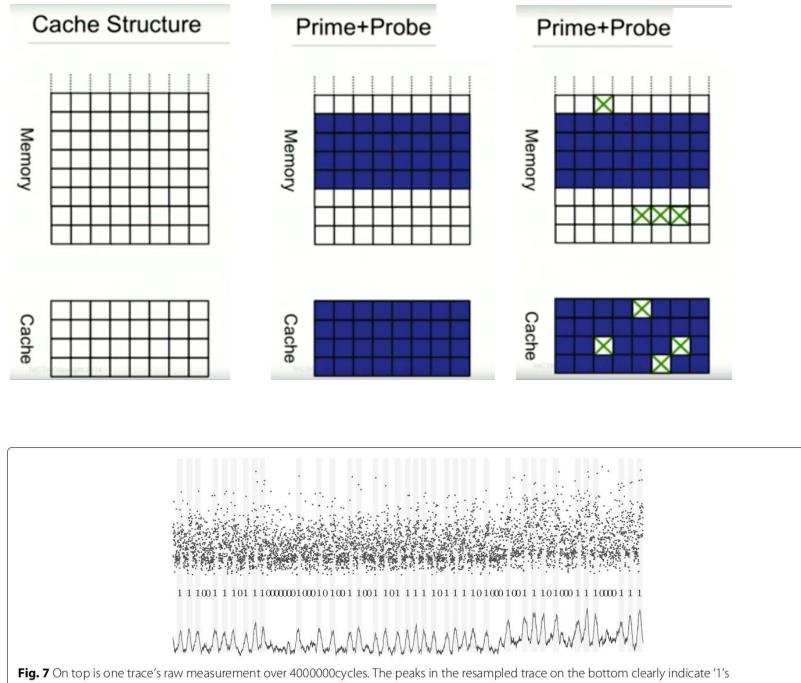


Fig. 2 The threat model: both attacker and victim run on the same physical machine in different SGX enclaves

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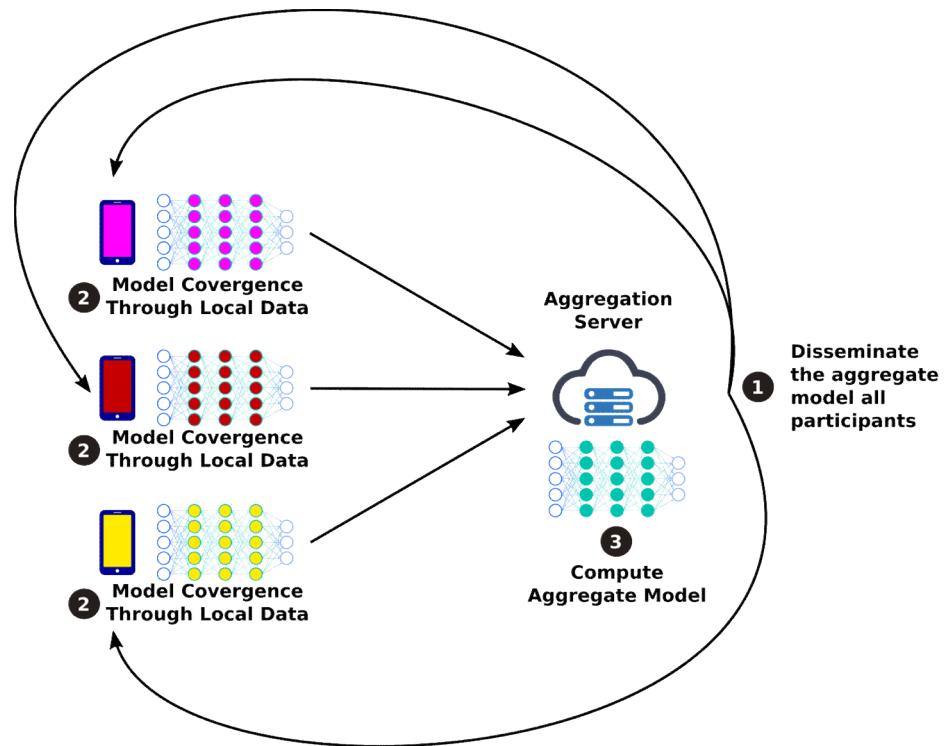
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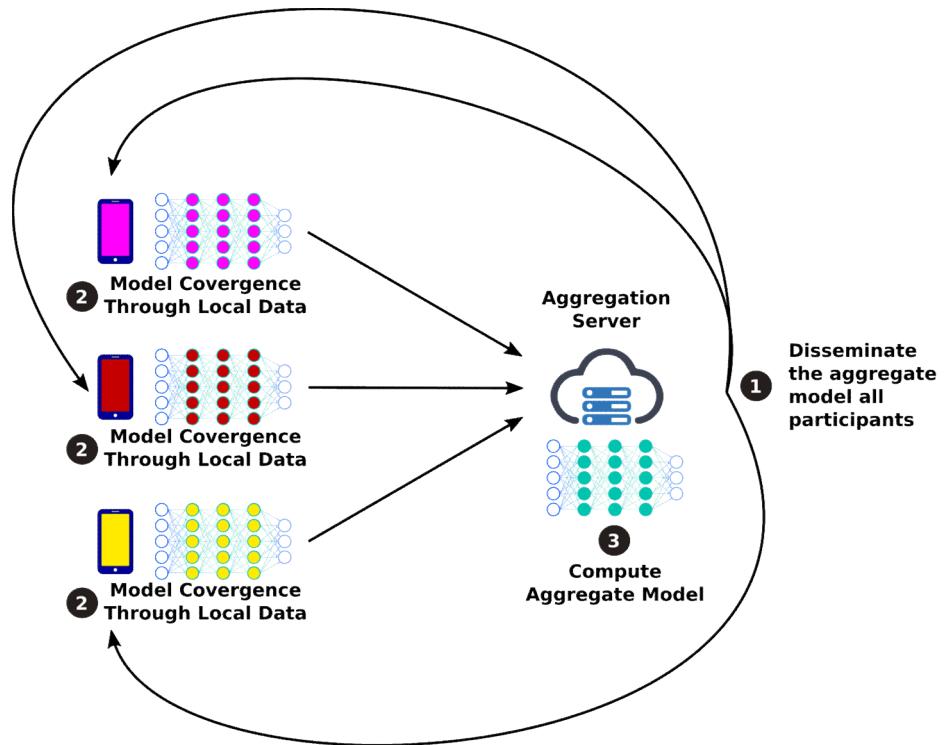
Federated Learning



Tutorial introducing SGX

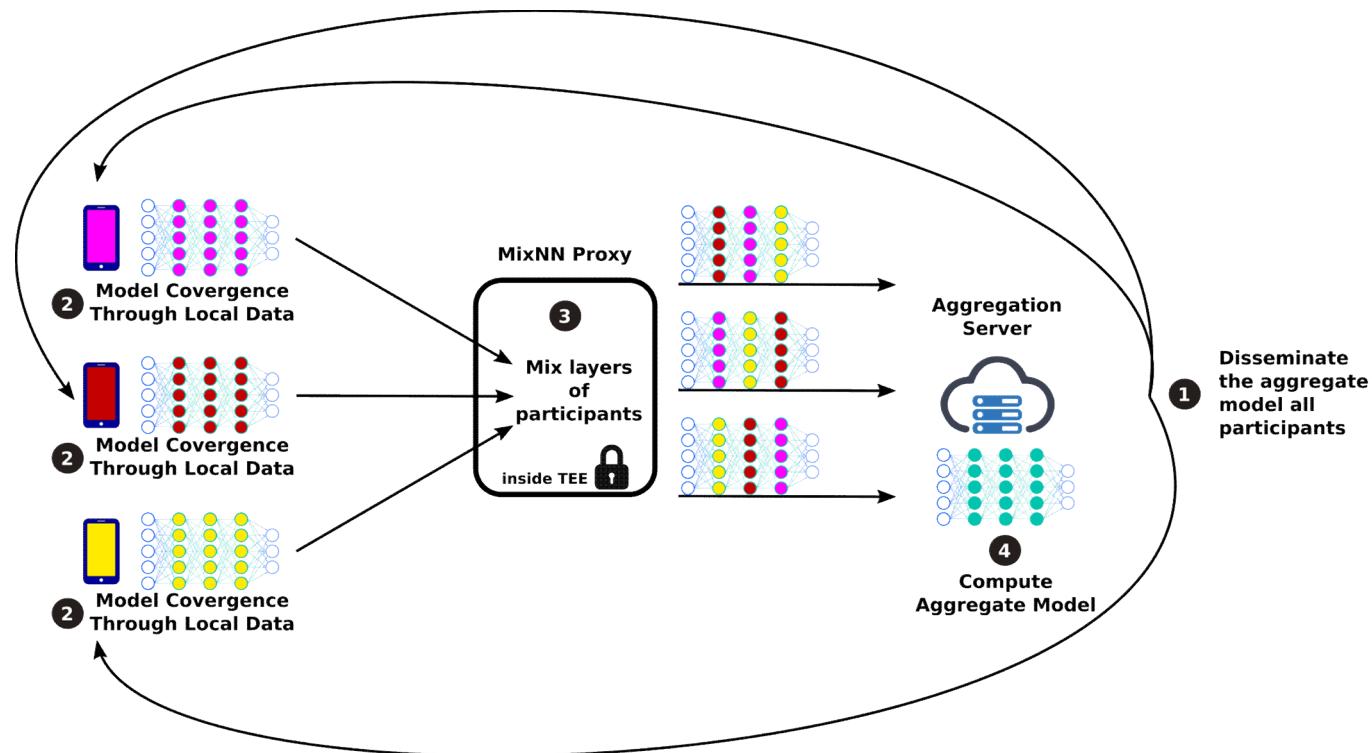
Federated Learning

- 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

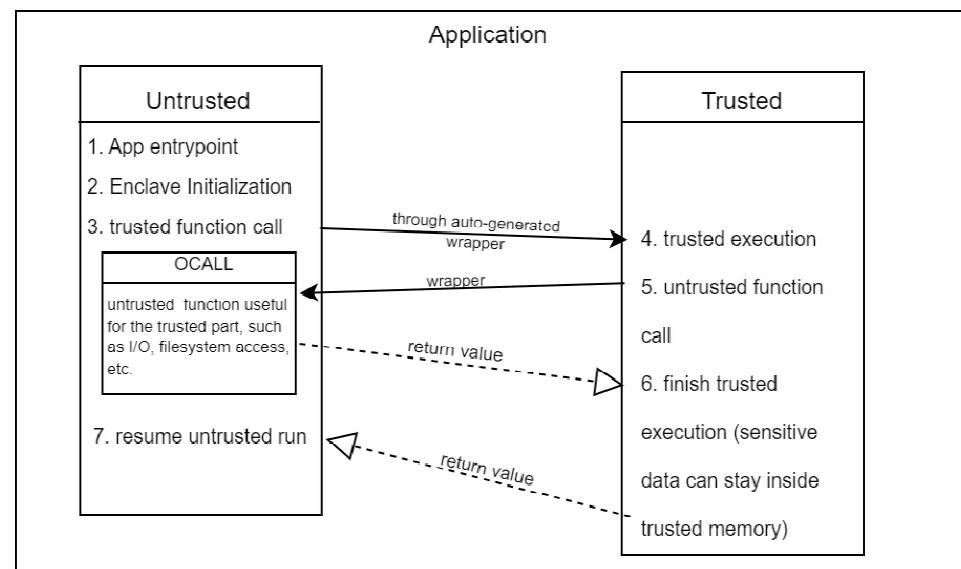
Tutorial introducing SGX

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

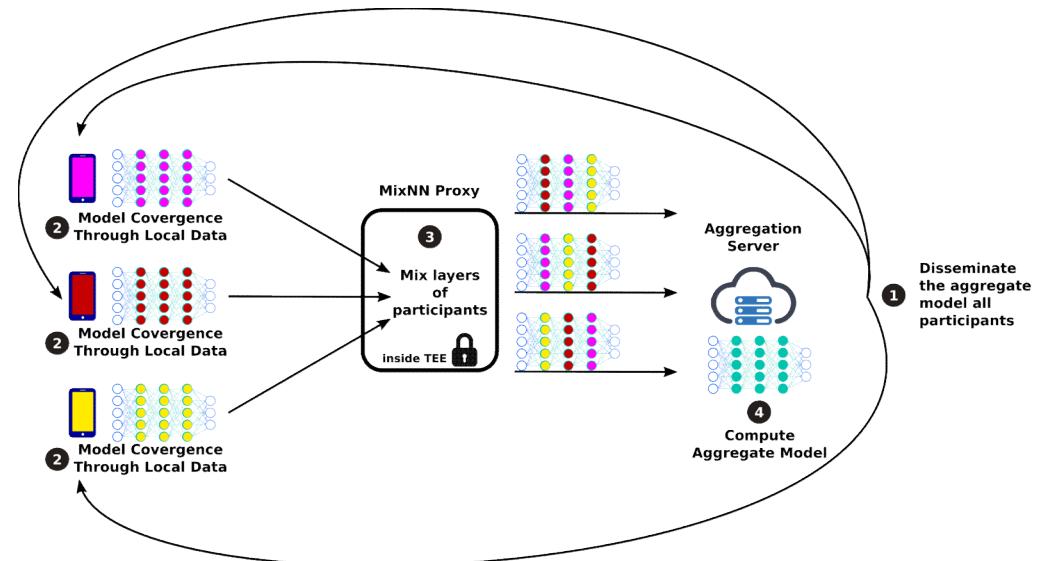
Multi Threading

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

Tutorial introducing SGX

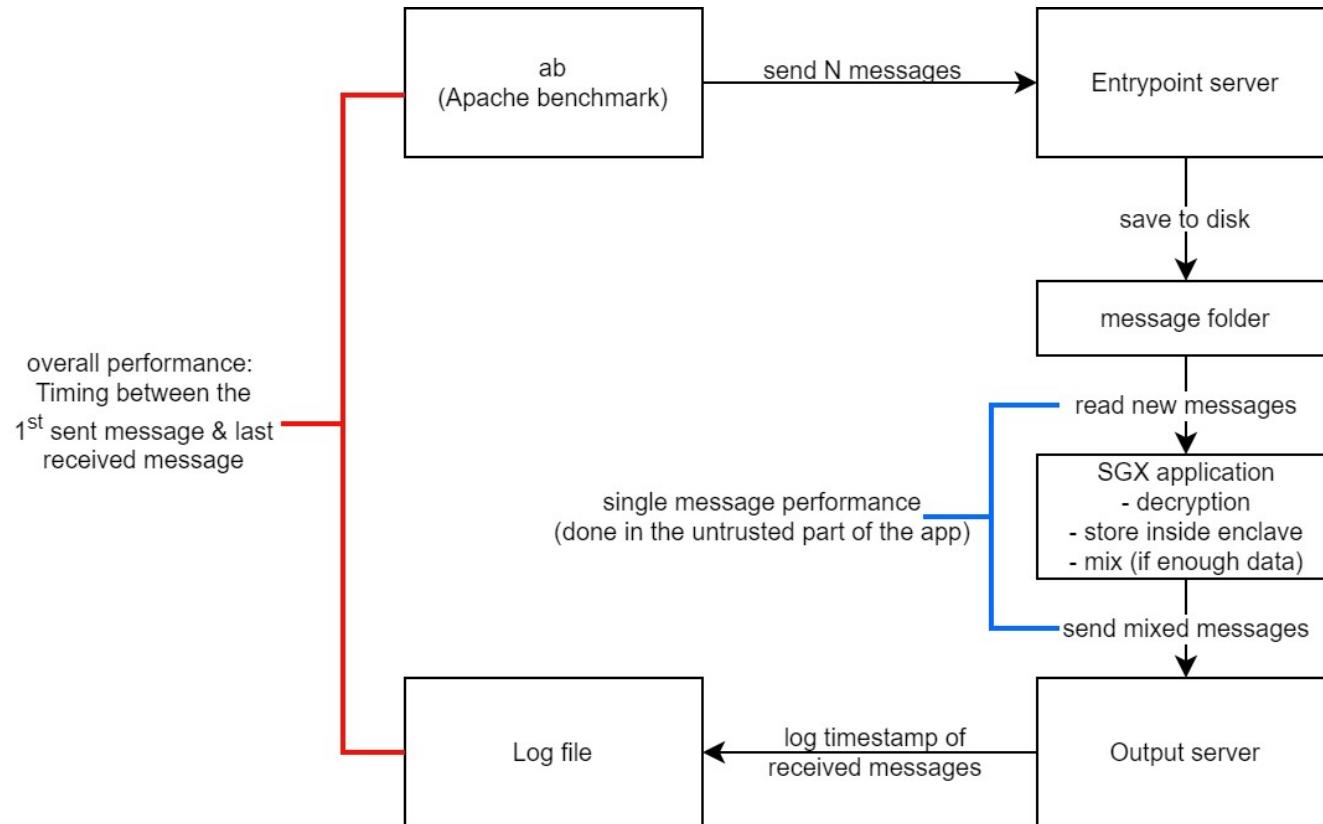
Implémentation MixNN

- 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 shows the GitLab interface for the project "sgx-basics". The sidebar on the left contains links for Project information, Repository, Issues (0), Merge requests (0), Security & Compliance, Deployments, Packages and registries, Infrastructure, Monitor, Analytics, Wiki, Snippets, and Settings. A "Collapse sidebar" button is at the bottom of the sidebar.

The main content area shows the project details: "sgx-basics" (Project ID: 40034), 13 Commits, 1 Branch, 0 Tags, and 348 KB Project Storage. It features a commit titled "crypto in untrusted part" by Adrien Baud, dated 3 months ago. Below the commit is a navigation bar with "master" selected, a search bar, and buttons for Find file, Web IDE, Download, and Clone. There are also buttons to Add README, LICENSE, CHANGELOG, CONTRIBUTING, Set up CI/CD, and Configure Integrations.

A table lists the project's files and their last commits:

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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Secure and Extensive Personal Data Management Systems with SGX

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

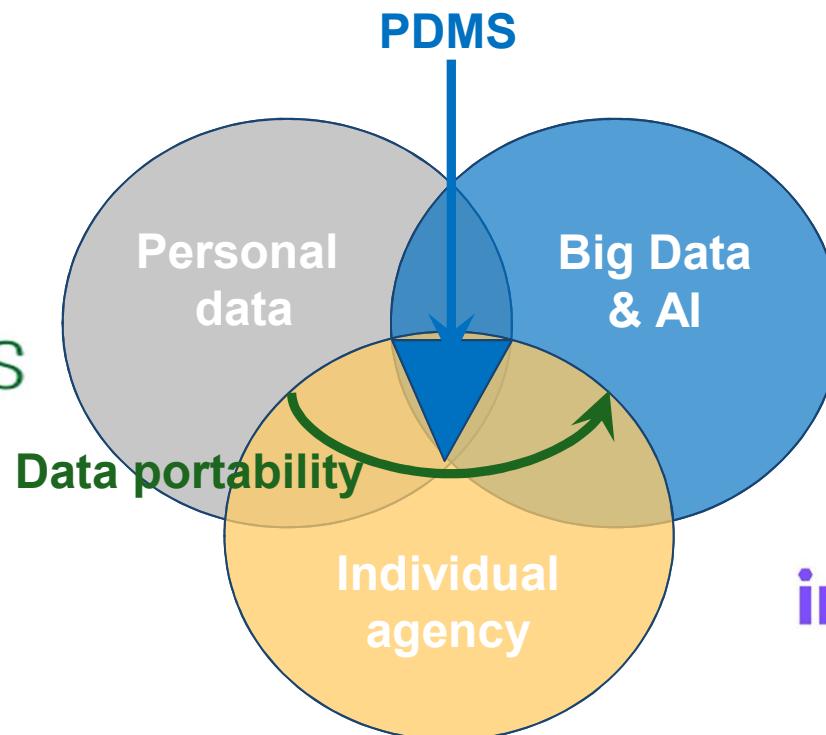
Act I: the right to Data portability

... the right to retrieve its own data



Act II: Personal Data Mgt Systems (PDMS)

... the tool to manage its own data



Personal Data Management Systems

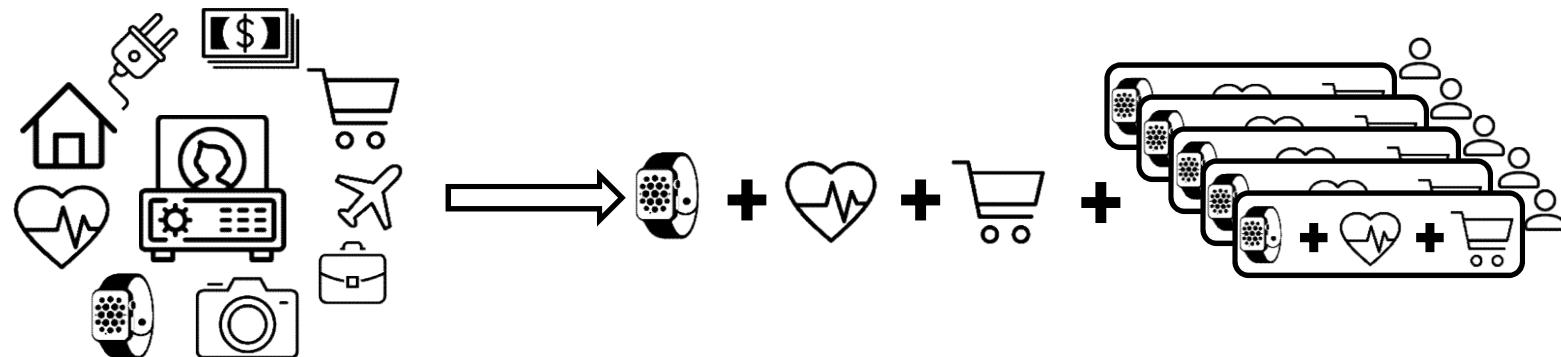
Solutions to gather the digital life of an individual

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

Boosted by regulations such as Data Portability (GDPR)

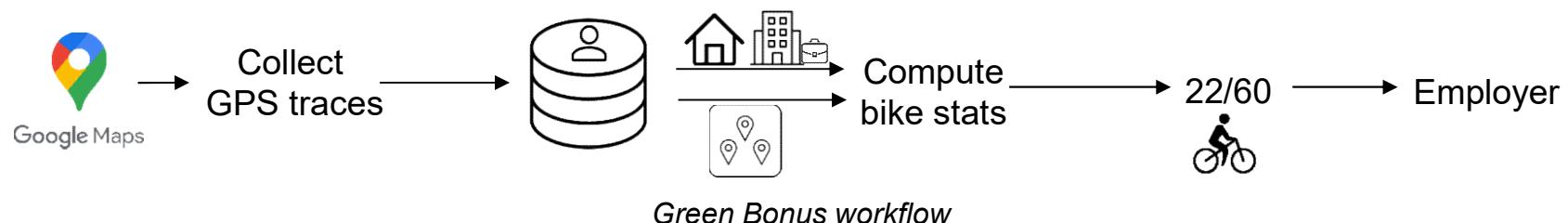
Crosses data from multiple data sources and/or multiple users

Promising paradigm : computation comes to data



Examples of PDMS related use-cases

Companies want to reward employees commuting by bike



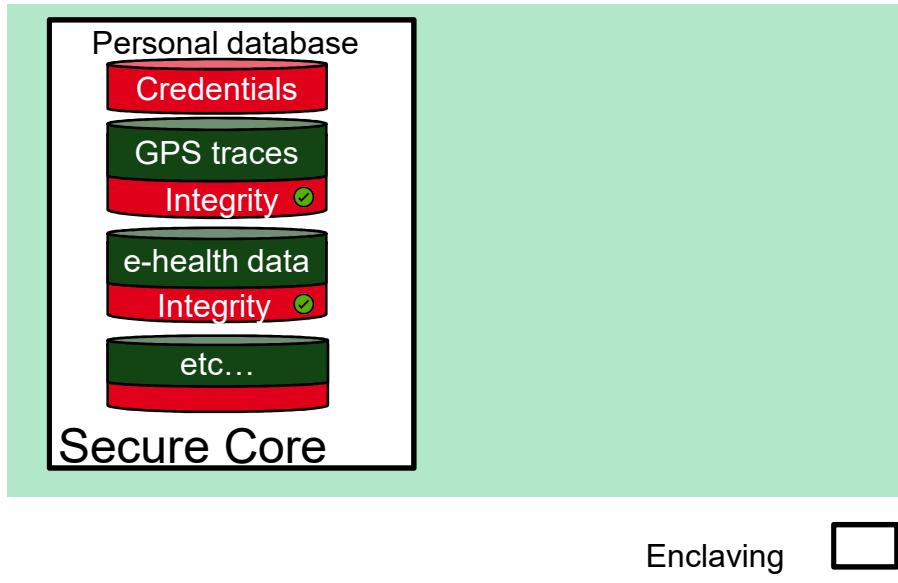
Citizens wants to get a quotation from a new health insurance company



Such use-cases require

- Privacy
- Verifiability
- Extensibility

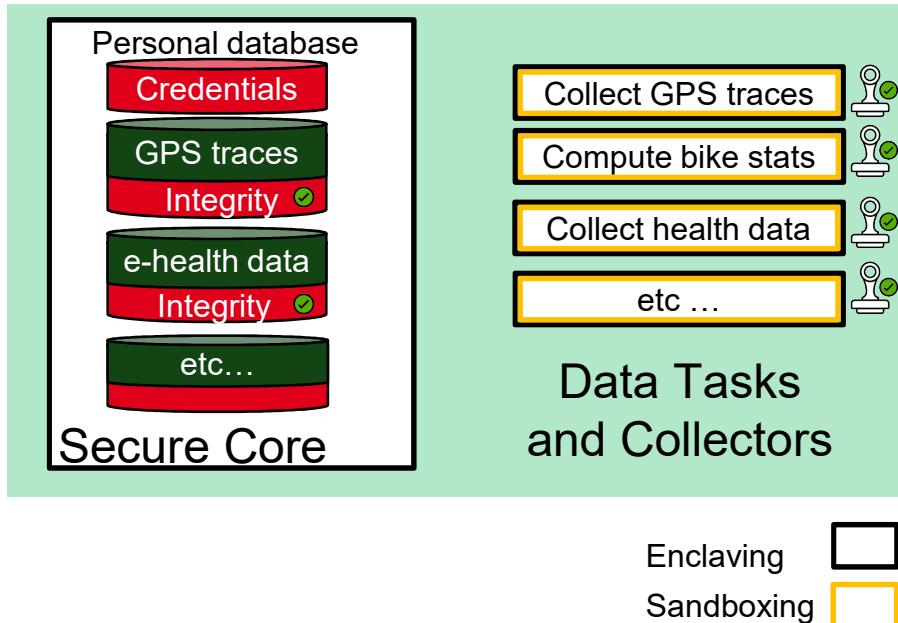
PDMS architecture leveraging SGX enclaves



Elements & Properties

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

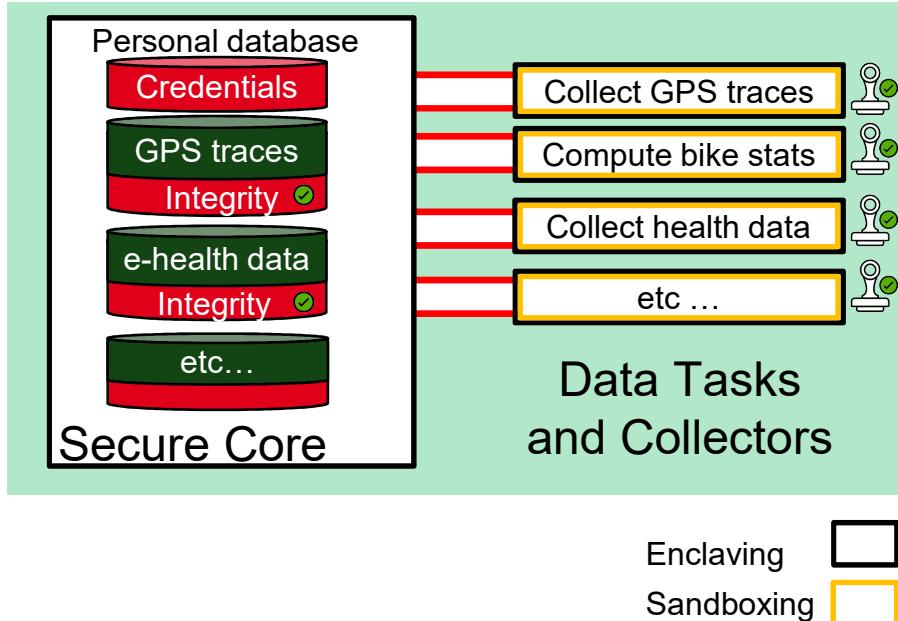
PDMS architecture leveraging SGX enclaves



Elements & Properties

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

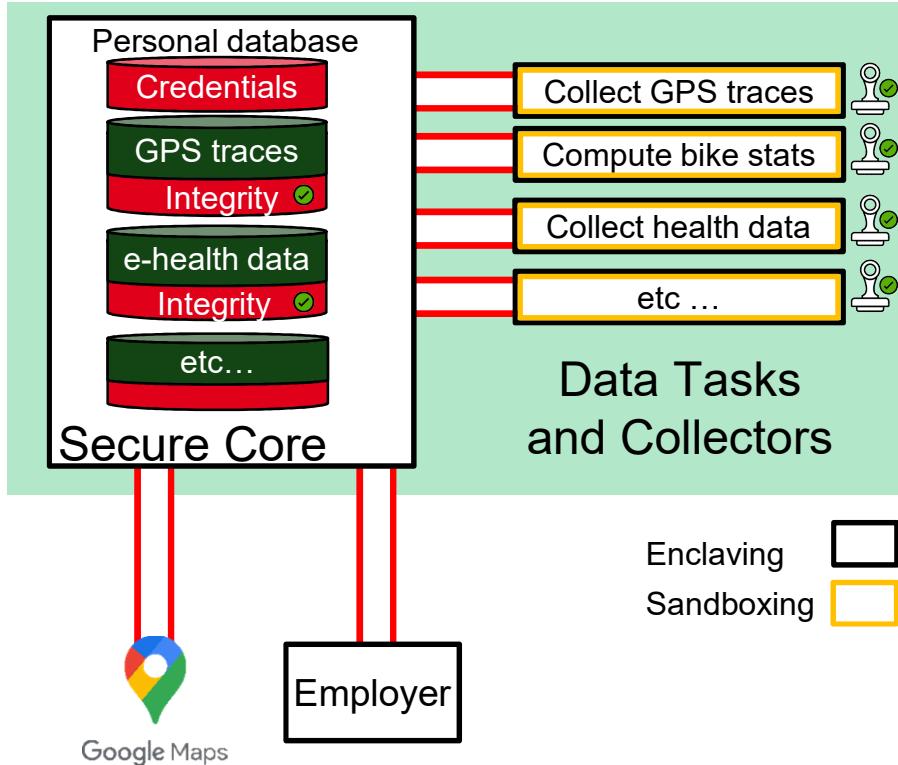
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- **Secure communications**

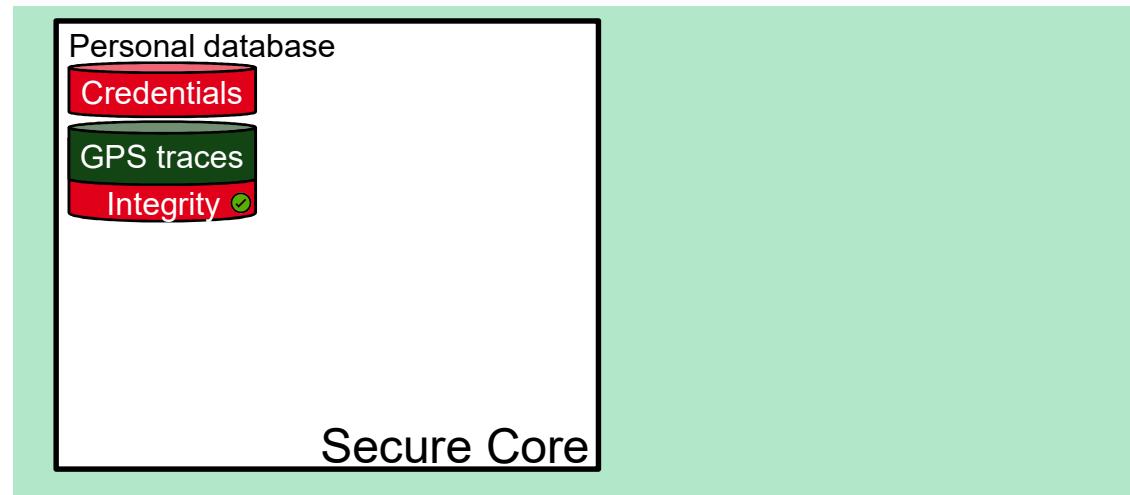
PDMS architecture leveraging SGX enclaves



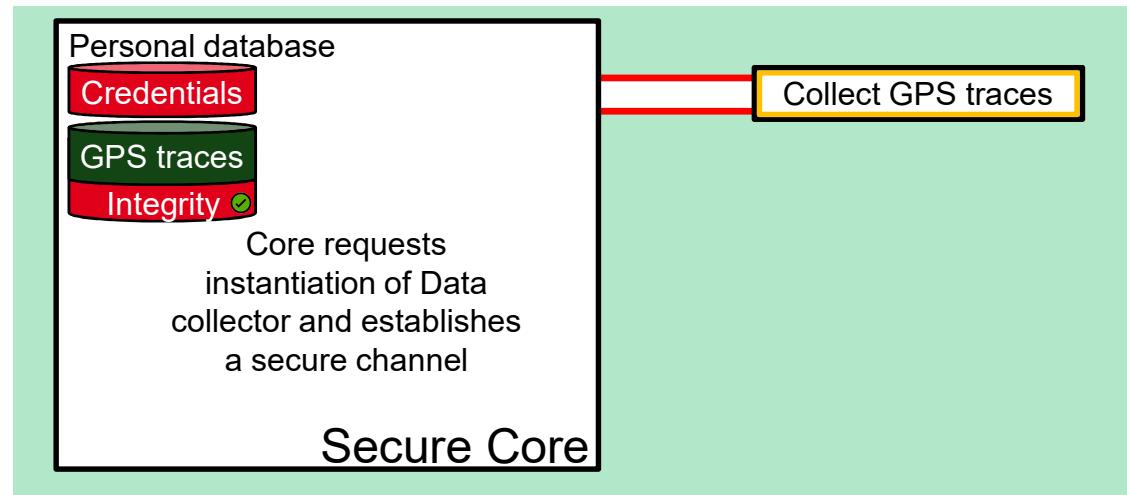
Elements & Properties

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

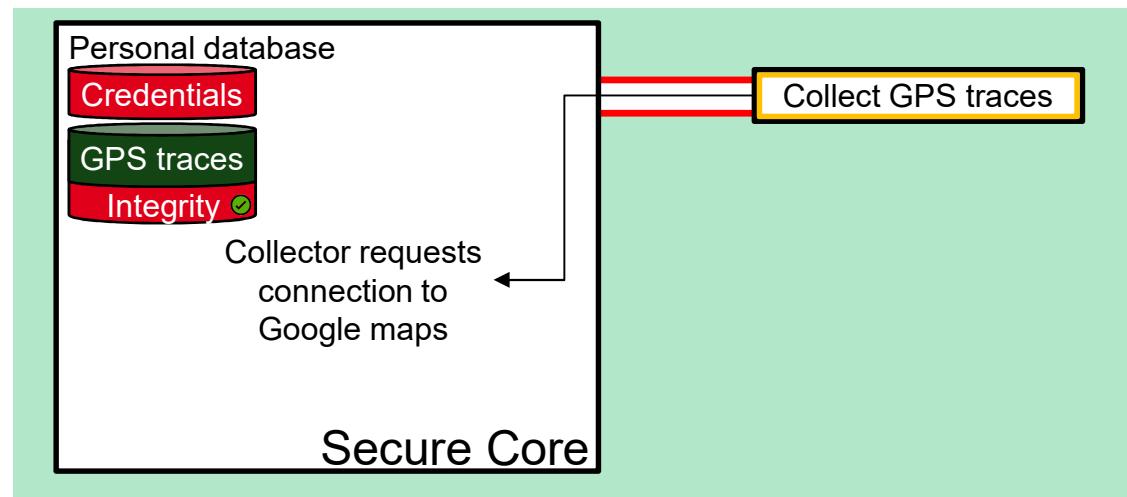
Data collection



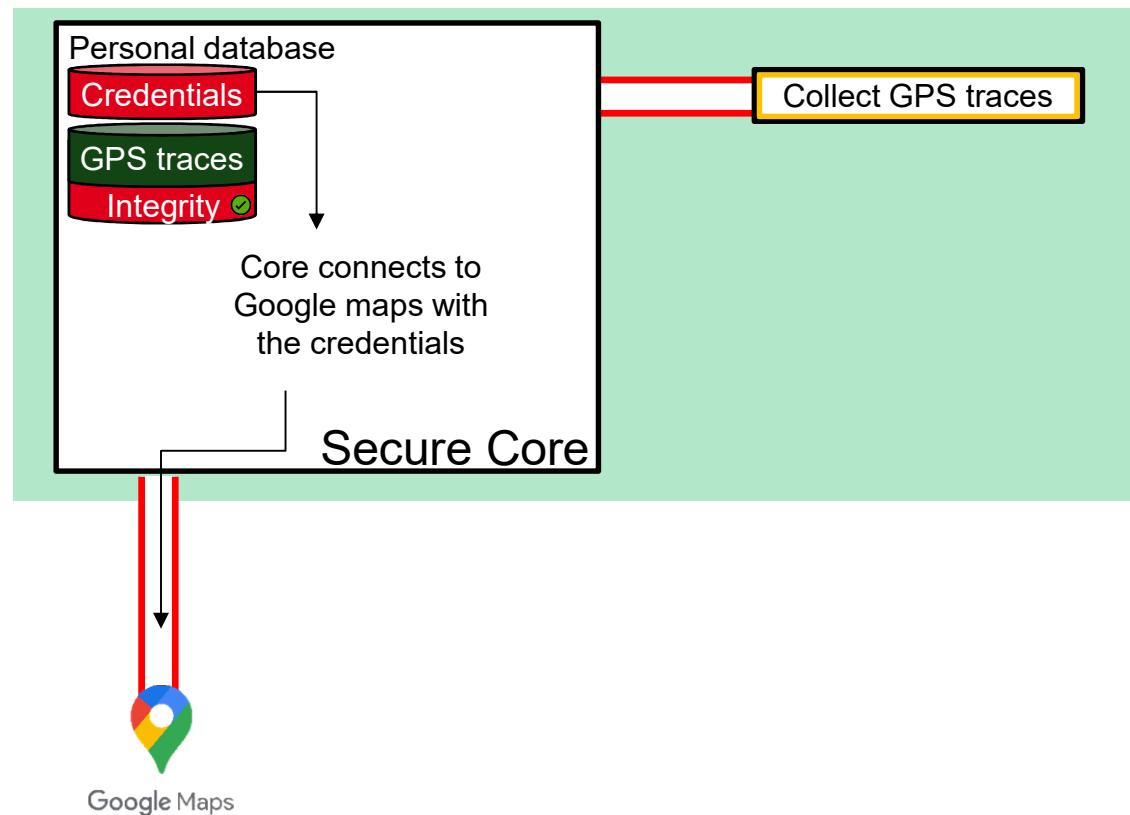
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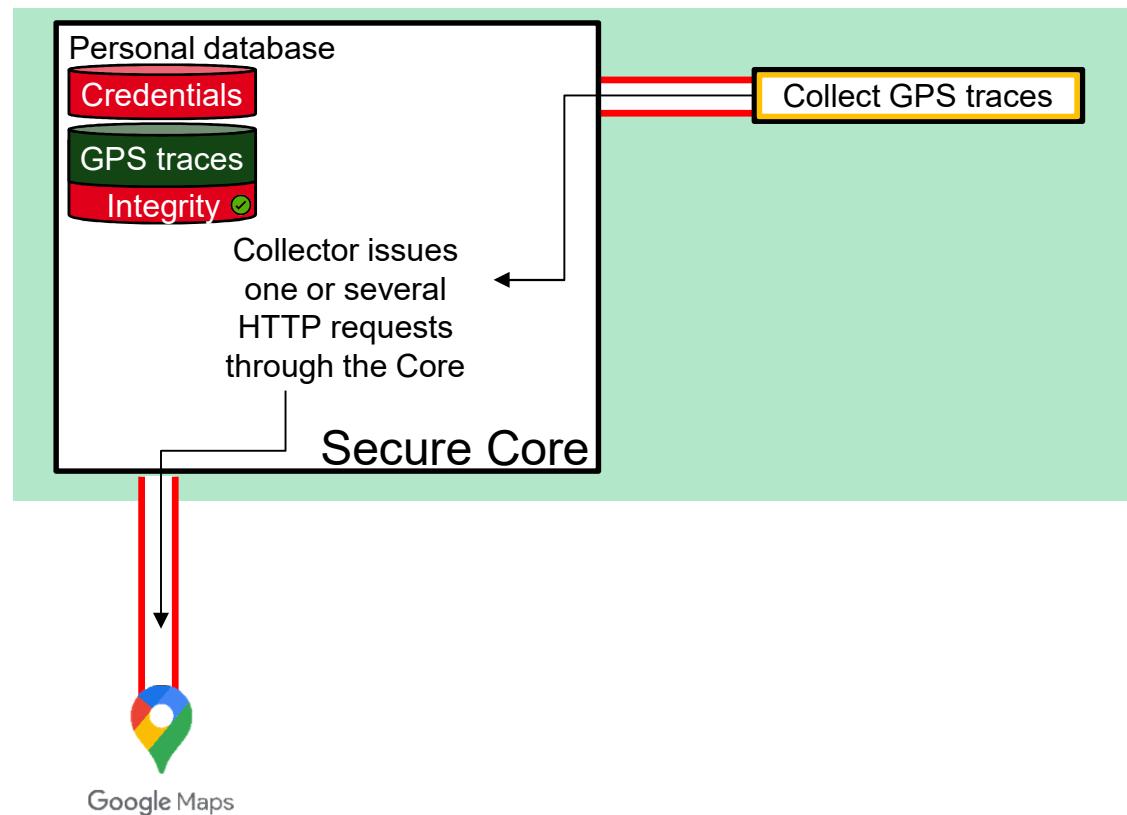
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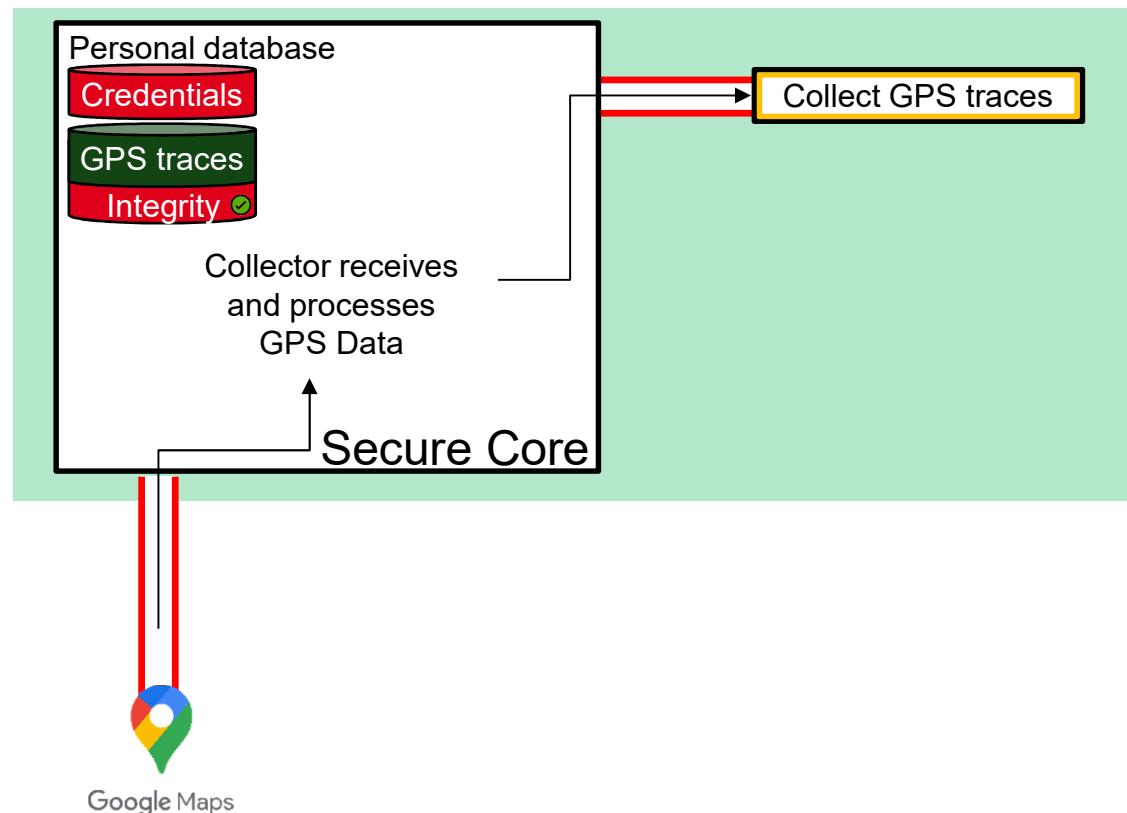
Data collection



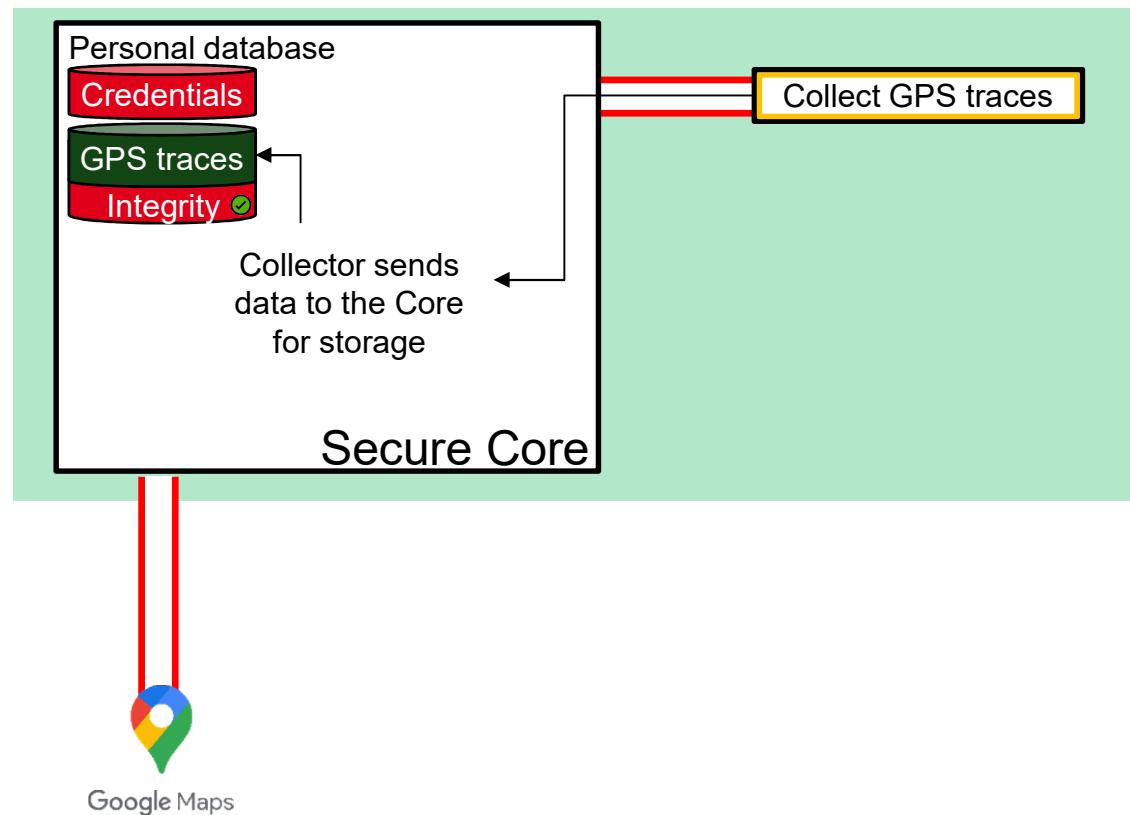
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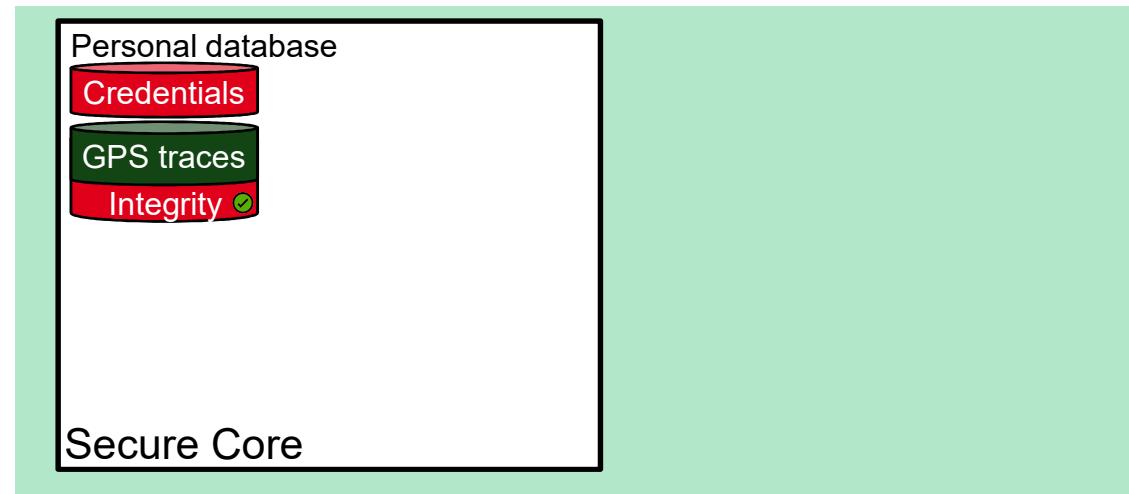
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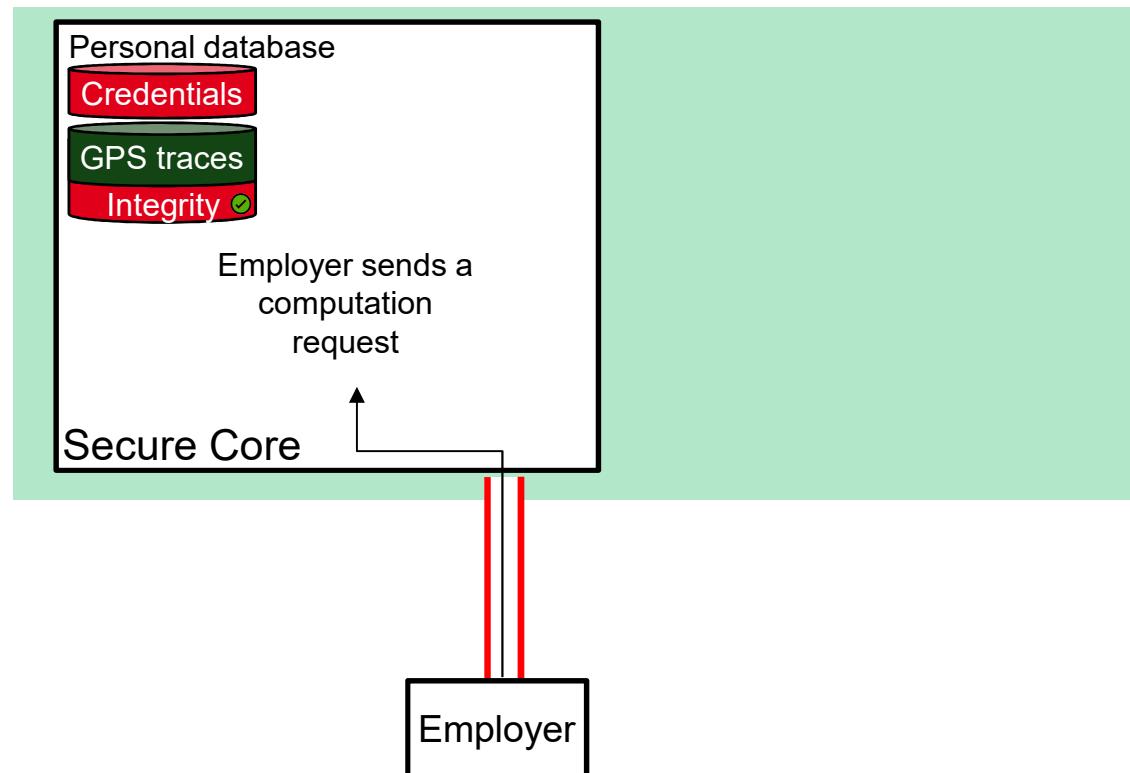
Data collection



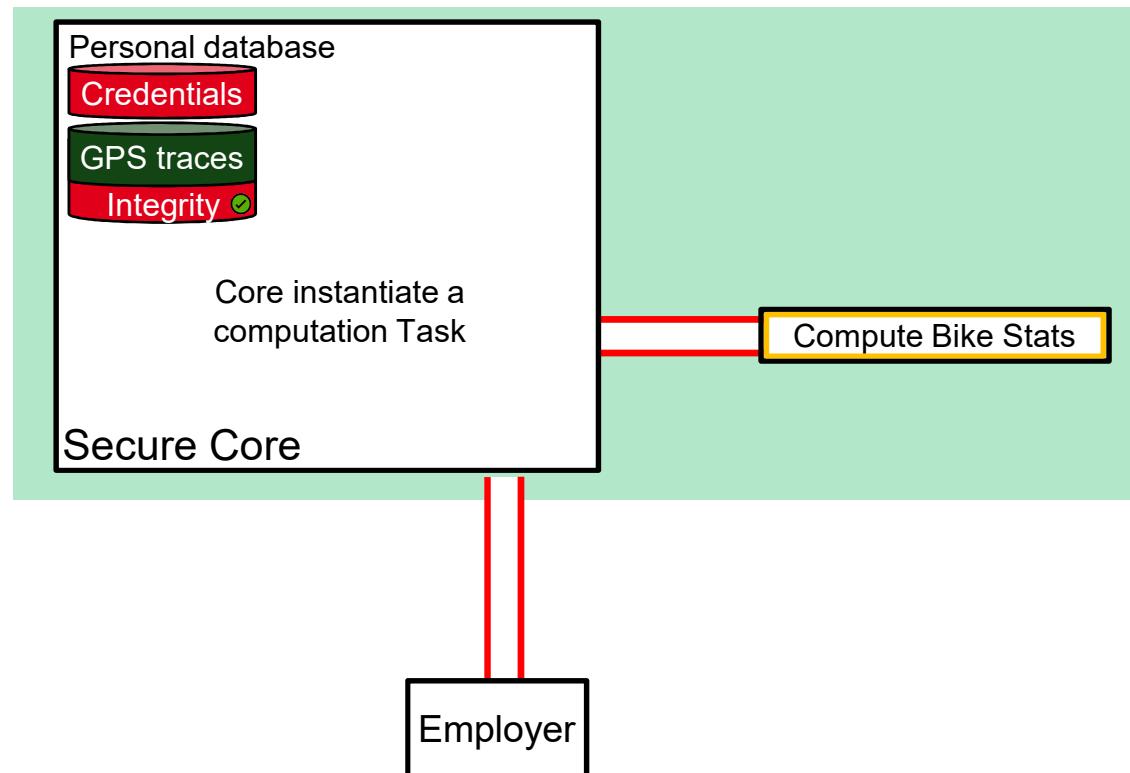
Data computation



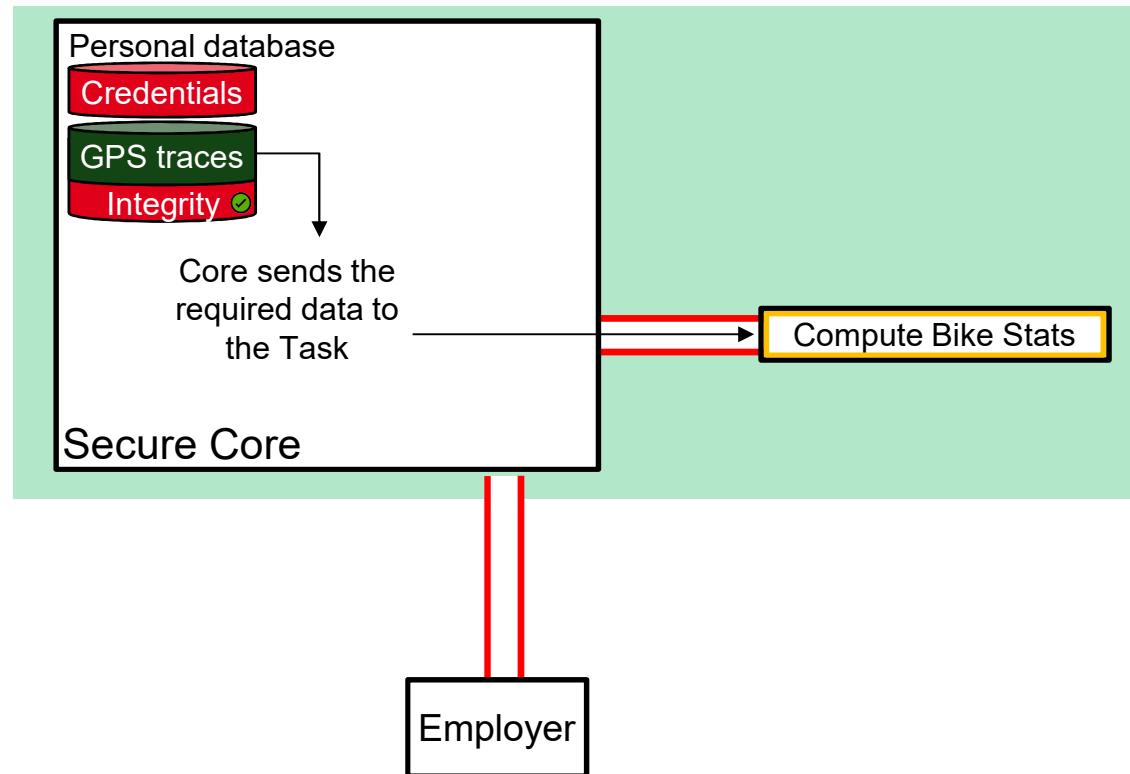
Data computation



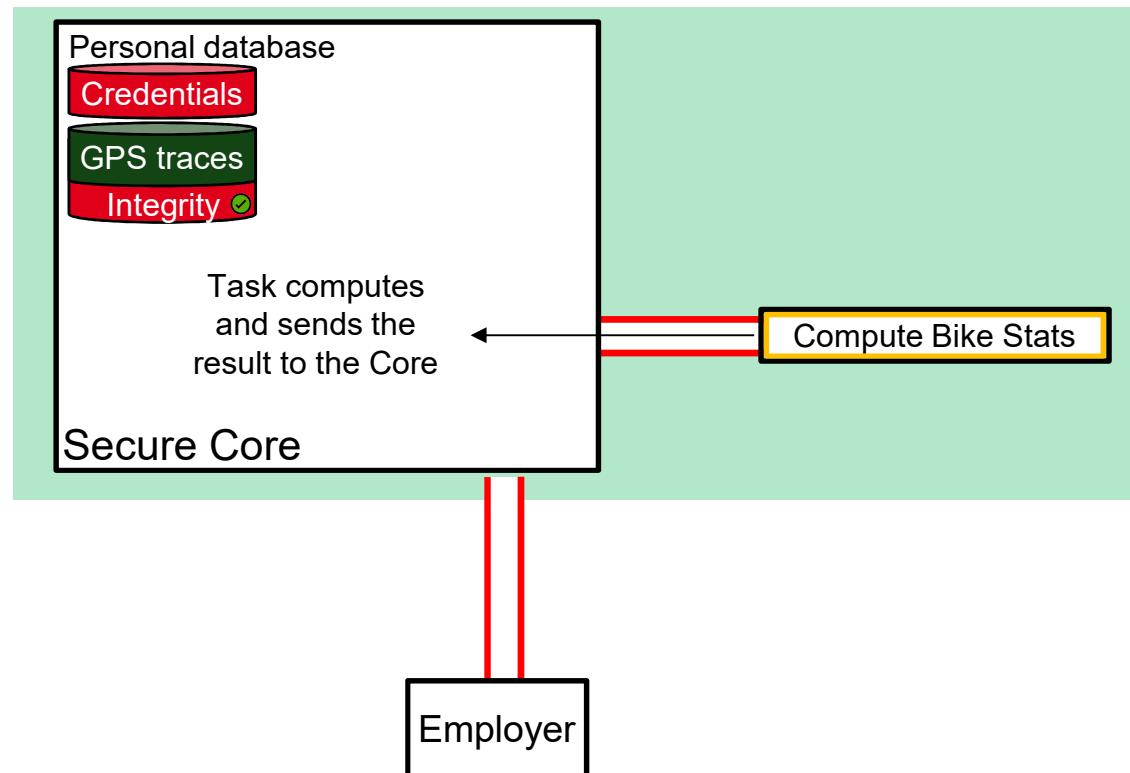
Data computation



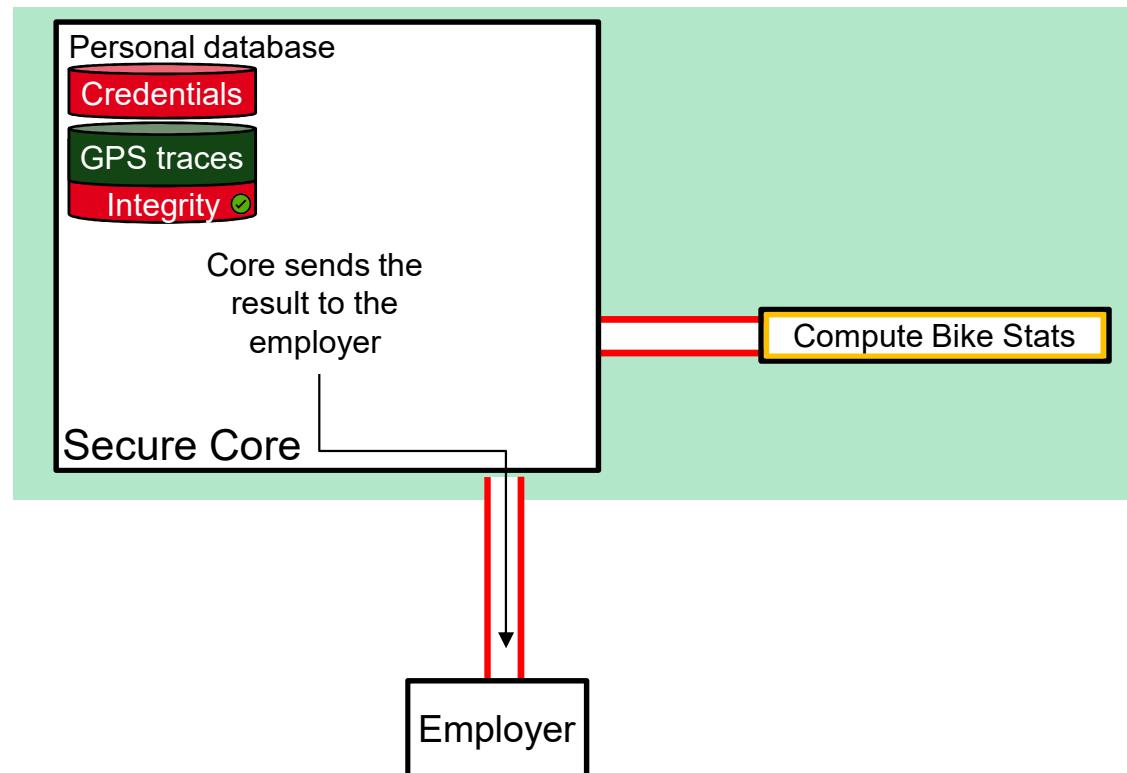
Data computation



Data computation



Data computation



Prototype PDMS on SGX ☐ project.inria.fr/espdm

SGX-ES-PDMS Administration Scenarios

ES-PDMS Controls Admin Platform

ES-PDMS Controls

Manage the platform.

ES-PDMS State Machine

Host is running

Core is running

Initialize host Start Core Stop

Http Server

Http server is running

Start Stop

Prototype PDMS on SGX □ project.inria.fr/espdm

Prototype PDMS on SGX ☐ project.inria.fr/espdm

The screenshot shows the SGX-ES-PDMS application interface with three main panels:

- CORE Panel (Red Border):** Displays log messages related to TLS connections and data exchange between the Core and Data Collector.
 - 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 Panel (Yellow Border):** Displays log messages related to data collection tasks.
 - COLLECTGPS 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 Panel (Grey Border):** Displays log messages related to an incoming HTTPS request.
 - 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

Prototype PDMS on SGX ☐ project.inria.fr/espdm

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/espdm

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**

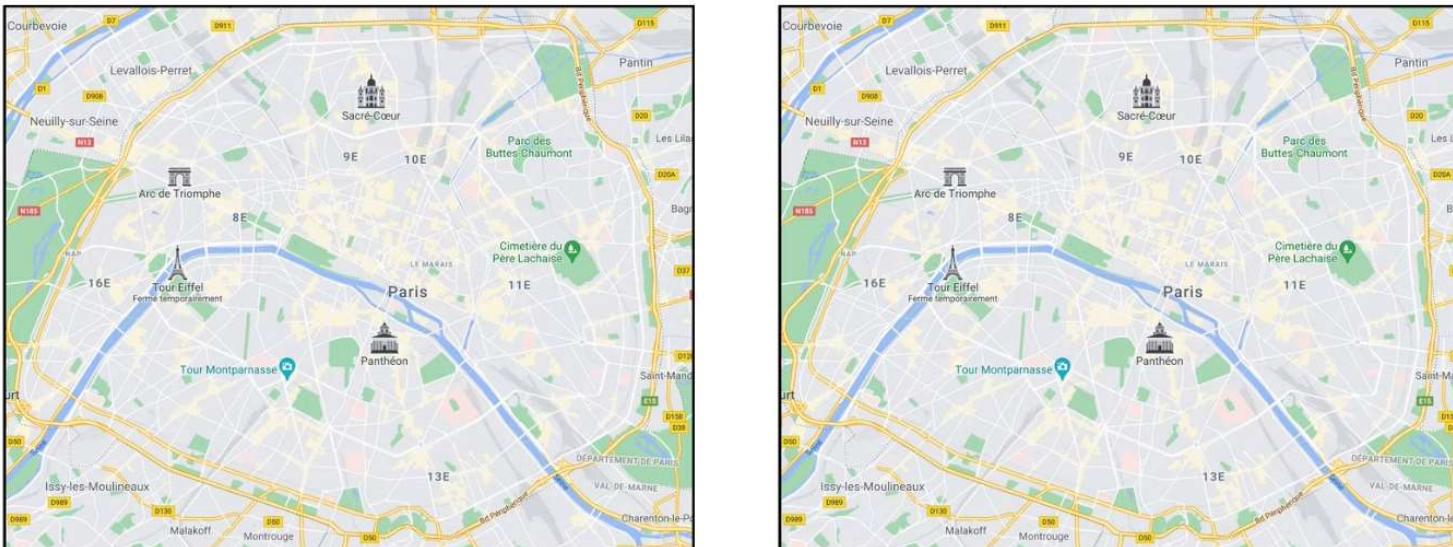
Note that:

- A POI is encoded on two 24 bits numbers
- POIs are highly sensitives 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 ?



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