

## Exploring Operating System Mechanisms for Practical and Resilient Confidential Computing

**Background.** Cloud computing underpins critical services in healthcare, finance, and AI. Yet, it faces a constant threat of cyberattacks and data breaches. In 2024, these cybercrimes exposed over [280 million records in the US's health sector alone](#). Data breaches are not only financially devastating for the cloud providers hosting customer services, costing up to [\\$4.4 billion in remediation on average in 2025](#), they also erode customers' trust in cloud providers.

To regain trust, cloud providers are now strengthening the security of their own infrastructure and isolating their customers' systems from it to minimize the risk of compromises in their platform from permeating to customers. In the latter case, particularly, providers are increasingly adopting specialized hardware from compute vendors (e.g., Intel, AMD). These are new processors with secure primitives built into the silicon that enable the creation of a secure “bubble” (called a Trusted Execution Environment or TEE) on the platform, where sensitive data and programs can run, even if the rest of the system and even the cloud administrator are compromised. After the initial exploration of TEE designs, the community has settled on the idea of isolating an application along with its complete execution environment, including libraries and supporting software, within a single TEE. This design has helped migrate many applications into TEEs with reduced performance and engineering costs. Especially, it enables cutting-edge workloads such as [large language model inference](#) to be deployed into TEEs without much adaptation.

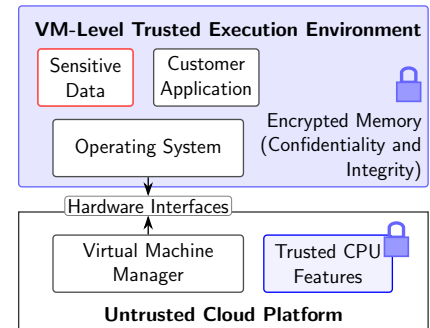


Figure 1: VM-Level TEEs in Cloud Confidential Computing

**New challenges.** The move toward incorporating the operating system into TEEs introduces two new challenges for cloud security. The first key challenge is the huge amount of code being placed inside a TEE, on which the security guarantees for the customer's application and data depend. This code (which is called the trusted computing base or the TCB of an application) includes the operating system, often consists of several [million lines of code](#) and known to have [thousands of vulnerabilities](#) that could be exploited by adversaries to compromise the security of the application within the TEE.

The second challenge lies in exploring how operating system design itself could evolve to better protect customer applications. Traditionally, the operating system's primary task is to efficiently manage resources, particularly facilitating software interaction with hardware devices. The operating system's place within the TEE necessitates a reevaluation of the OS's role, not just as a resource manager, but as a component that actively shapes the security of the TEE. The steps taken during my doctoral studies demonstrated the potential of this direction by exploring how traditional OS's operation, like managing system memory, could be retrofitted into security mechanisms to strengthen TEE's security.

so that its vulnerabilities minimally affect the security guarantees offered to cloud customers. Toward the first challenge, I propose to look at the interface.

In the latter challenge,,

and the opportunity lies in exploring operating system-based mechanisms to address the long-standing security challenges of TEEs.

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to make more robust and practical, building on the observation that the industries' shift toward VM-level TEEs also exposes a golden opportunity: the OS can now actively shape the security of CCC.

At UBC, I will pursue this agenda under the supervision of Prof. *Aastha Mehta*, who has deep expertise in both systems security and OS. I will also enrich this research with perspectives from UBC's researchers, especially systems and cloud computing researchers at Systopia Lab and CIRRUS Lab. Plans for these

collaborations will be detailed in the remainder of this proposal, along with the focuses of my postdoctoral research: *side-channel attacks* and *private data processing*.

**Focus 1: Side-channel attacks.** *Side channels* are a critical yet persistent class of vulnerabilities at the software-hardware boundary of TEEs. They are indirect signals – such as the time difference measured when accessing a memory location – through which an attacker can infer private information. Such attacks are widely acknowledged as a formidable threat to CCC (AWS, Azure, IBM, and Alibaba). Efforts to completely remove side channels often run into roadblocks: some side channels are buried deep in the processor’s internal circuitry, requiring massive hardware redesigns to eliminate; others come from everyday cloud resource management operations, and removing them would impair flexibility.

A more practical, less intrusive approach is to mitigate these side-channels by obscuring side-channel signals from programs. However, current state-of-the-art mitigation techniques fall short; systems such as Klotski and Obelix are complex to adopt as they require developers to rewrite or recompile their entire software. Even when applied, these systems can slow programs by hundreds or even thousands of times. Worse, to remedy the severe performance hit, security trade-offs are often made, but they are ad hoc and lack a sound theoretical basis.

My postdoctoral work will tackle the limitations of previous research from an OS vantage point. I aim to extend the limited prototype of my doctoral research implemented on a minimal OS by incorporating side-channel mitigation into Linux, an OS most widely used in cloud data centers. Also, I plan to explore theoretical models to enable principled trade-offs that enable better performance.

This direction synergizes with the collective expertise at UBC. Primarily, my supervisor, *Aastha Mehta*, with profound experience in side-channel attacks on TEEs and formal models for side-channel defenses, would provide invaluable feedback to the research. Further, the work of userspace memory management by *Margo Seltzer* and *Alexandra Fedorova* will play an essential role in making the side-channel mitigation technique using memory management practical in a complex OS such as Linux. The large TCB of commodity OSes also makes side-channel elimination particularly challenging – it requires tracking potential leaks across millions of lines of code. To this end, the study of cross-system *information flow tracking*, pioneered by *Margo Selter* and *Thomas Pasquier*, will make it a tractable problem.

**Focus 2: Private data processing.** A common scenario for CCC deployments is *private data processing* involving multiple stakeholders, as shown in **Table 1**. For instance, companies like *23andMe* provide personal health data analytics as a cloud service. Its users upload private data to the service’s server, which runs a health analytics program on the data and returns the results to the user. The service must handle users’ personal data carefully – this is, while mandated by regulations like *GDPR*, often not trusted by users. A dilemma arises: On the one hand, the user wants to verify that the service is using their data responsibly, for example, never giving it to third parties. On the other hand, to prove this, the service must publicize its data processing to users for verification, which might contain trade secrets.

Stakeholder	Sensitive Asset	Security Interest
Service users	Personal data	Ensure data confidentiality
Service providers	Proprietary data processing	Keep trade secrets confidential

Table 1: Representative private data processing stakeholders, and their assets and interests.

To resolve this *conflict of interests*, existing deployments employ a mediator in a TEE, which is trusted by both service users and providers (**Figure 2**). The service provider first sends the data processing program to the mediator, trusting it to keep the program secret. Similarly, the users provide personal data without needing to examine the program. On users’ data, the mediator now runs the service provider’s program in a way that strictly maintains the confidentiality of users’ data.

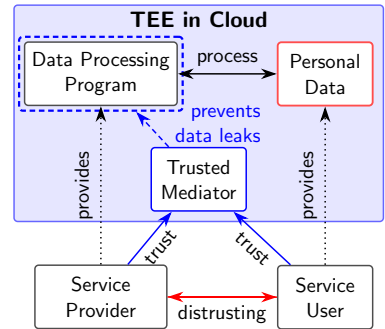


Figure 2: How CCC resolves stakeholders’ conflicts

Unfortunately, most research prototypes addressing this challenge fail to introduce a deployable solution. Recent solutions like [PAVE](#) and [Erebor](#) achieve security by placing the program inside a sandbox. The sandbox enforces strict information flow control on the program, for instance, preventing it from saving personal data to a file or communicating with other programs. As a result, this approach severely limits flexibility and compatibility with many workloads, especially complex ones and ones involving cooperating programs.

My proposal looks to incorporate a trusted mediator into the OS to improve usability. This is achieved through dynamic information flow tracking, a common technique in OS research. Using this, the mediator would prevent only the point at which sensitive data is about to be extorted, while allowing benign file accesses and network operations. Thus, the private data processing system would be compatible with a wide range of cloud workloads. I envision that whole-system information flow tracking expertise from *Margo Selter* and *Thomas Pasquier* will be of tremendous help. Scaling the trusted mediator design across cloud machines would also require distributed cloud computing expertise, which I plan to employ the help of *Mohammad Shahrads* from the ECE department.

# **1 Appendix: Guide (REMOVE IN FINAL)**

The proposal should be written in clear, non-technical language that allows a non-specialist to comprehend the overall content and importance of the work. Members of the Killam Postdoctoral Fellowships and Prizes Committee are from abroad range disciplines and may not have expertise in your area of study.

Although the fellowship may be used to extend or expand upon doctoral work, it must be made clear that you are not intending to use the award to wrap up a thesis. While it is expected that a postdoctoral fellow will be taking the next step beyond the PhD thesis, you must differentiate clearly between the postdoctoral project and the thesis research. Feel free to include hyperlinks to provide links to additional information.

As applicants must make UBC their base, it is important – particularly for applicants whose primary research materials are elsewhere – to indicate what travel is involved, to where, and for how long. You should describe how you will deal with the remoteness of the primary materials.

The adjudication committee is very interested in “fit” with the selected UBC department or unit and the university’s research programs. You must provide information on how your research relates to that of specific campus programs and advisors. If a colloquium is envisioned, a possible title should be proposed. If you will visit in classes, please suggest which ones. Since inter-disciplinarity is often a valuable dimension (the Killam Trusts declares that a candidate shall not be “a one-sided person”), specific details on proposed inter-departmental connections are welcome.