Wallet

Confidential Serverless Computing

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USENIX NSDI 2026

Serverless computing

More than **50%** of cloud customers use serverless functions[1]

[1] https://www.datadoghq.com/state-of-containers-and-serverless/

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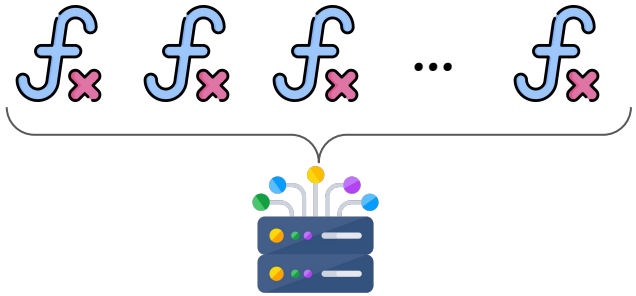
Thousands of functions deployed on shared hardware[2]



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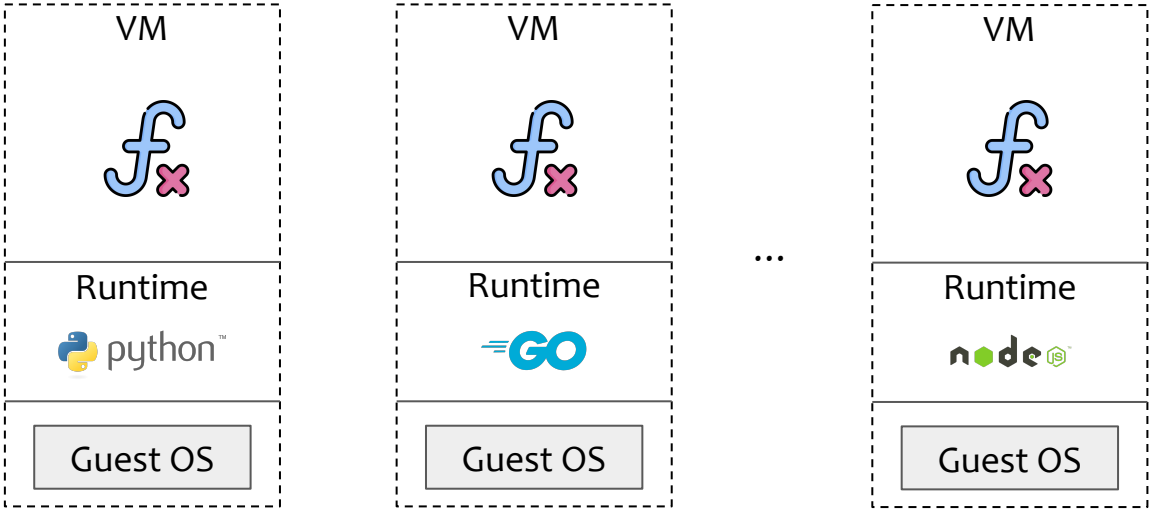
[2] https://www.amazon.science/publications/firecracker-lightweight-virtualization-for-serverless-applications

Trust issues in the cloud



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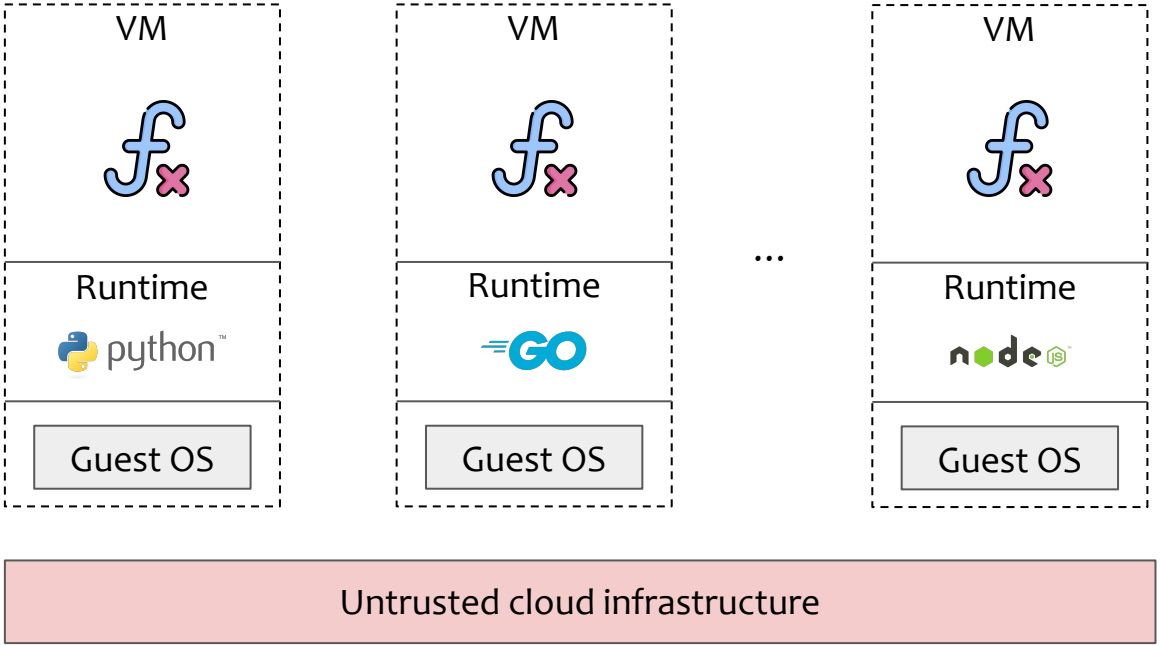

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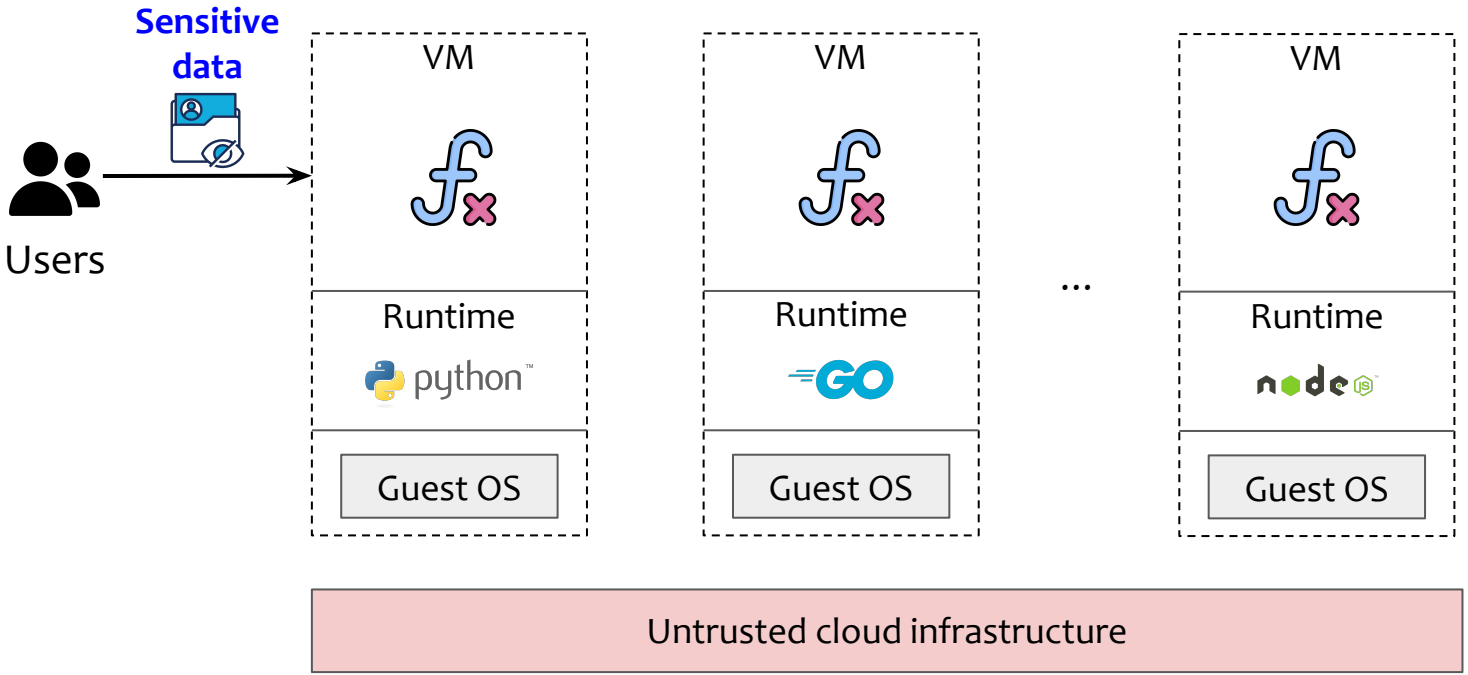

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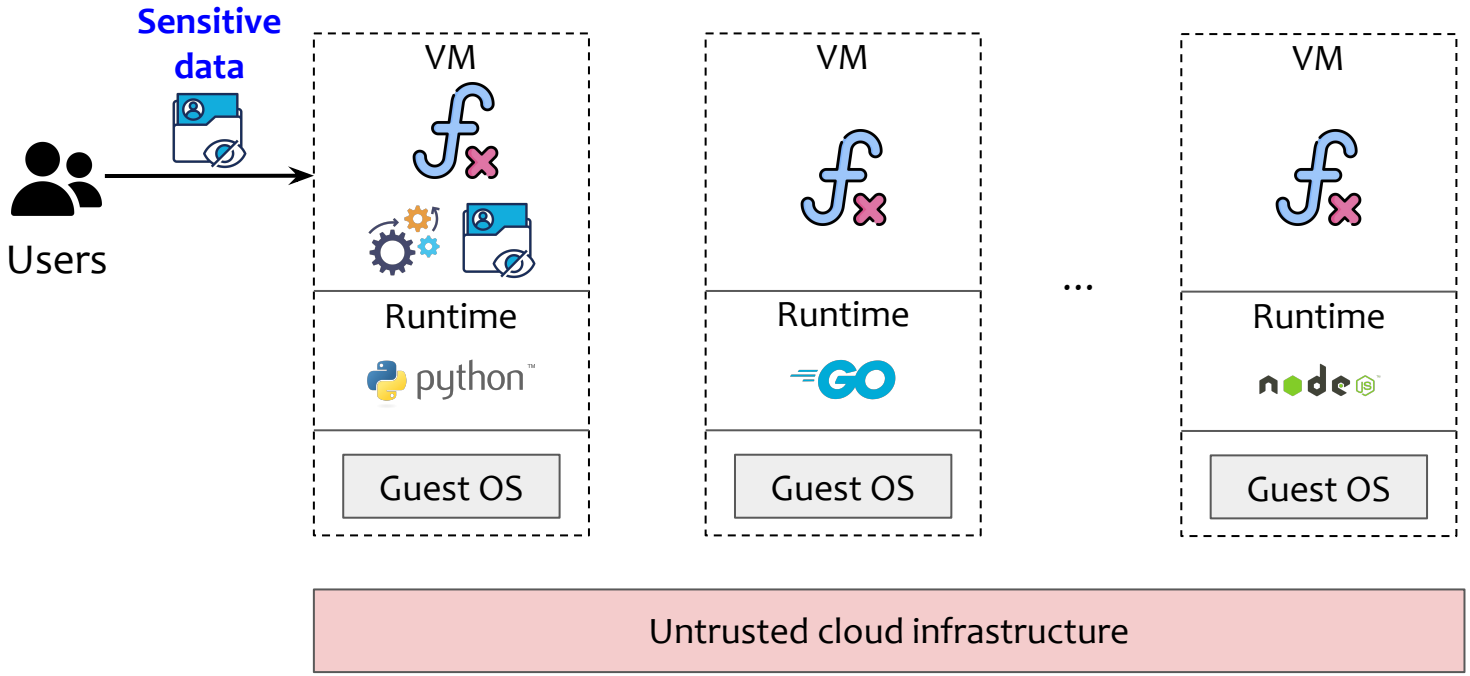

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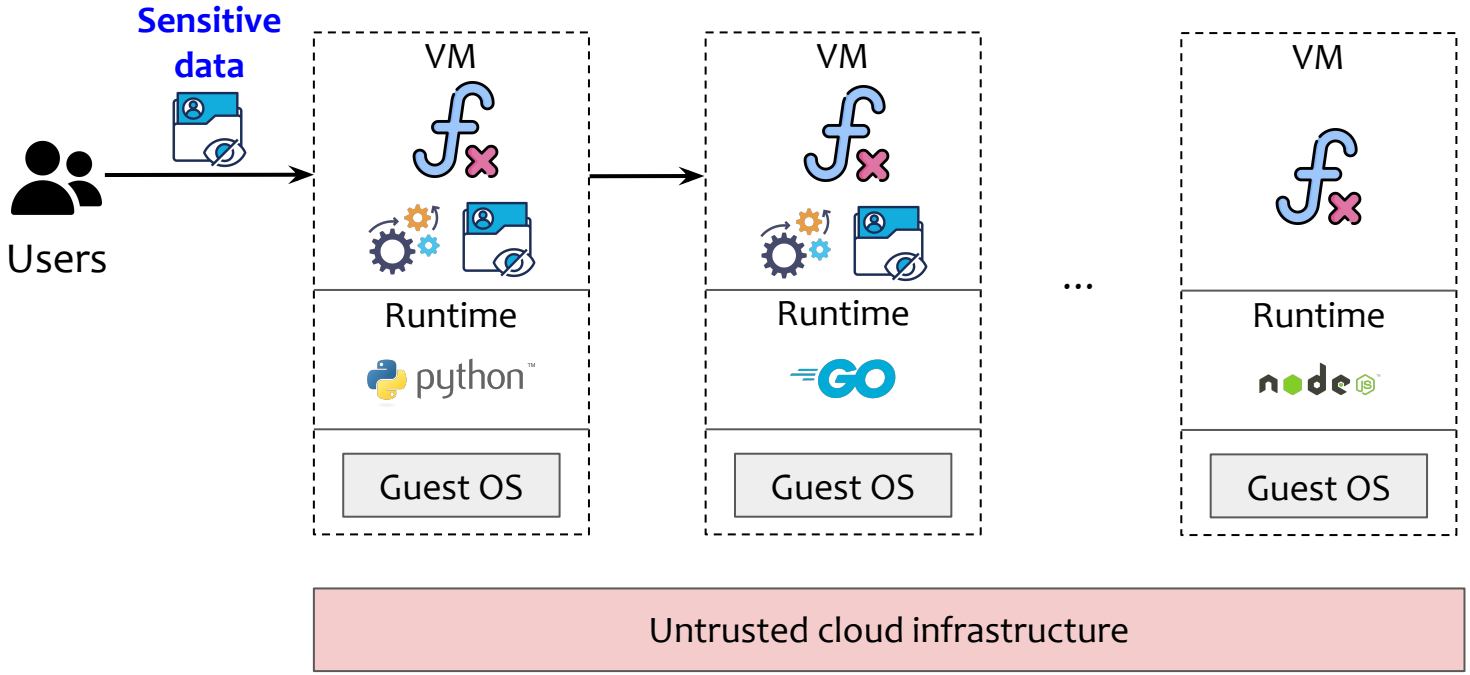

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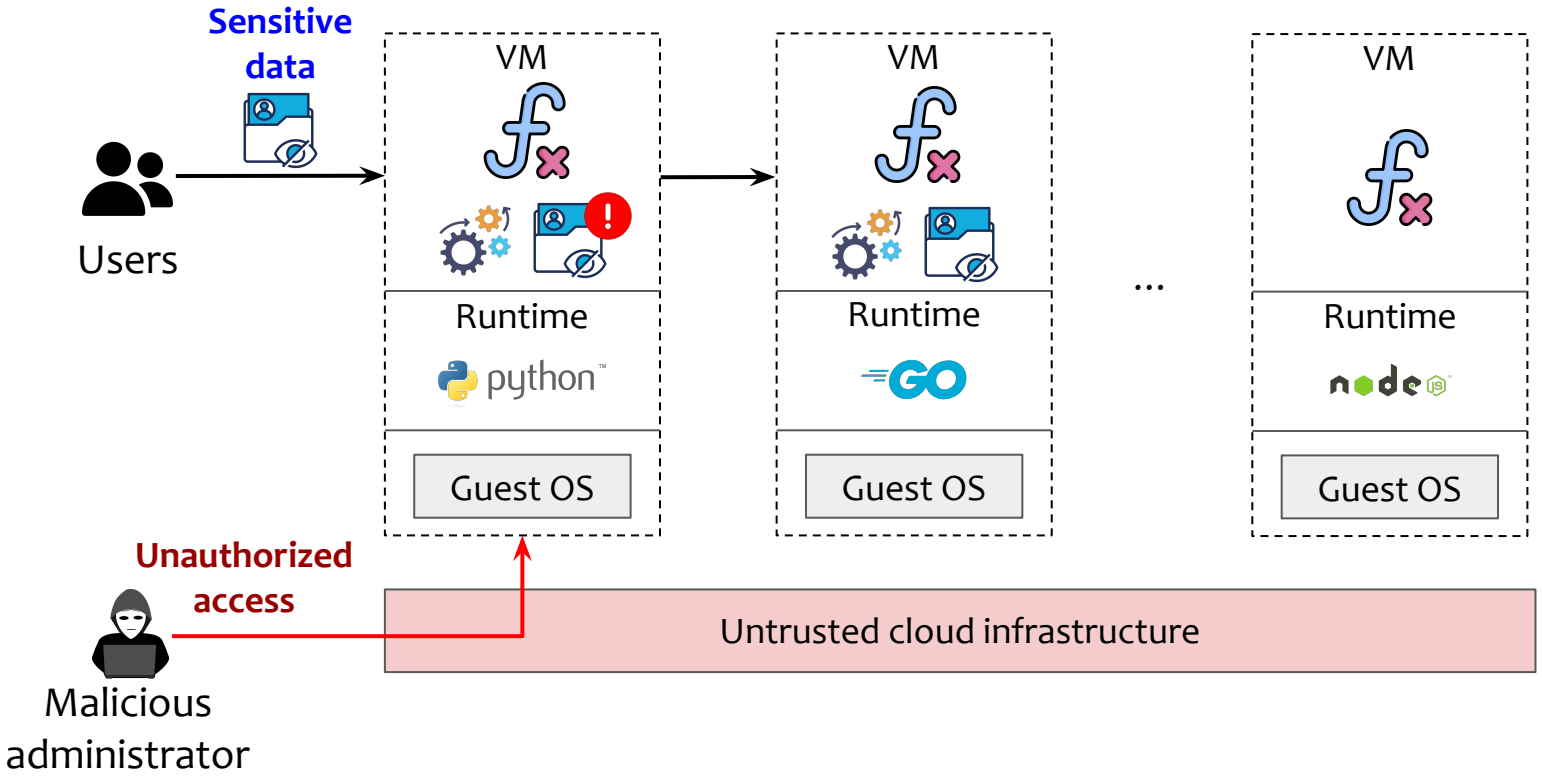

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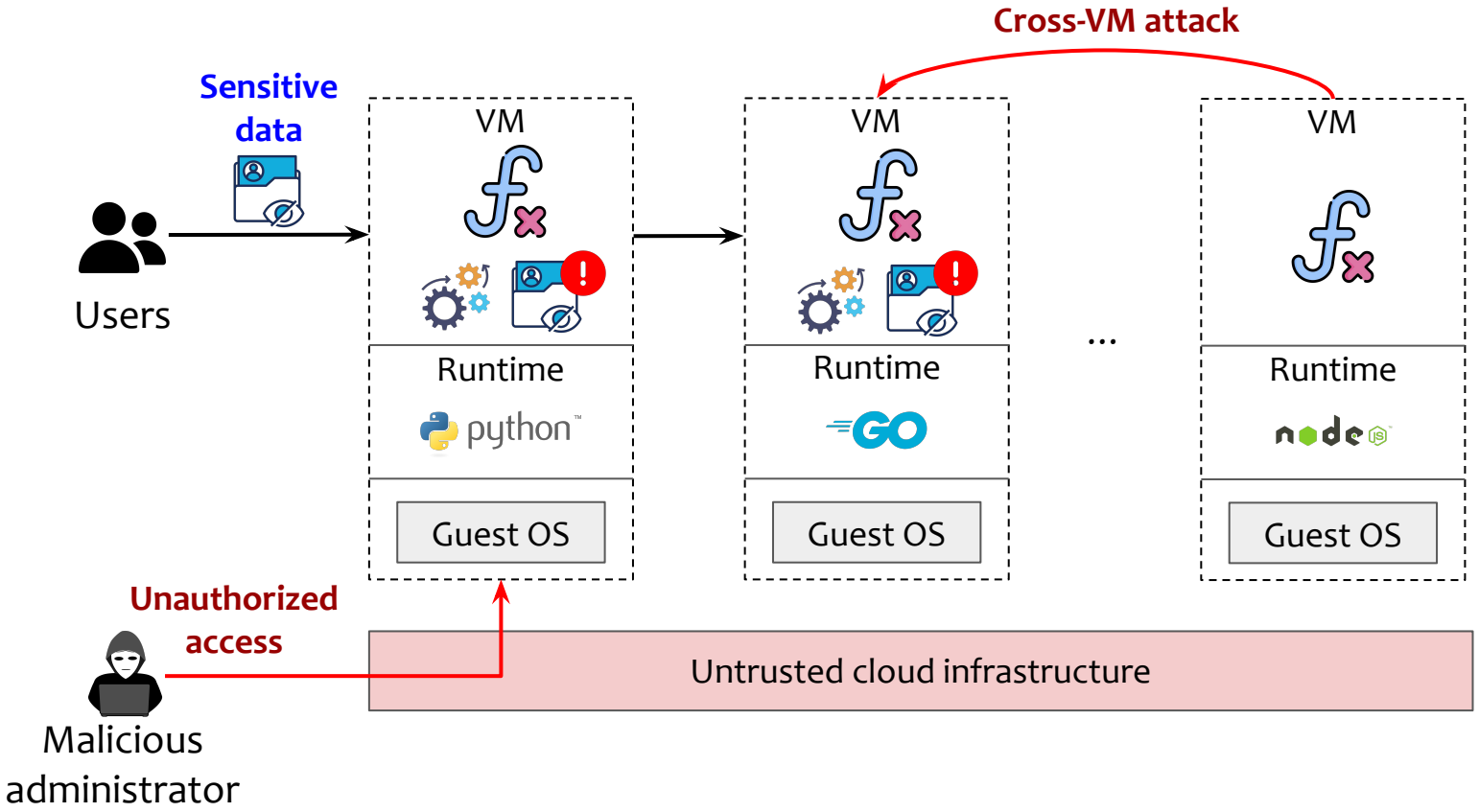

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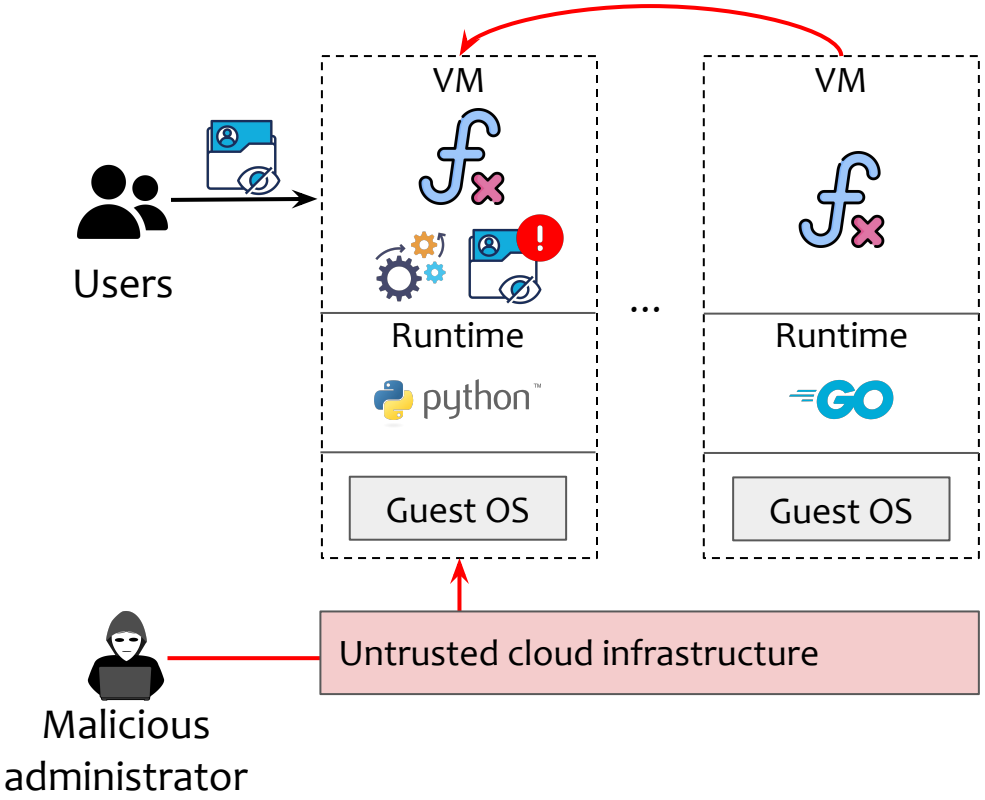
Problem statement

How do we enable **trustworthy serverless computing** in the cloud?

Can we use confidential virtual machines (CVMs)?

CVM properties:

- No trust in hypervisor
- Inter-CVM isolation
- Memory encryption
- Remote attestation



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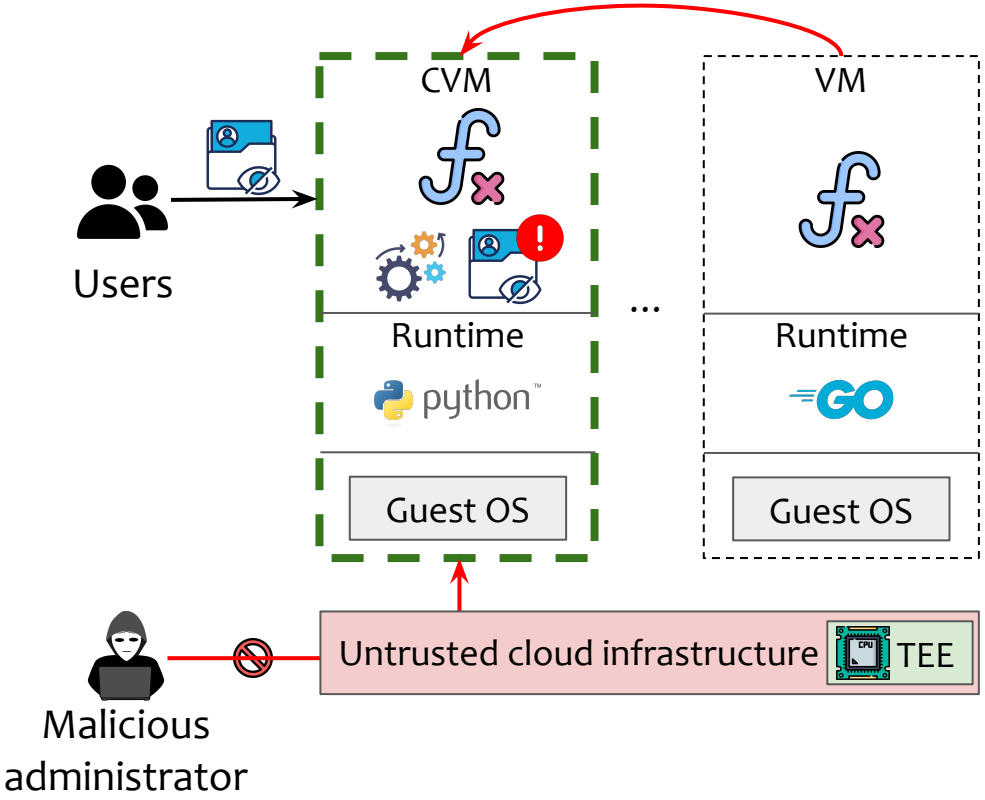

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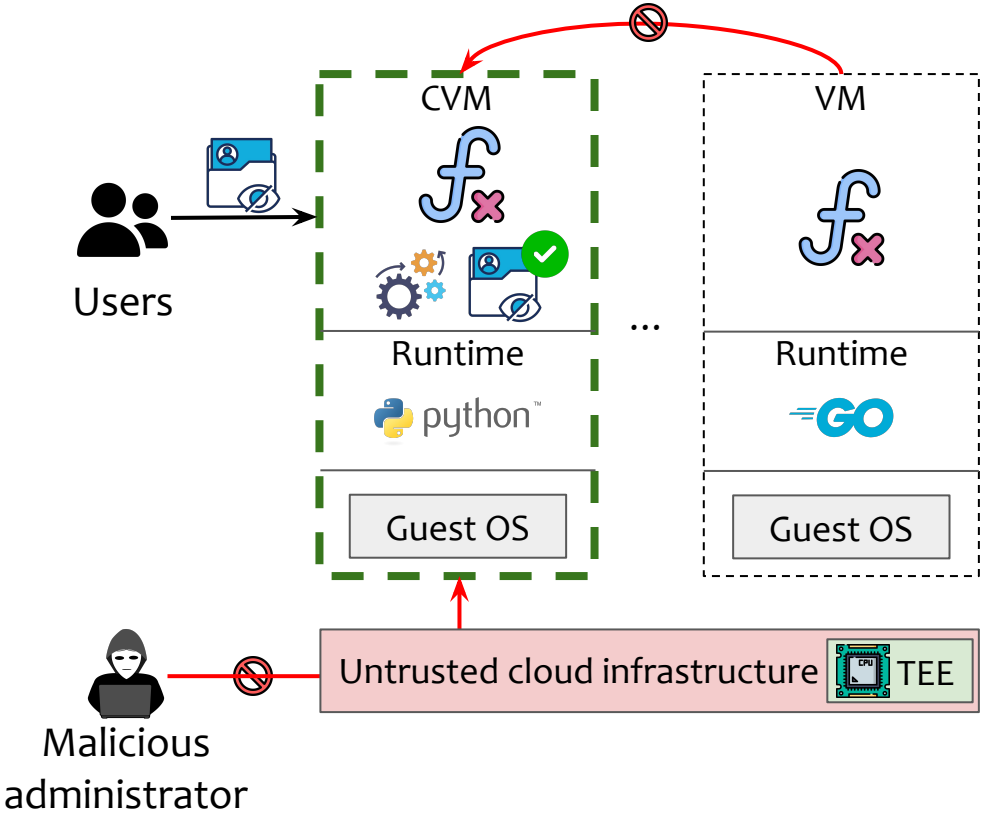

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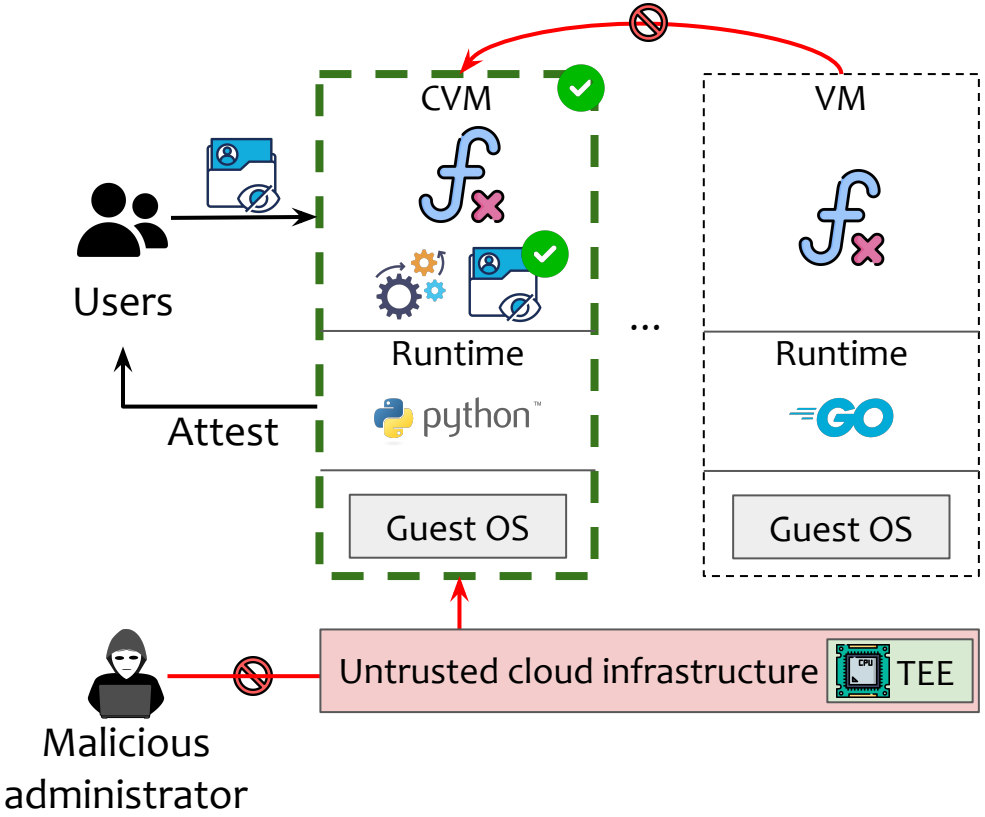

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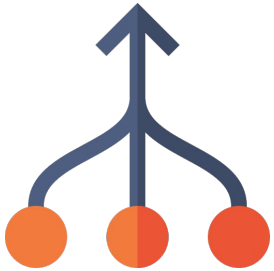
Core CVM Issues for serverless workloads

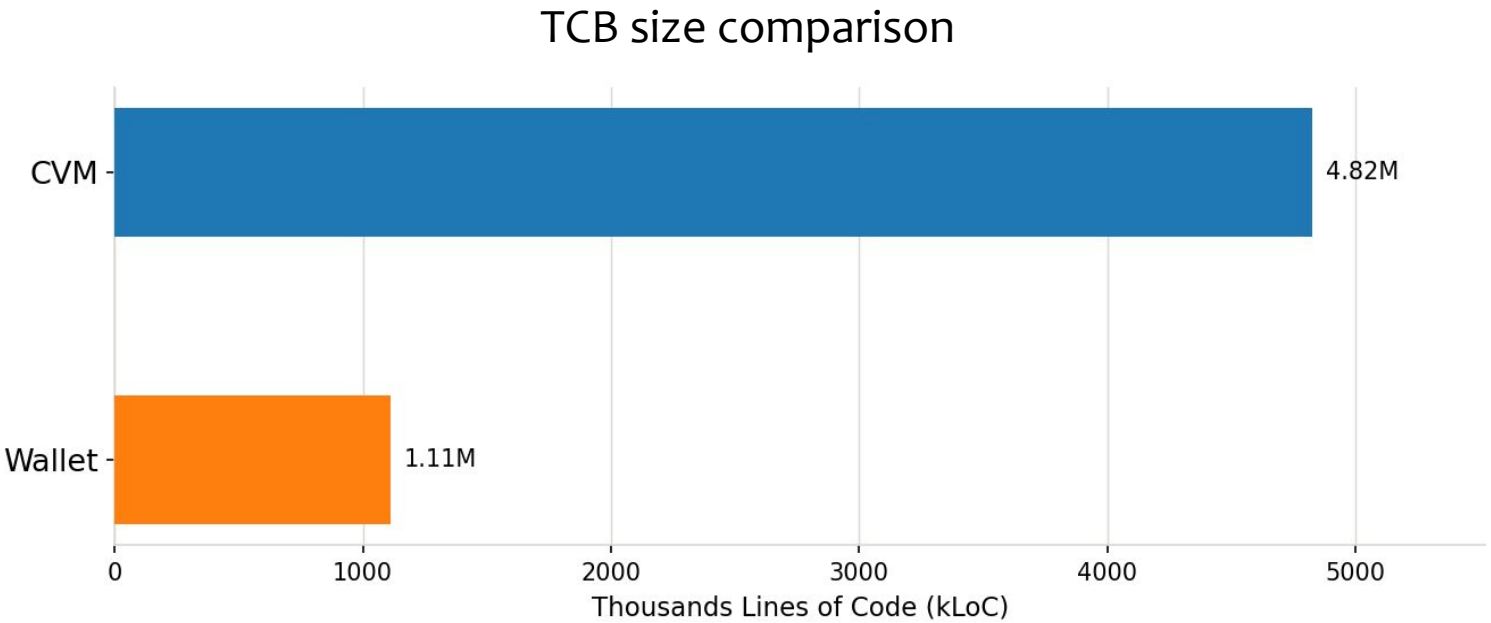
#1: Large Trusted Computing Base (TCB) and high boot times



#2: Impractical function consolidation

#3: High inter-function communication costs

#1: Large TCB and high boot times



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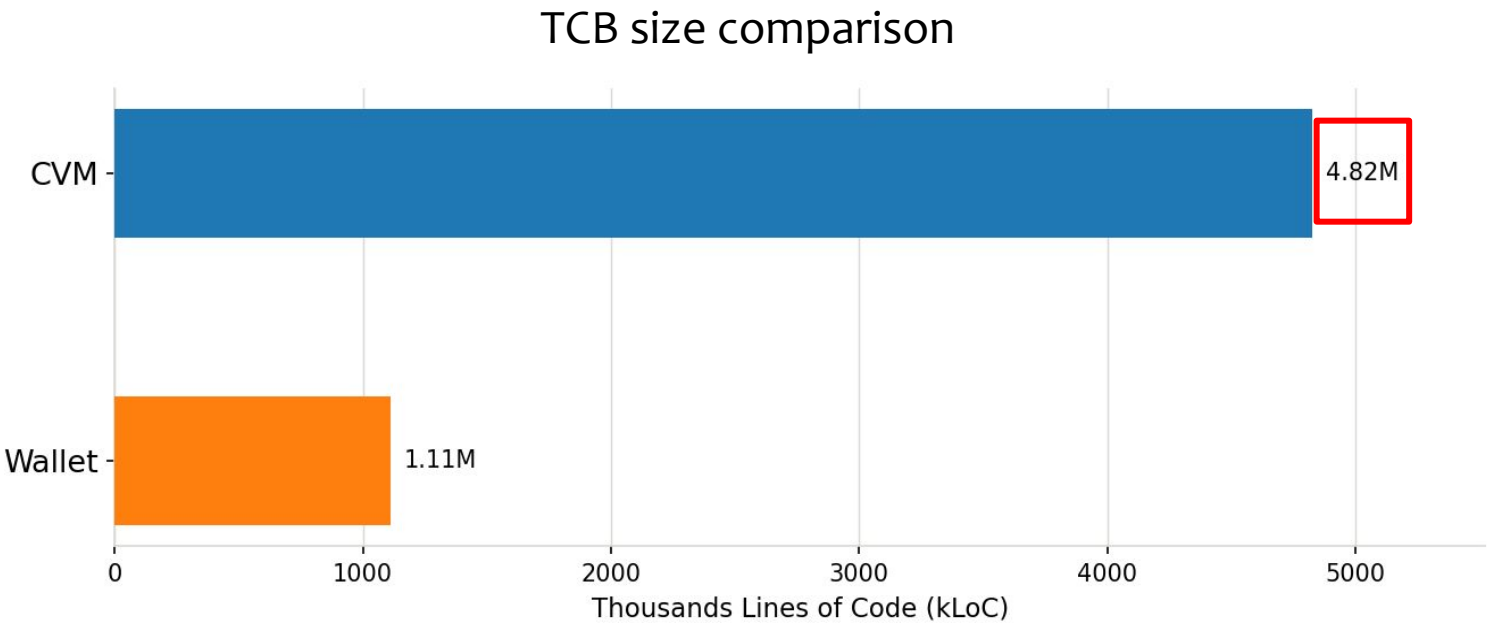

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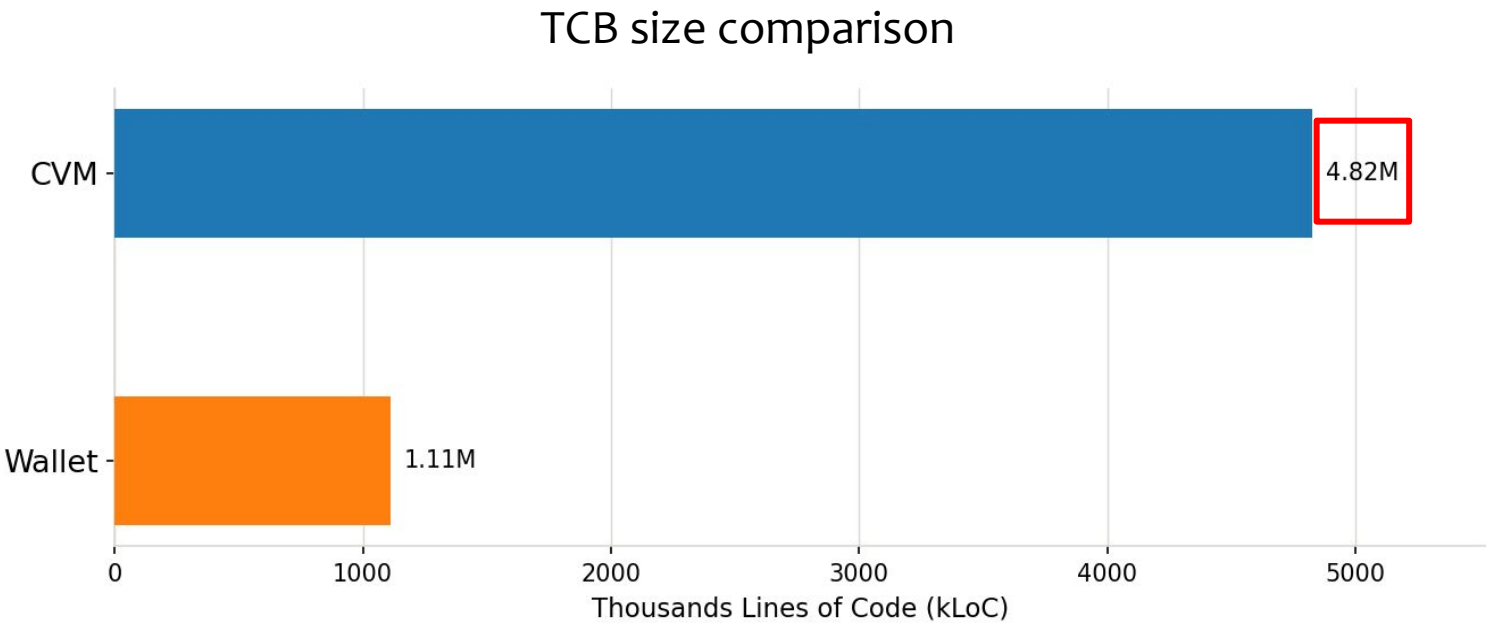

4.3x lower TCB compared to Linux CVM stacks

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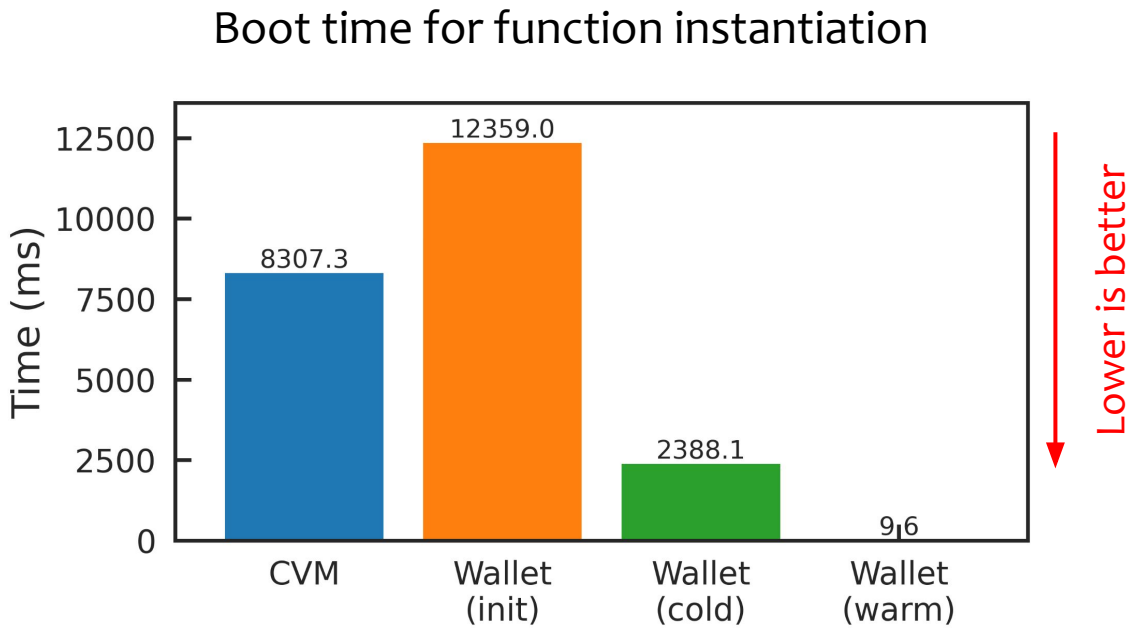

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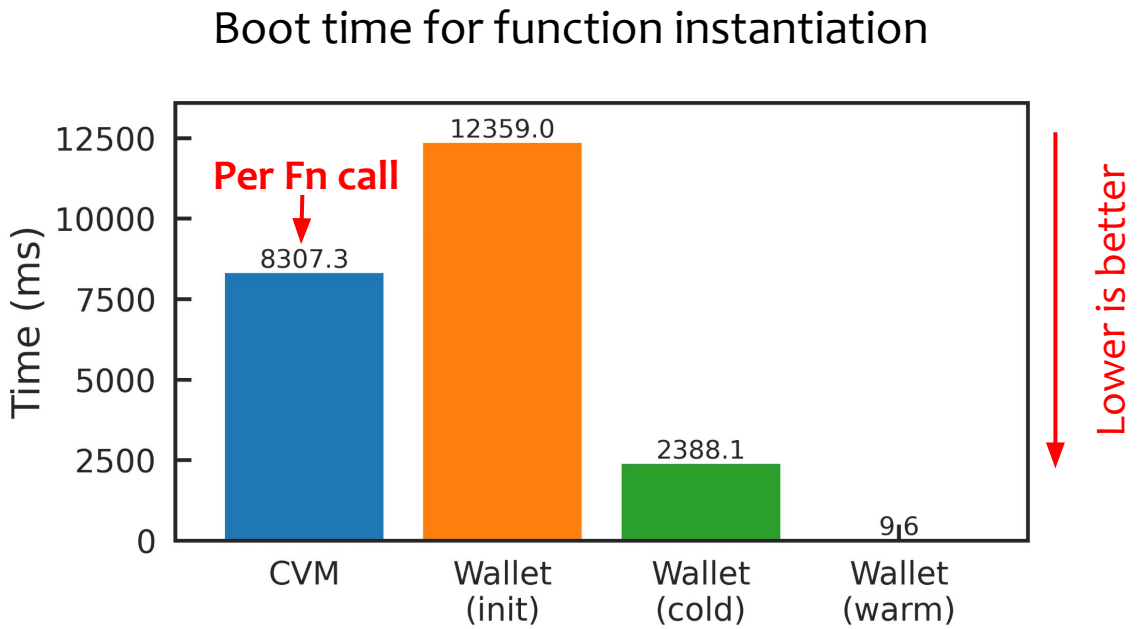

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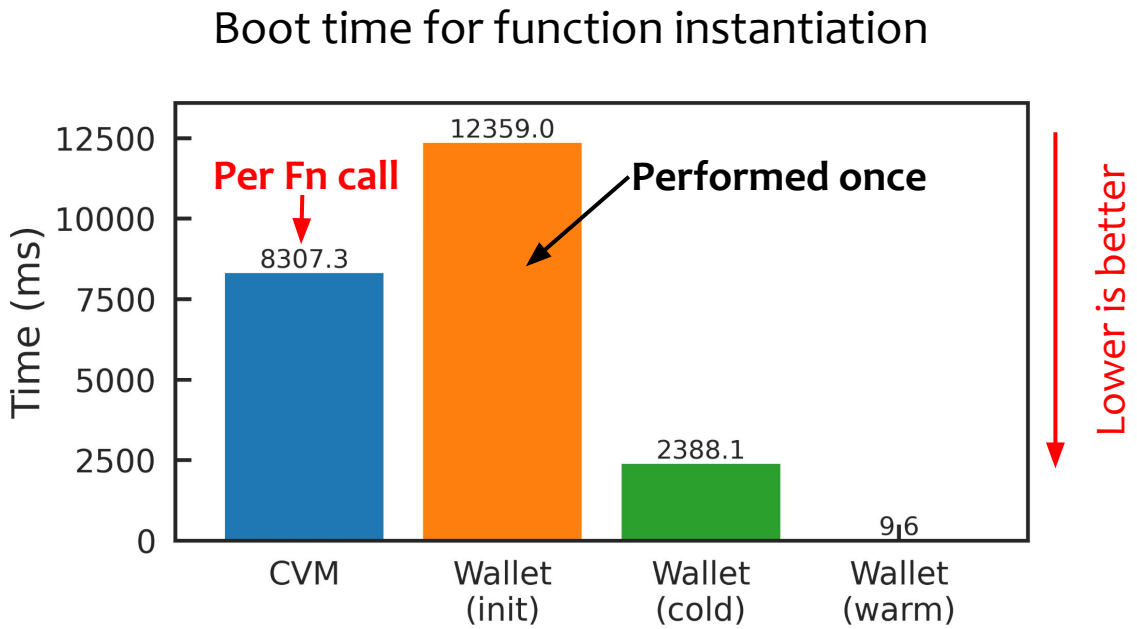

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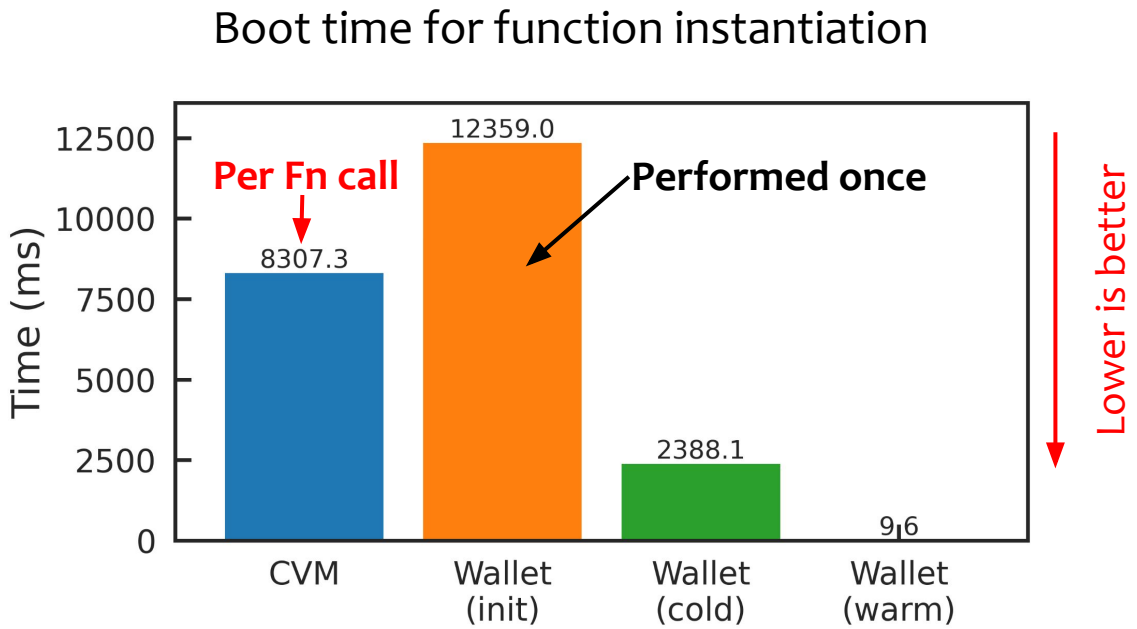
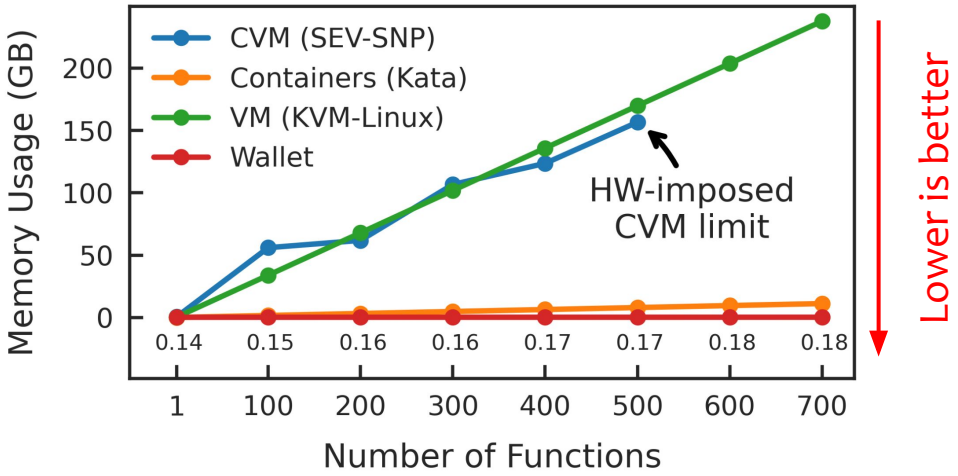


Almost negligible boot time

#2: Impractical function consolidation

Memory usage with increasing number of functions (1 Function / VM)



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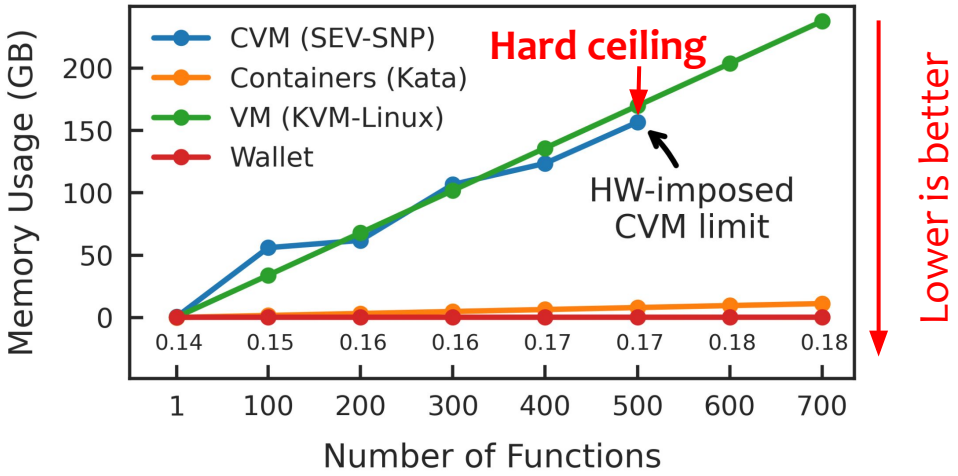

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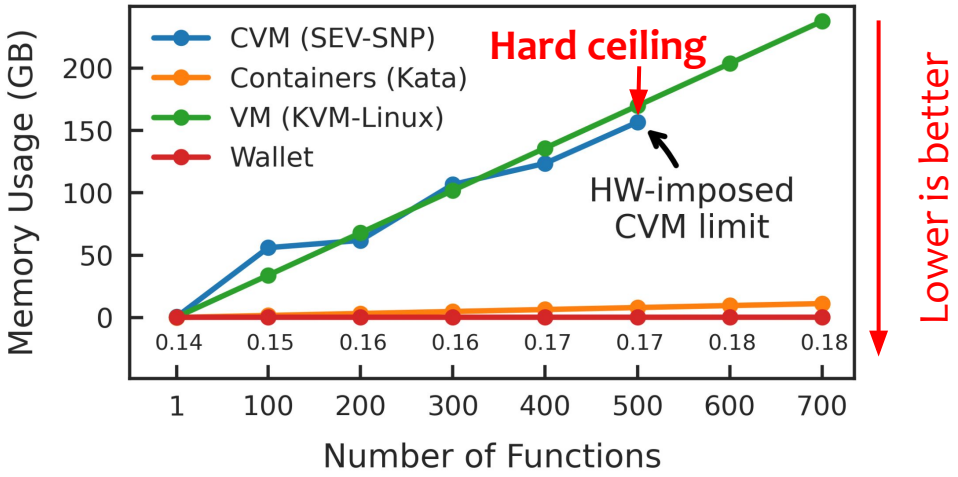
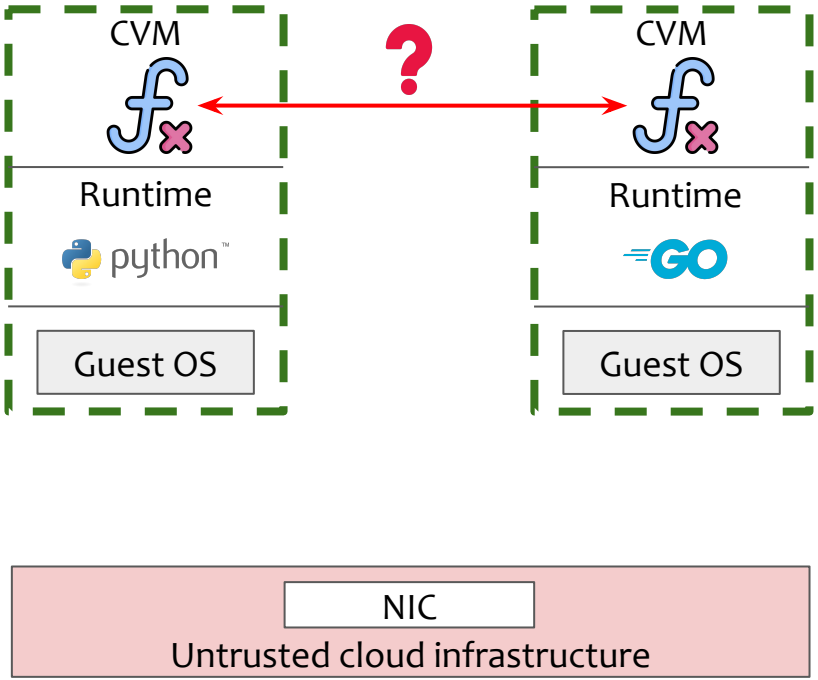


Up to **78%** improvement in memory consumption and **907×** higher deployment density

#3: High inter-function communication costs

CVM networking penalties:

- Disallowed DMA
- Bounce buffer copy overhead
- Crypto operations overhead



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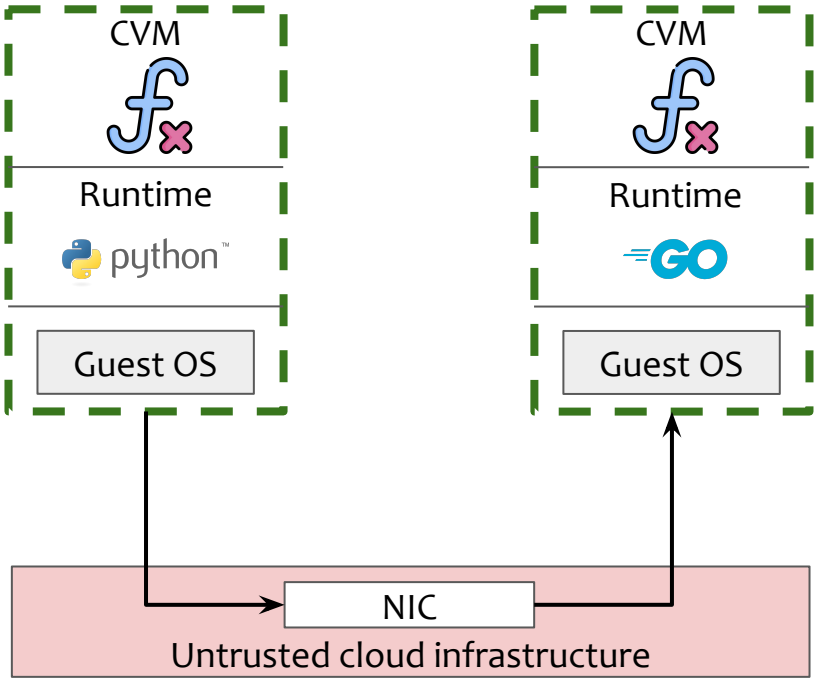

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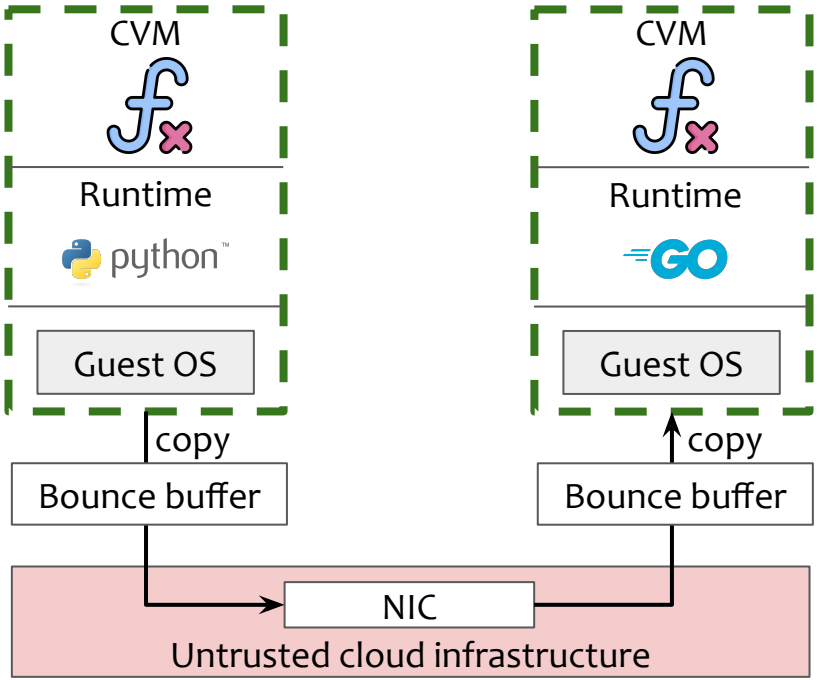

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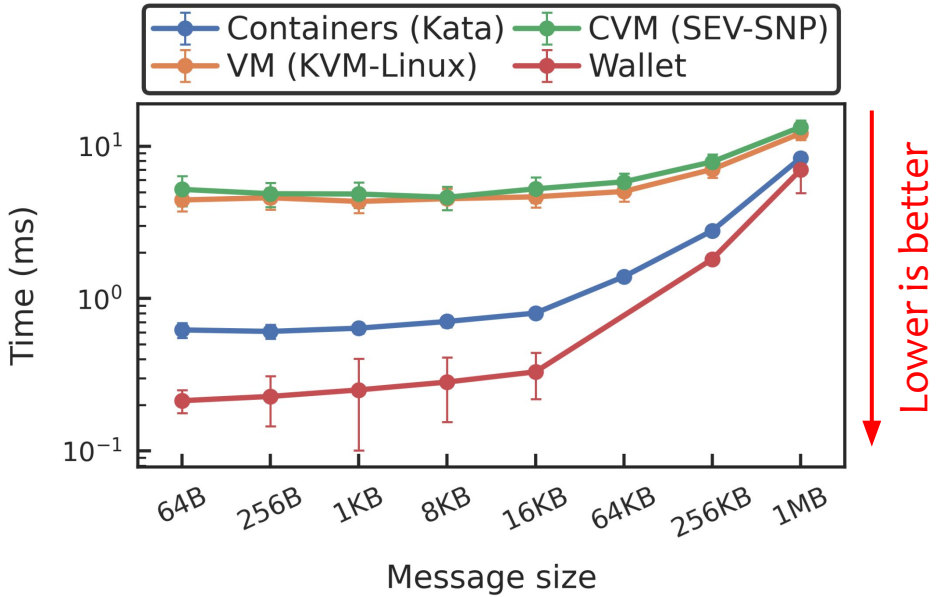
Latency of data transfer between two functions with increasing message size



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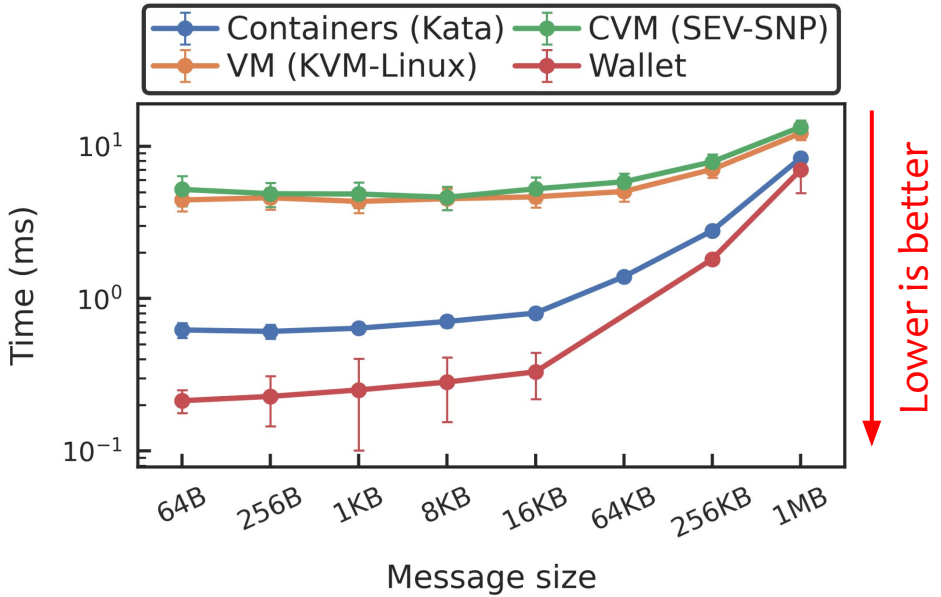
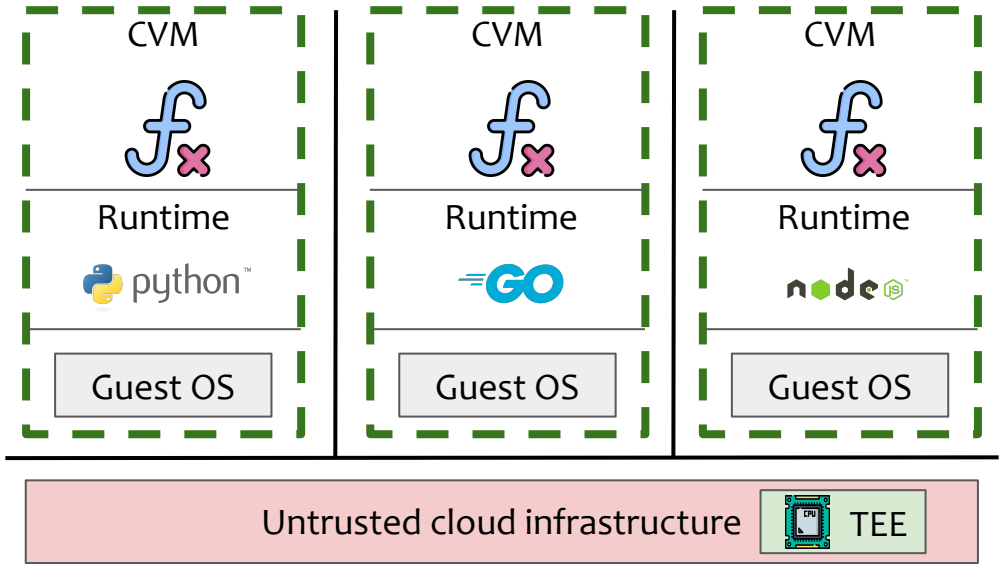


Up to **27x** lower data transfer latency compared to CVMs

Outline

- ~~Motivation~~
- Key idea
- Design
- Implementation
- Evaluation

Key issue of CVM-based serverless computing



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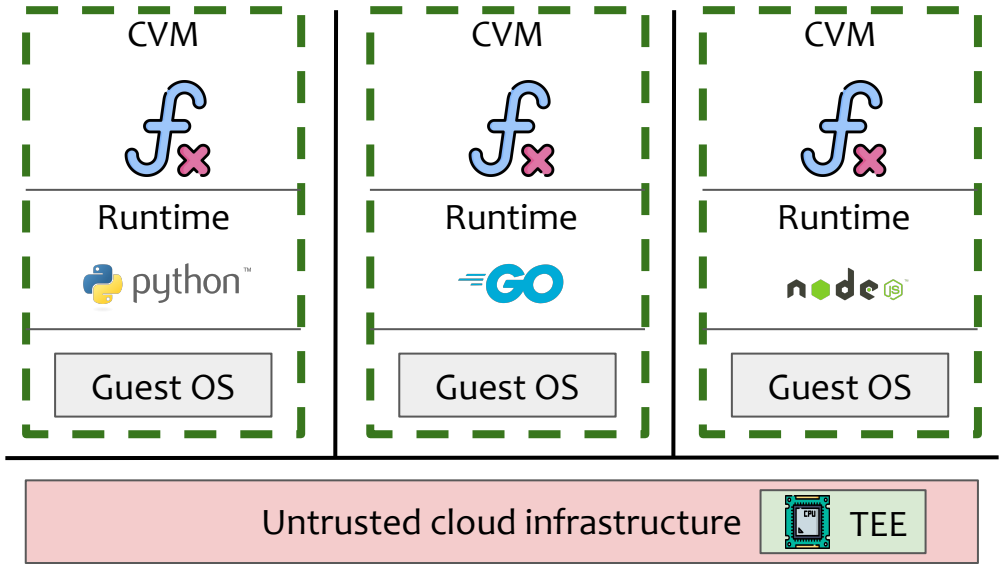
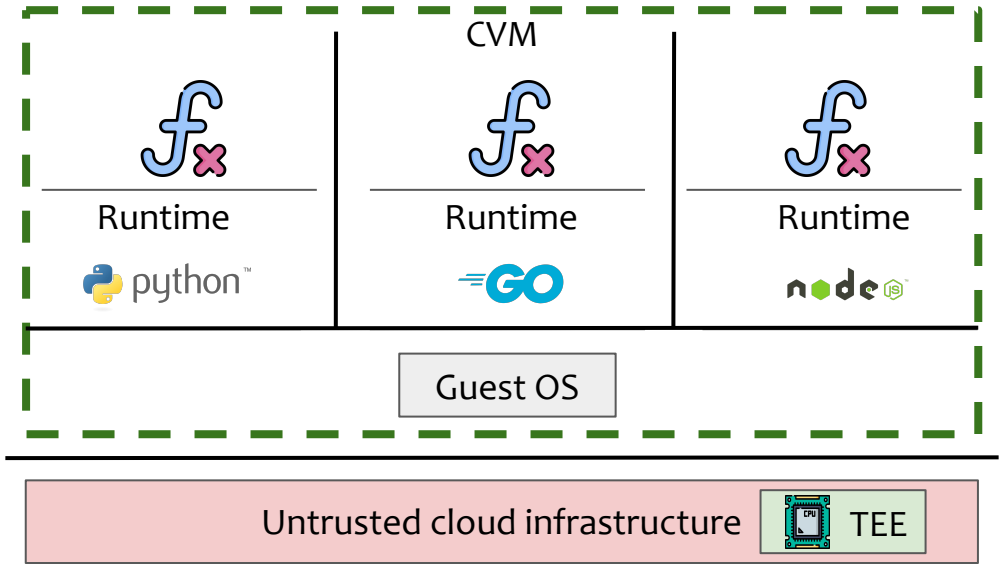


CVM is **ill-suited** as the deployment unit of a single serverless function

Research challenge



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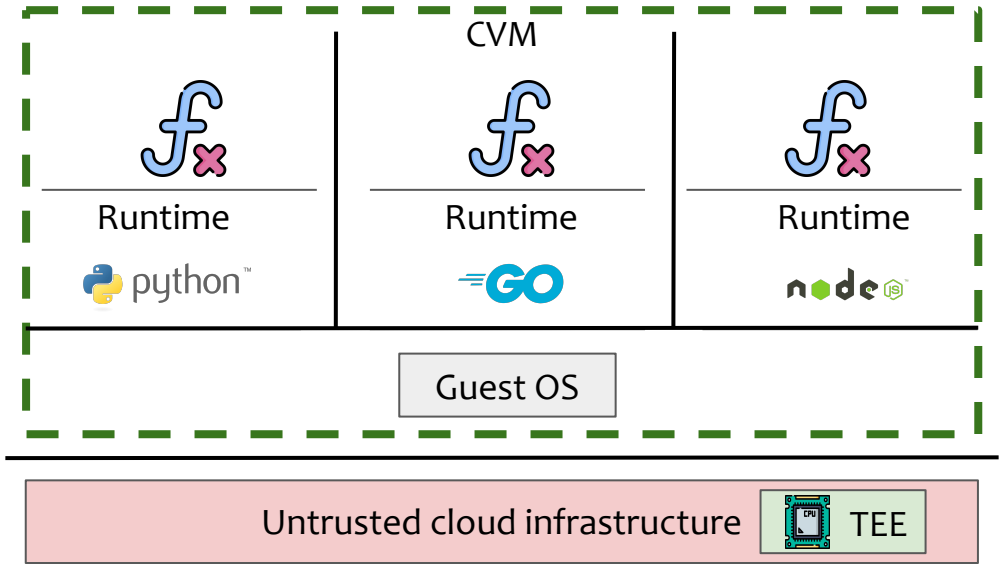
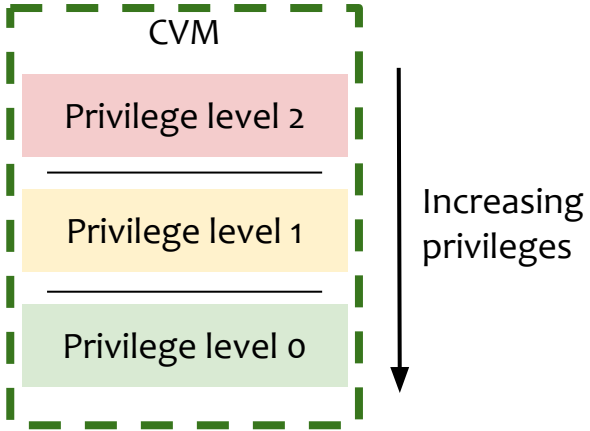


Can we pack **thousands, isolated** serverless functions in a **single CVM**?

Key idea: Nested virtualization

CVM partitioning

- Separation of CVM in distinct privilege levels
- HW-enforced access control
- Dynamic access level management



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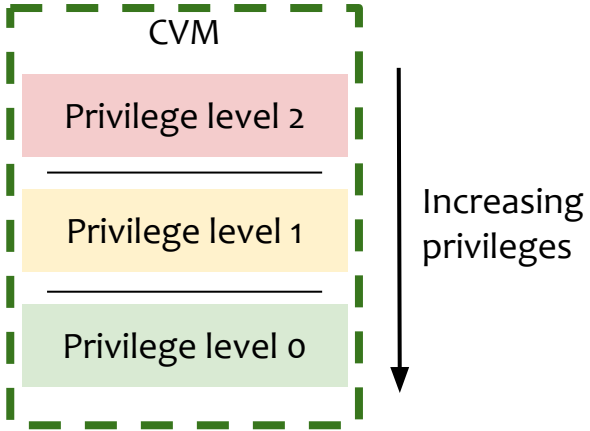
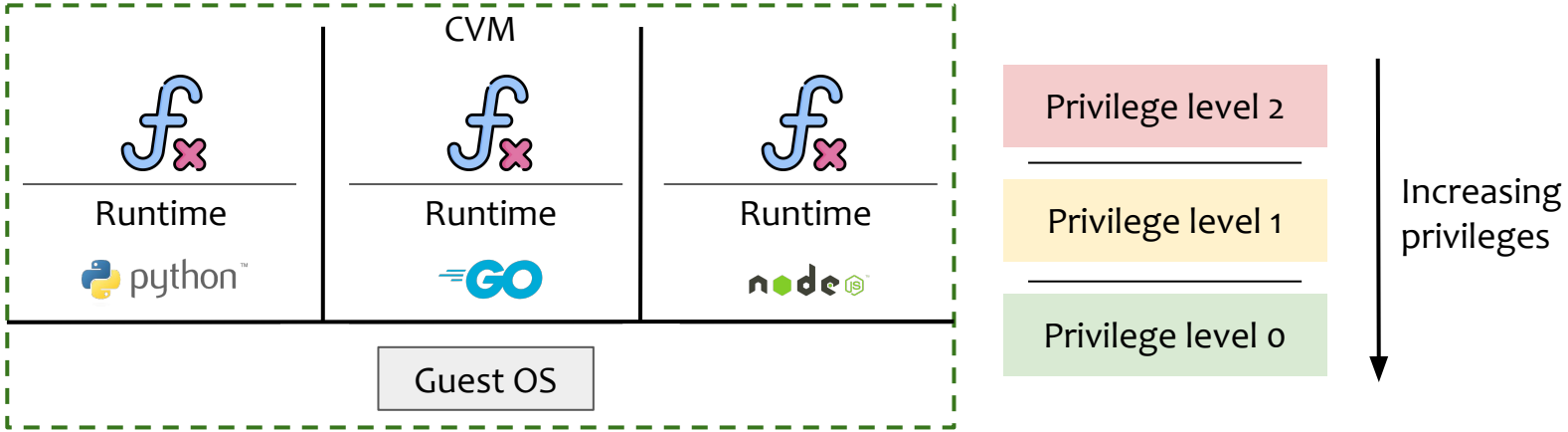


Leverage **CVM partitioning** to split a CVM into smaller isolated compartments

CVM partitioning for serverless computing



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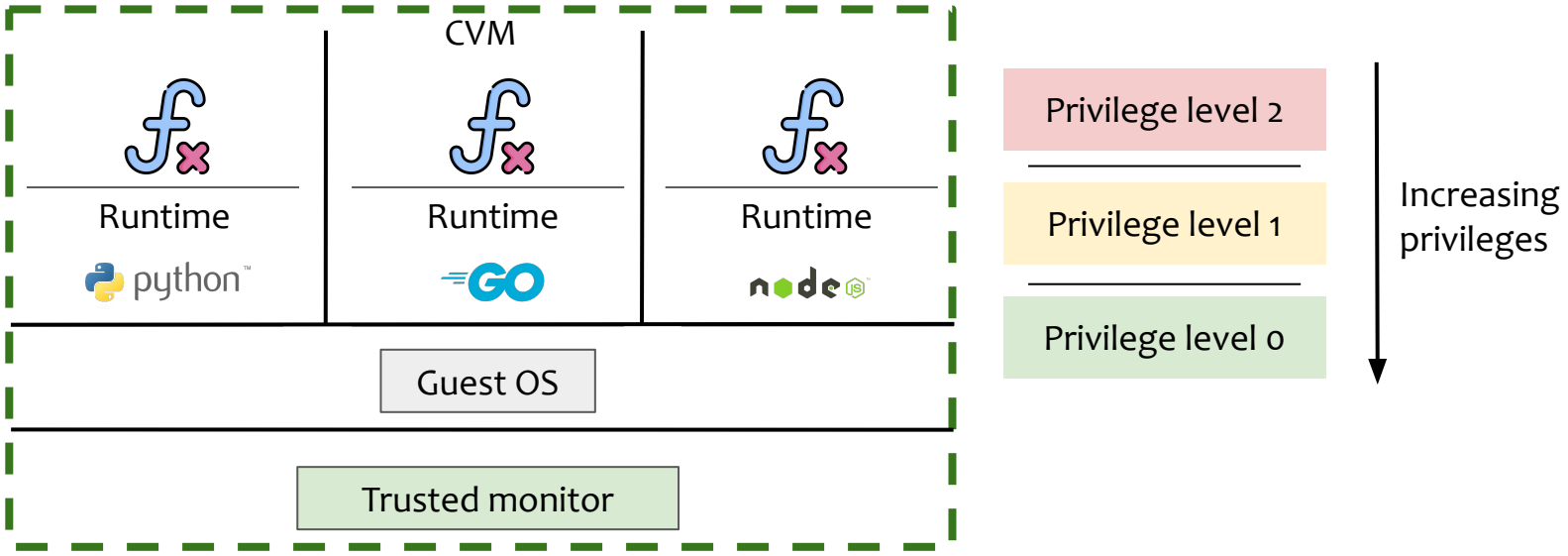

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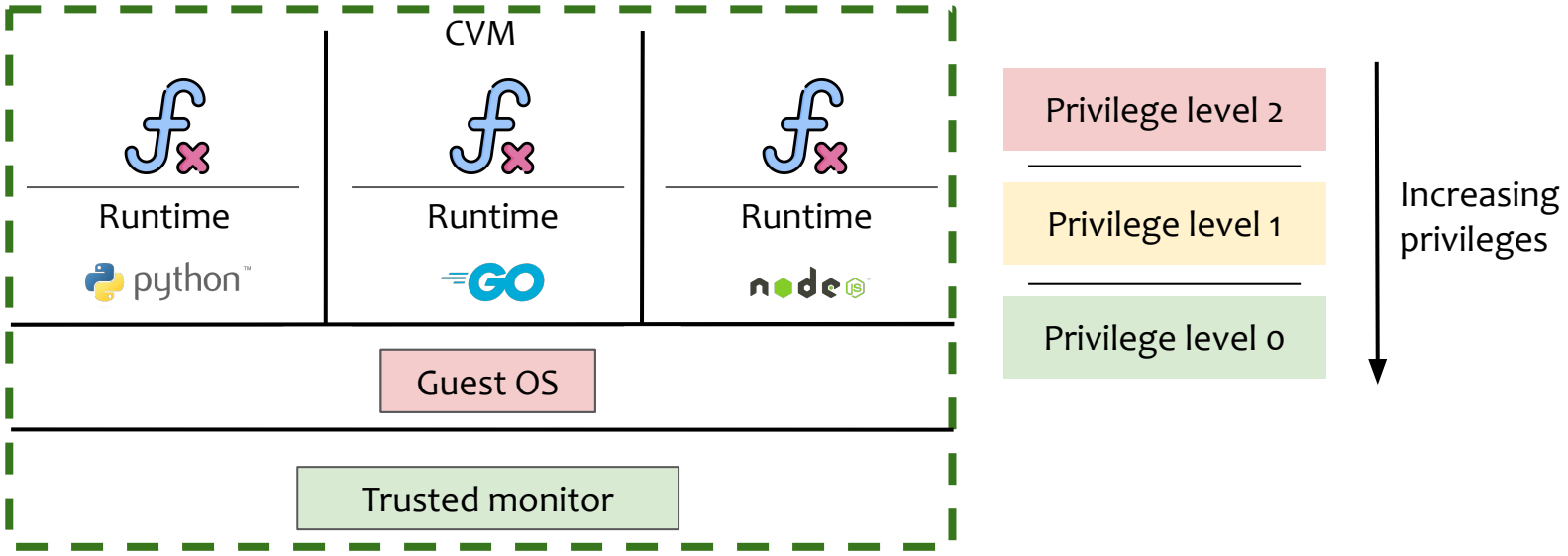

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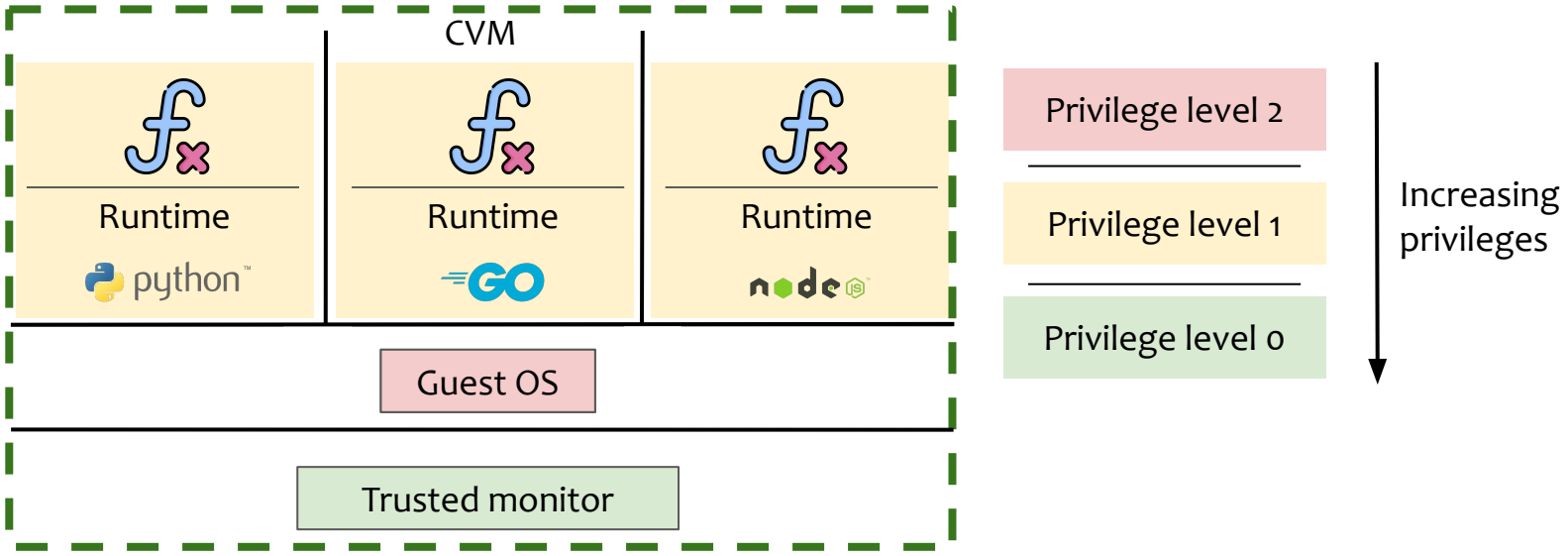

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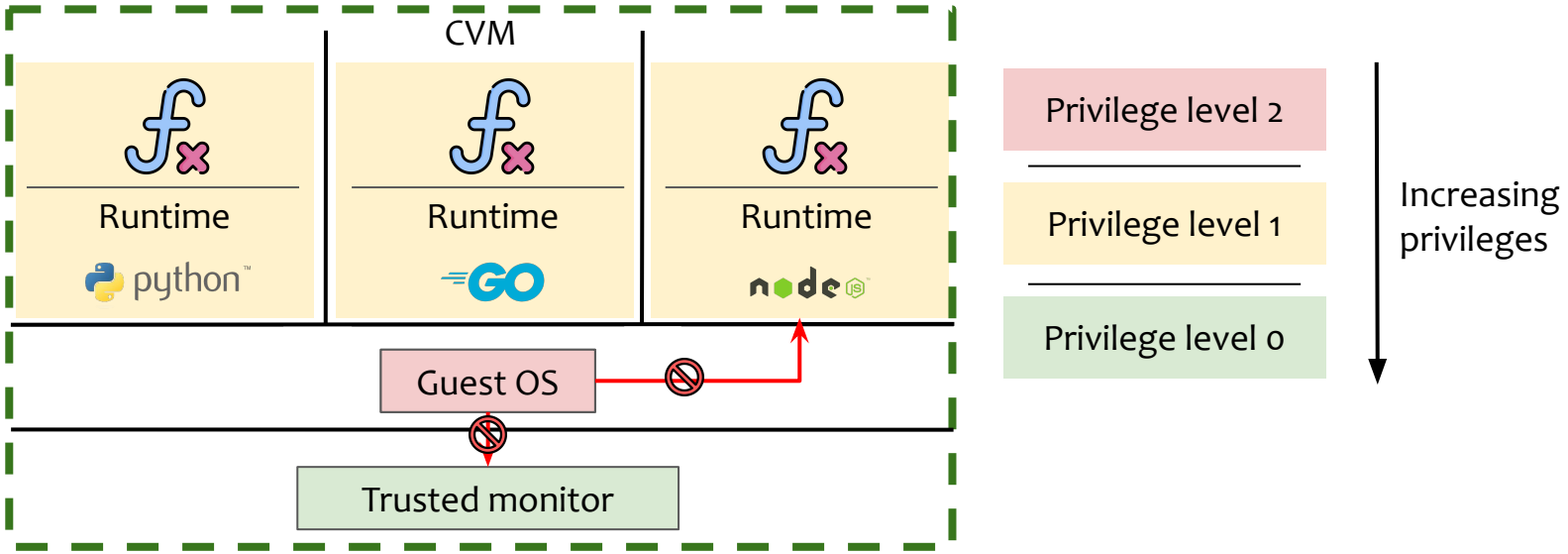

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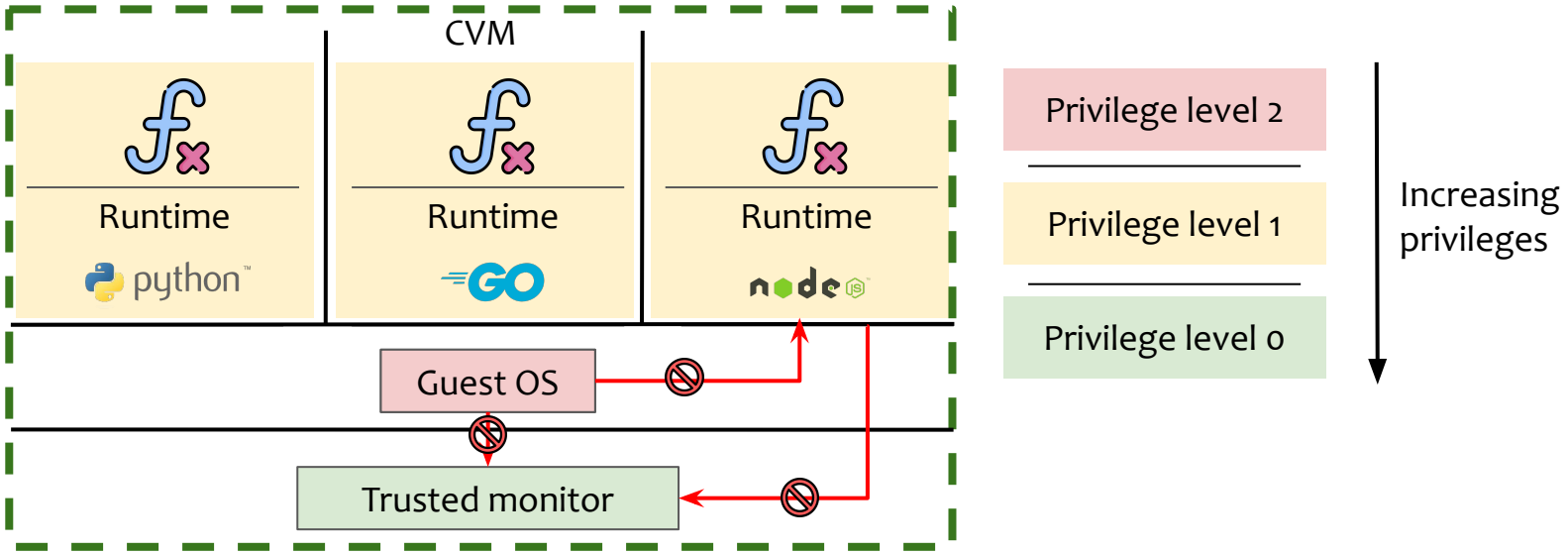

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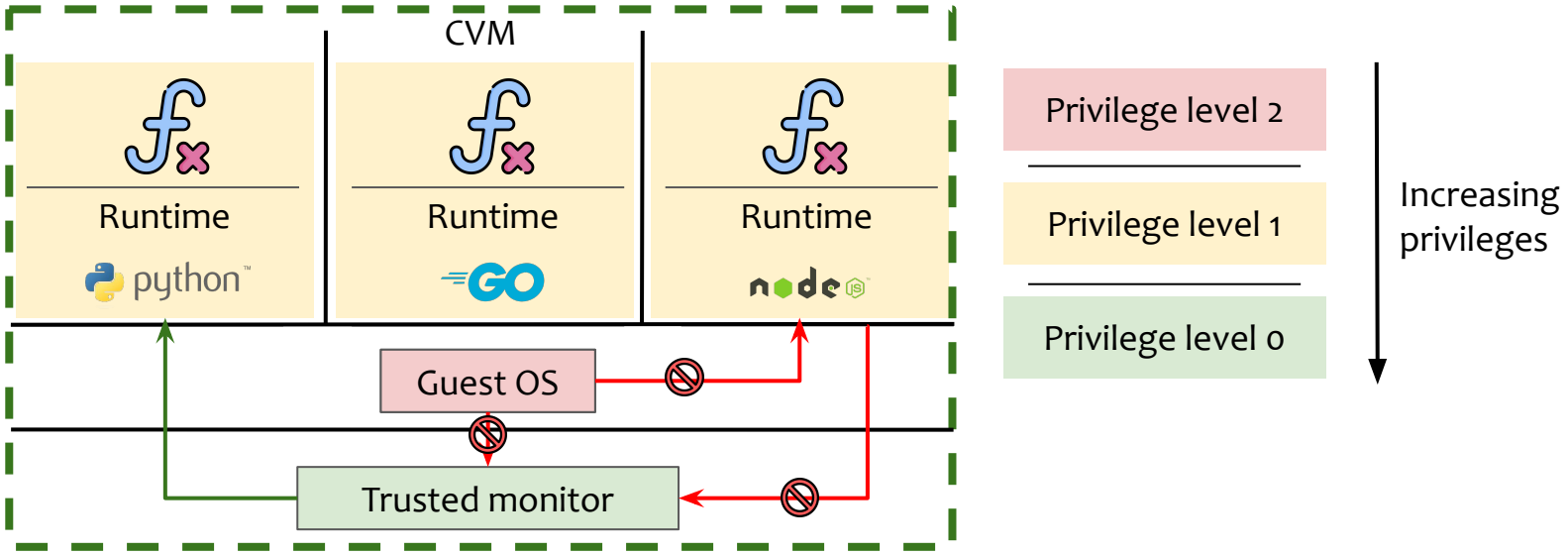

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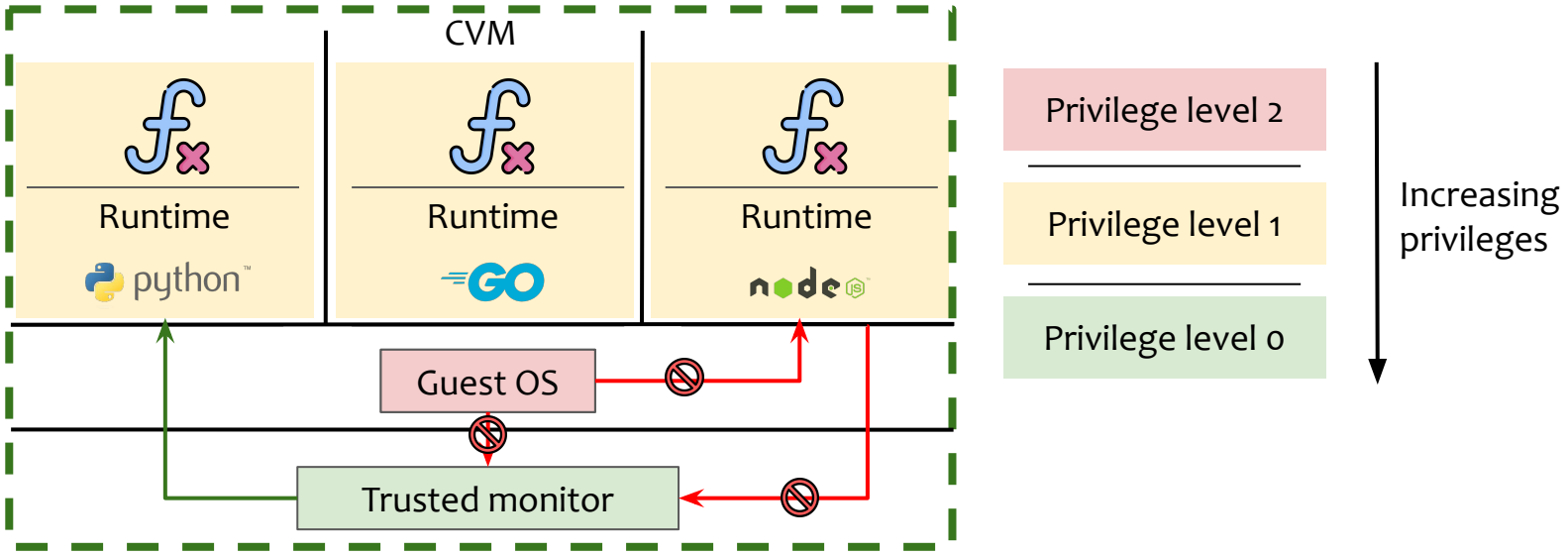

Serverless functions are **isolated** among themselves and **decoupled** from the GuestOS

Outline

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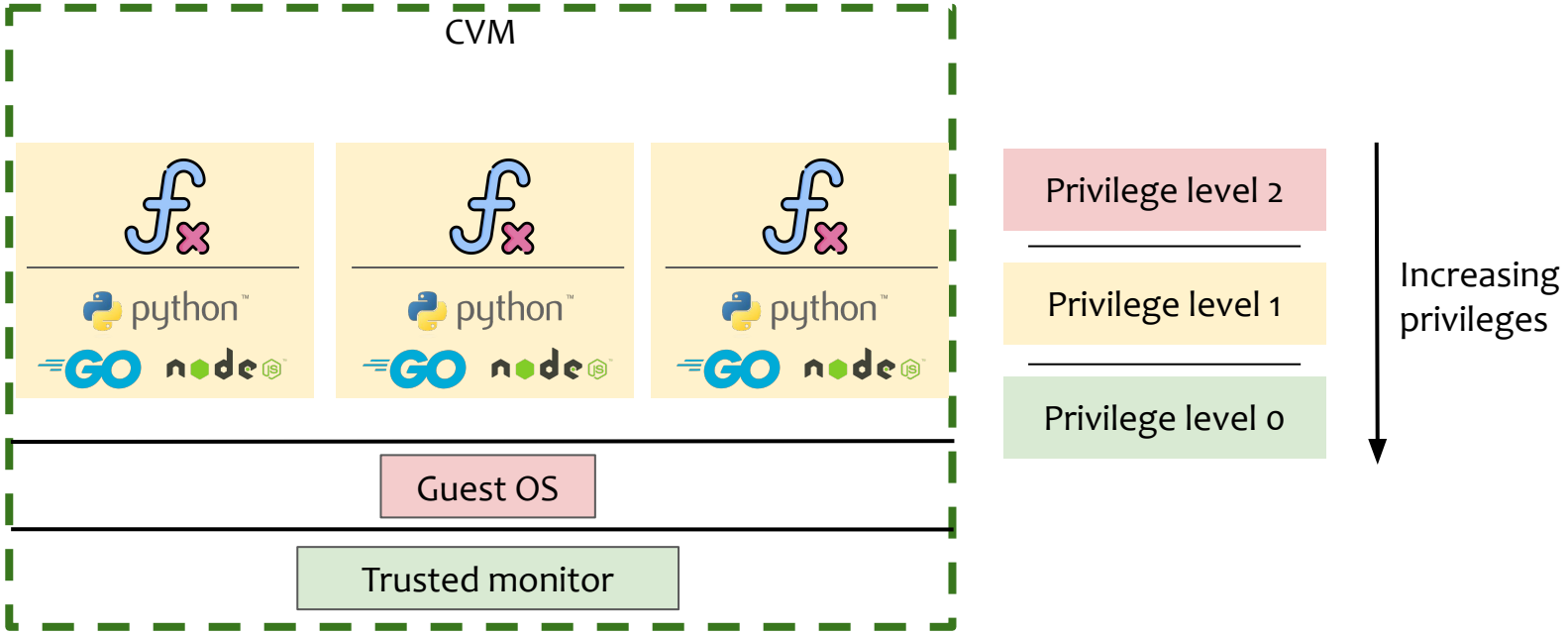

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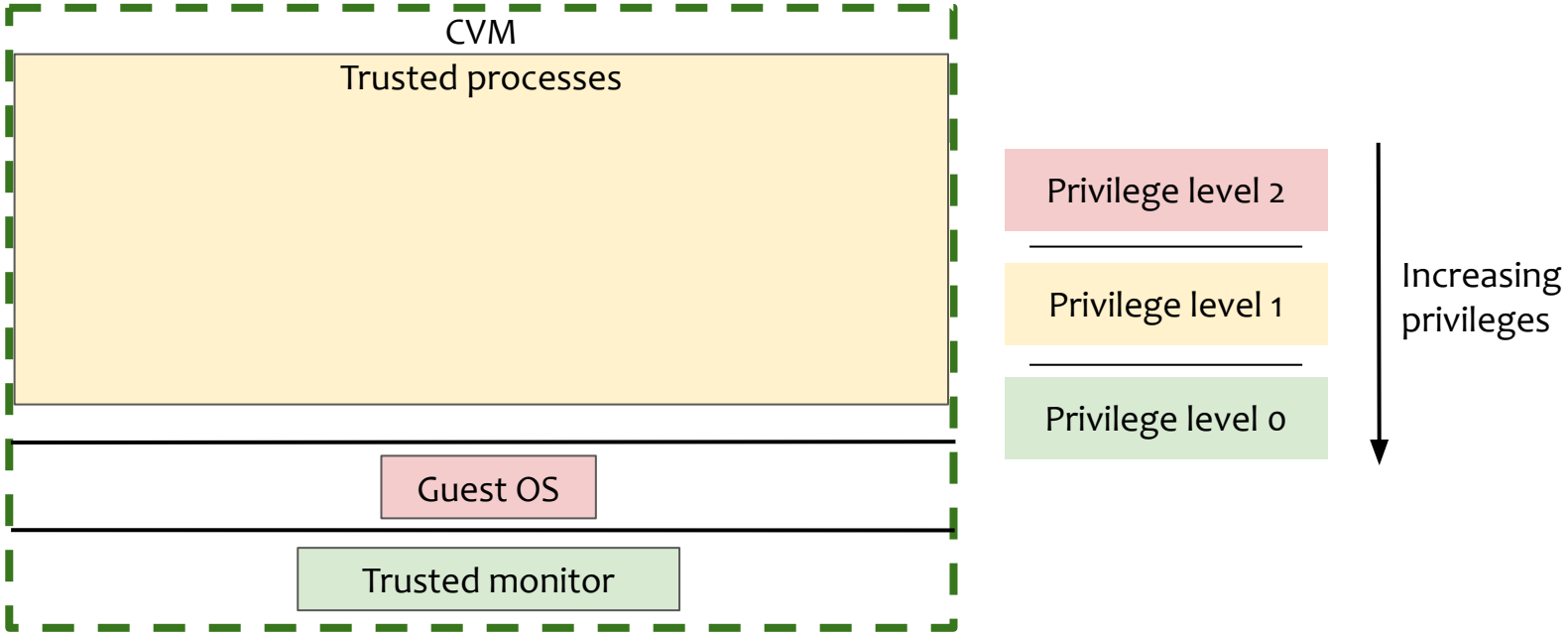

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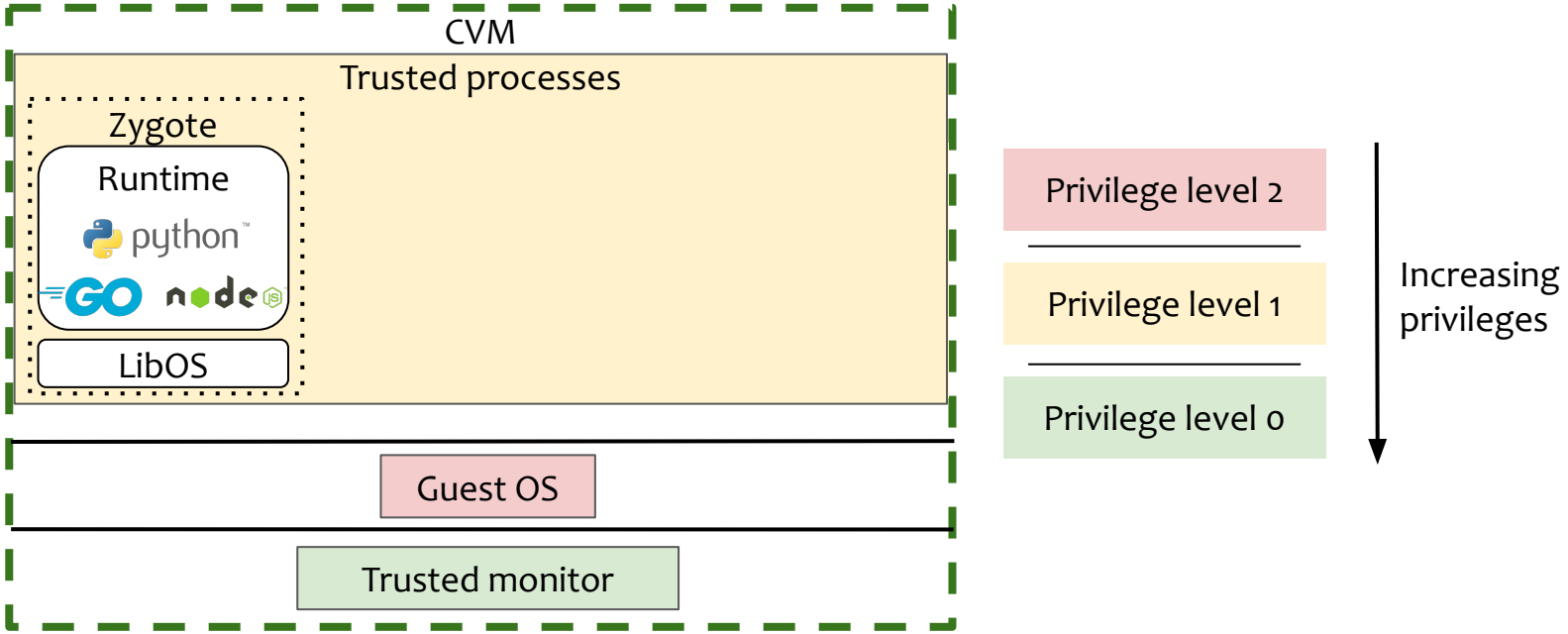

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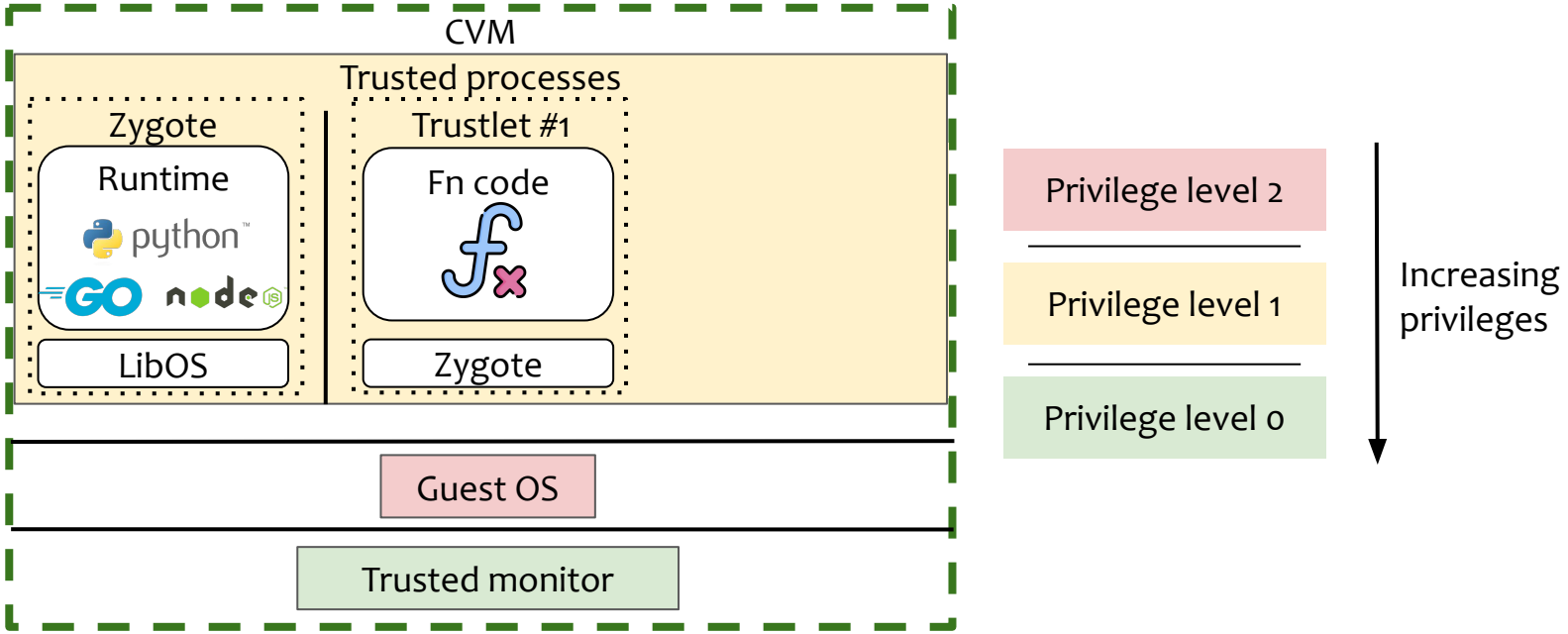

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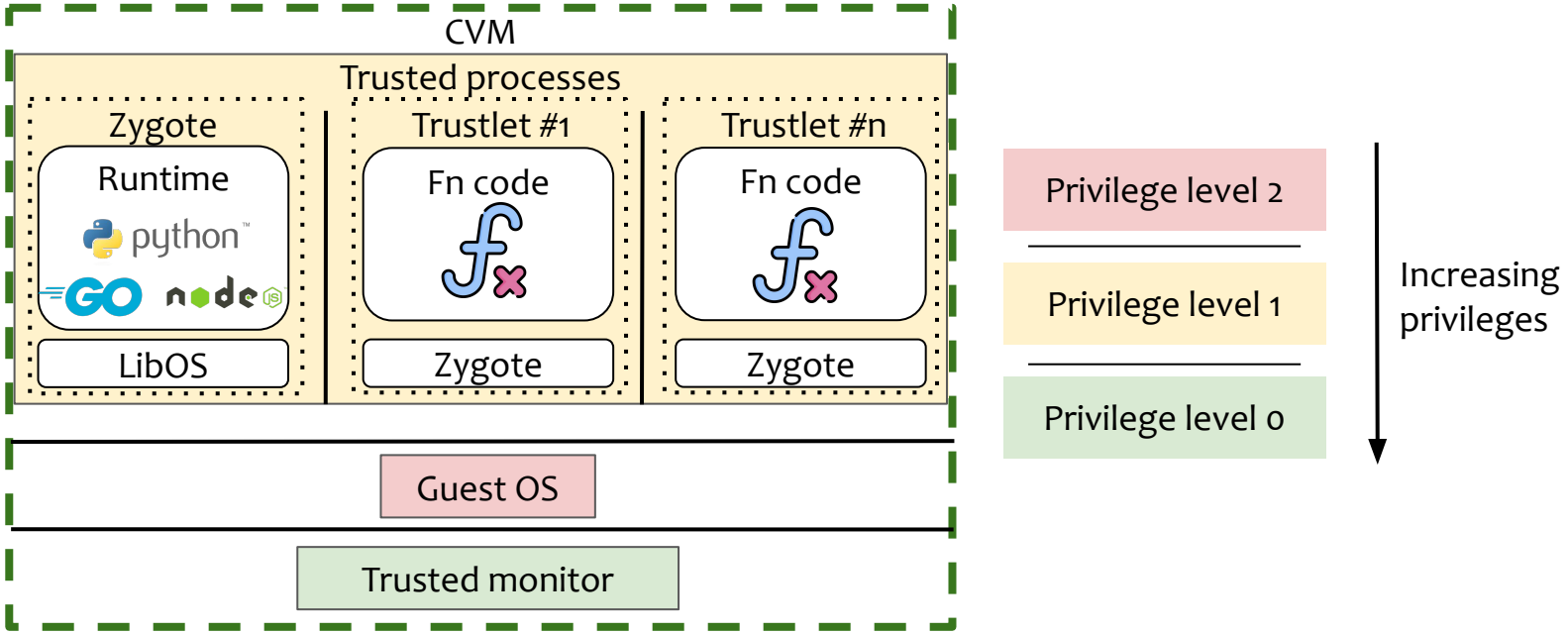

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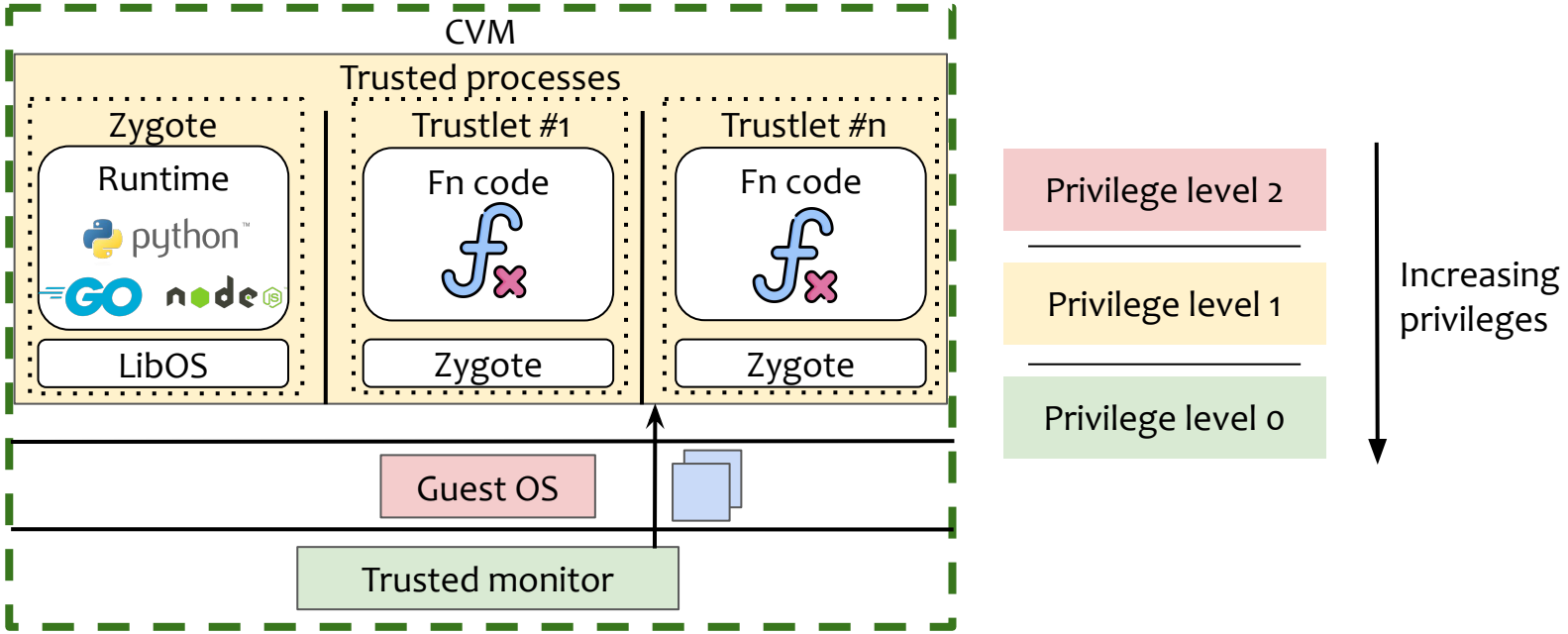

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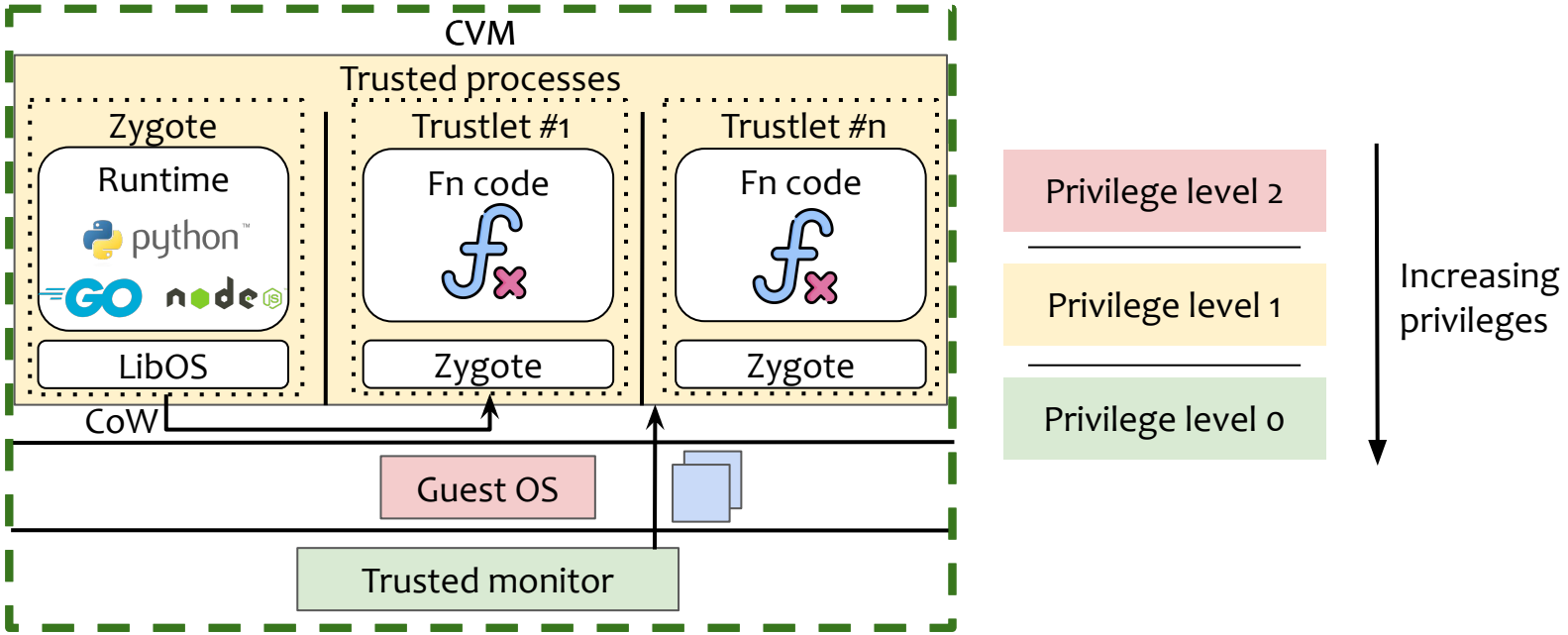

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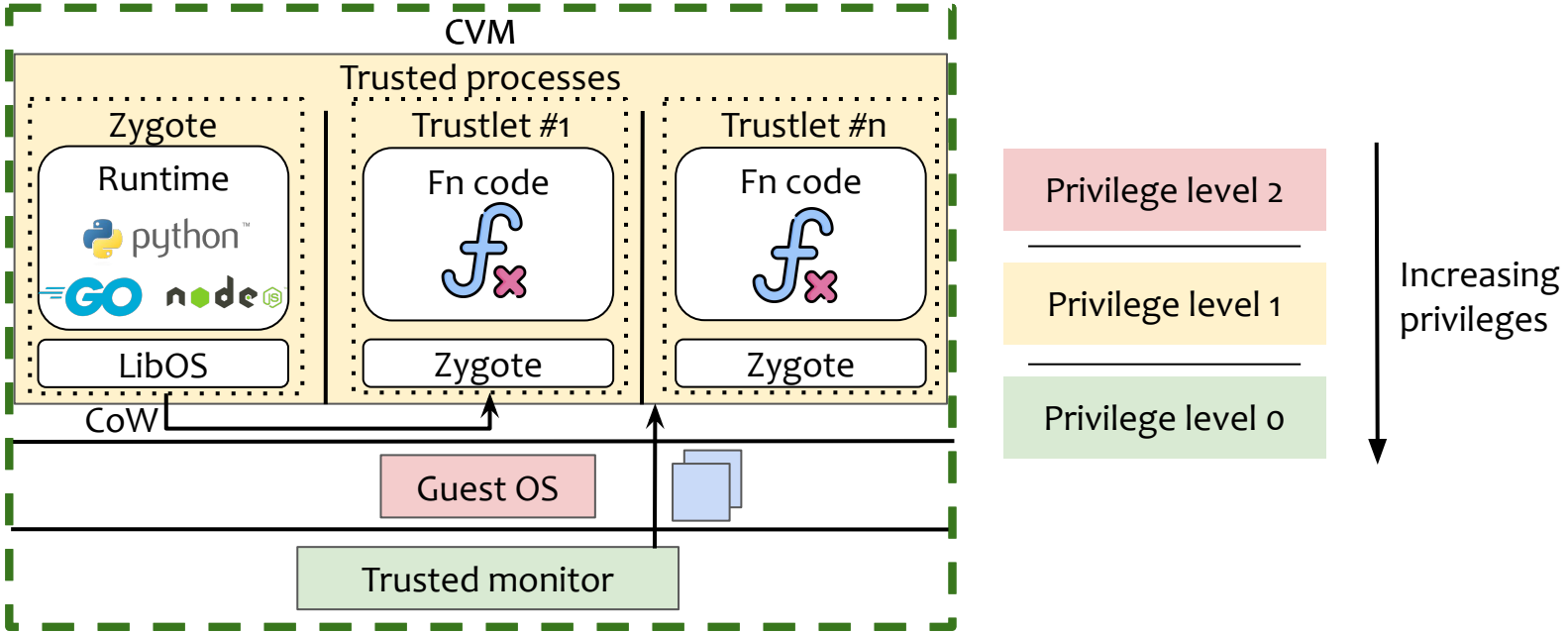
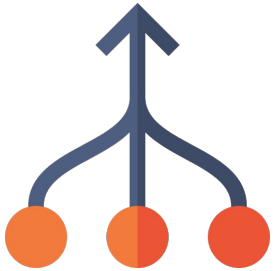


Wallet re-architects the **CVM** based on the **requirements of serverless computing**

Design challenges

#1: Large Trusted Computing Base (TCB) and high boot times

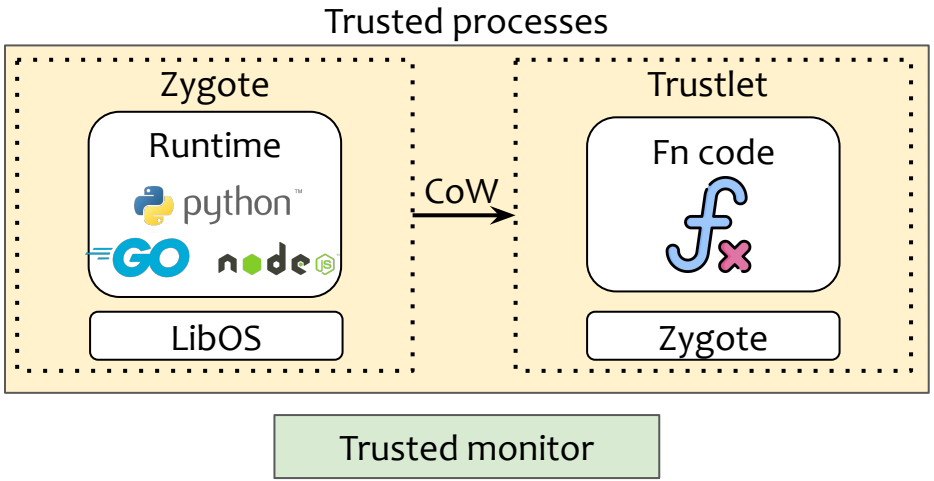


#2: Impractical function consolidation

#3: High inter-function communication costs

#1 Low TCB and boot time

- Trusted Monitor
  - Minimal software component
- Zygote
  - LibOS-based
  - Initialized once
- Trustlet
  - Derived from a Zygote
  - Copy-on-Write



#1 Low TCB and boot time

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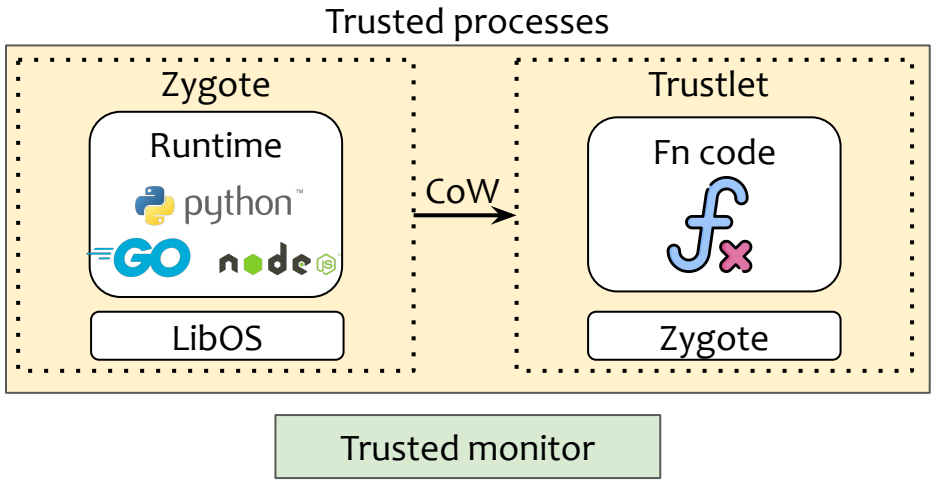
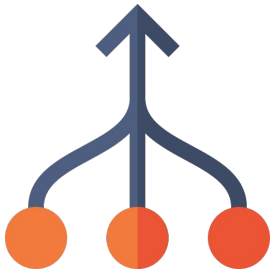


The **minimal** trusted monitor along with **CoW** minimize the TCB and boot time

Design challenges

#1: Large Trusted Computing Base (TCB) and high boot times

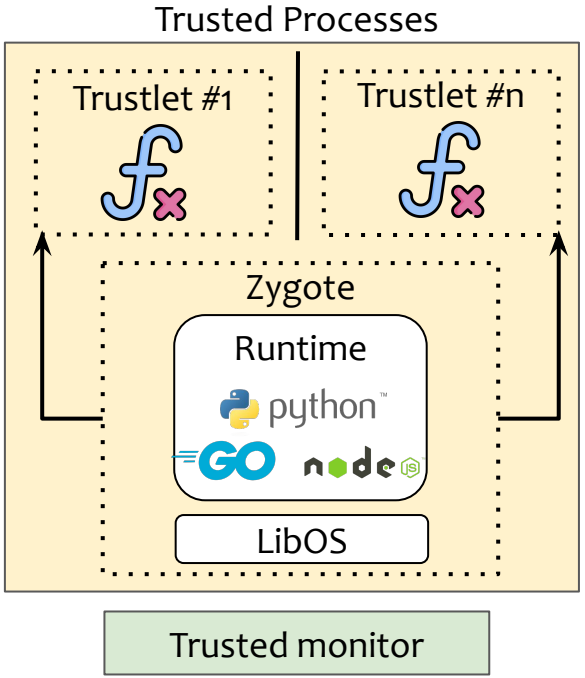


#2: Impractical function consolidation

#3: High inter-function communication costs

#2 Practical function consolidation

- Trusted monitor
  - Isolation via page tables
  - Memory deduplication
- Zygote
  - Shared between multiple trustlets
  - Static in memory
- Trustlet
  - Contains only the function code



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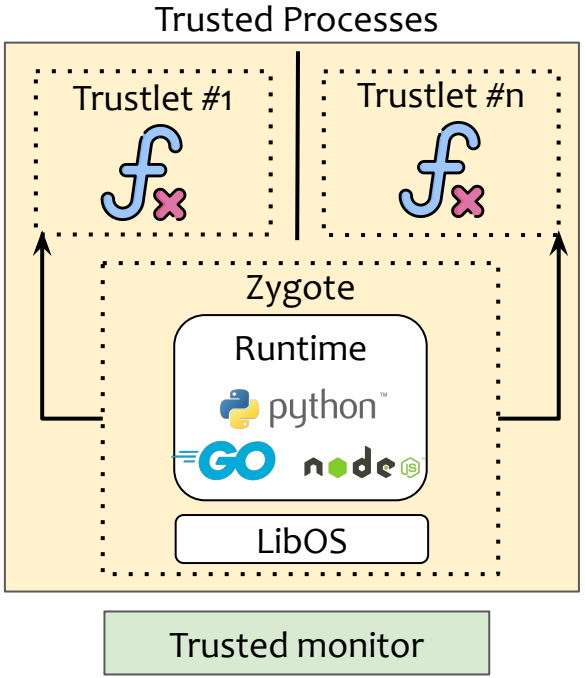

Software-based isolation and **memory deduplication** overcome the CVM density limit

Design challenges

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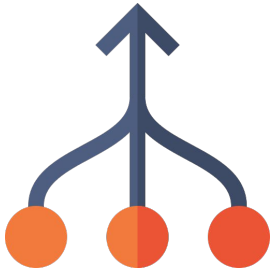

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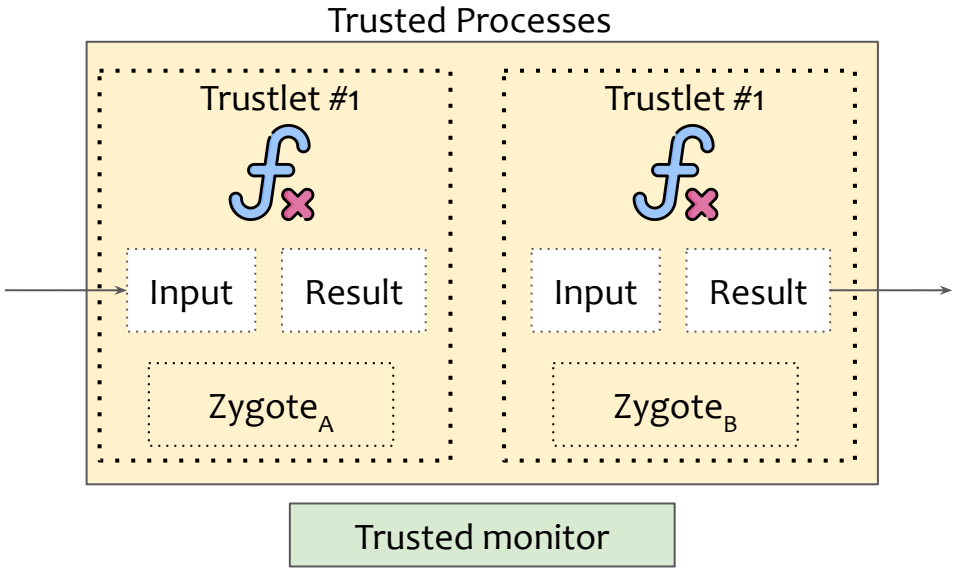
#3 Efficient inter-function communication

- Shared-memory data objects
- Configured by the trusted monitor
- Zero-copy function chaining



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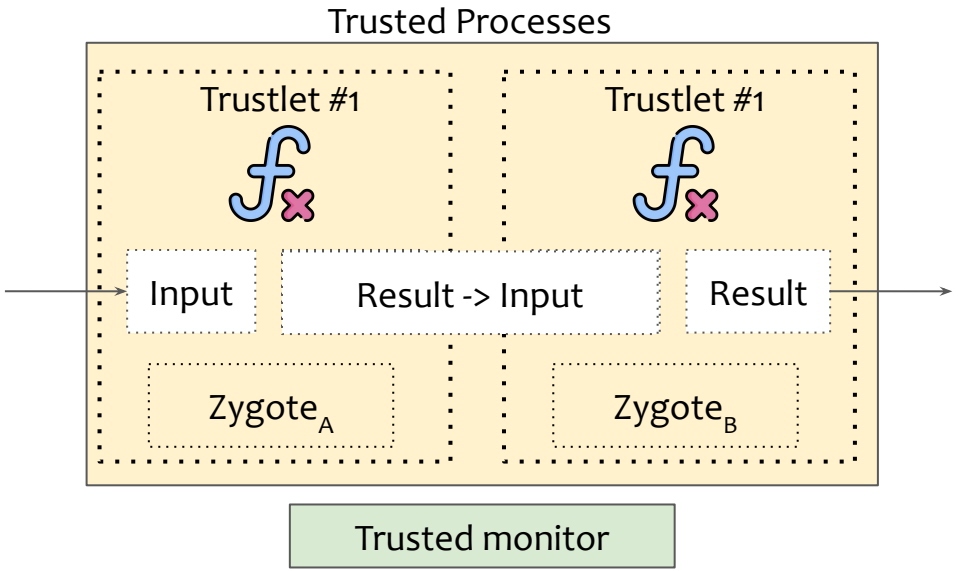

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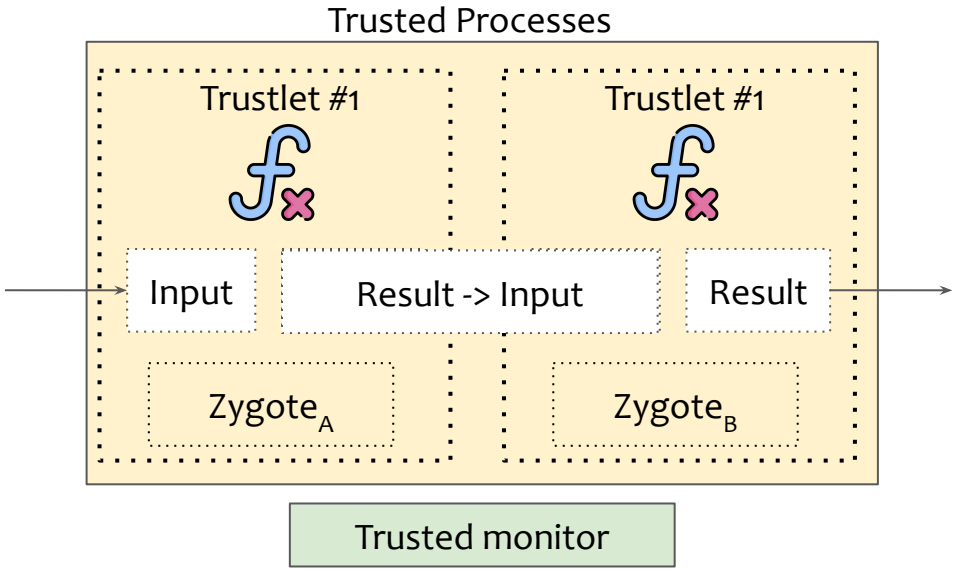
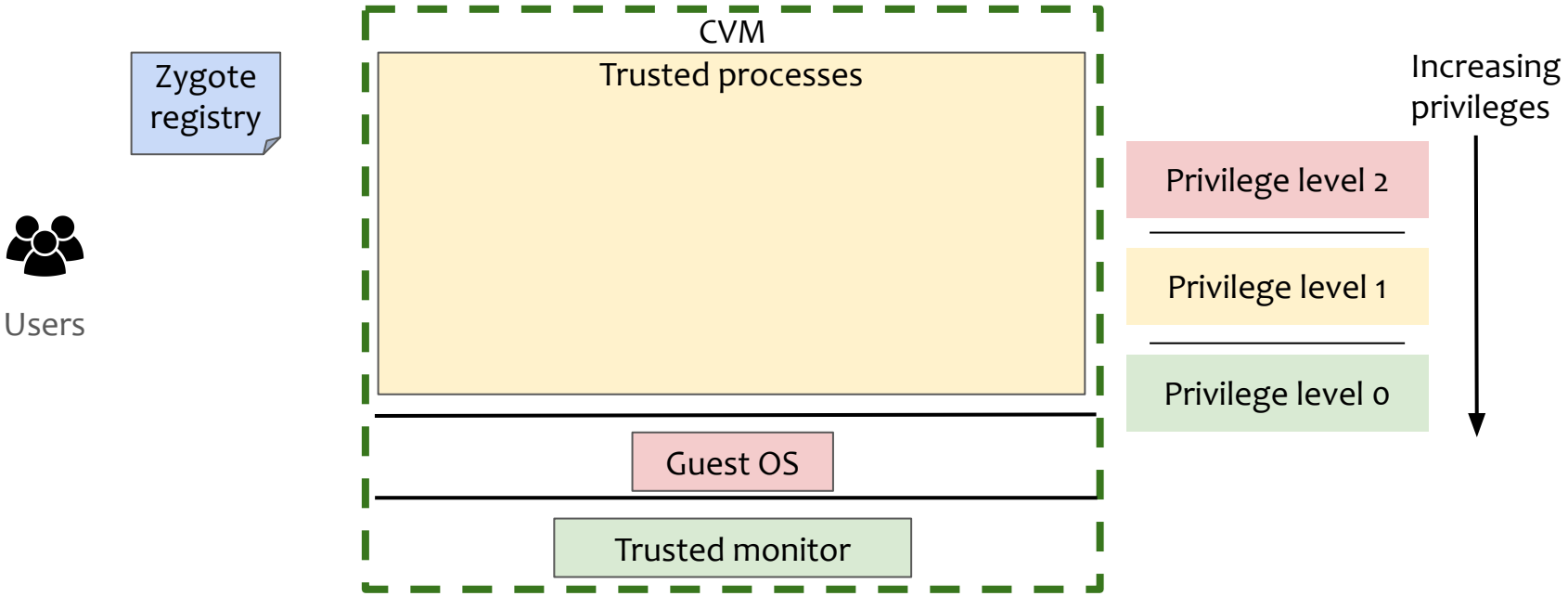


Shared-memory data objects optimize chaining of co-located functions

Deployment workflow - Trustlet



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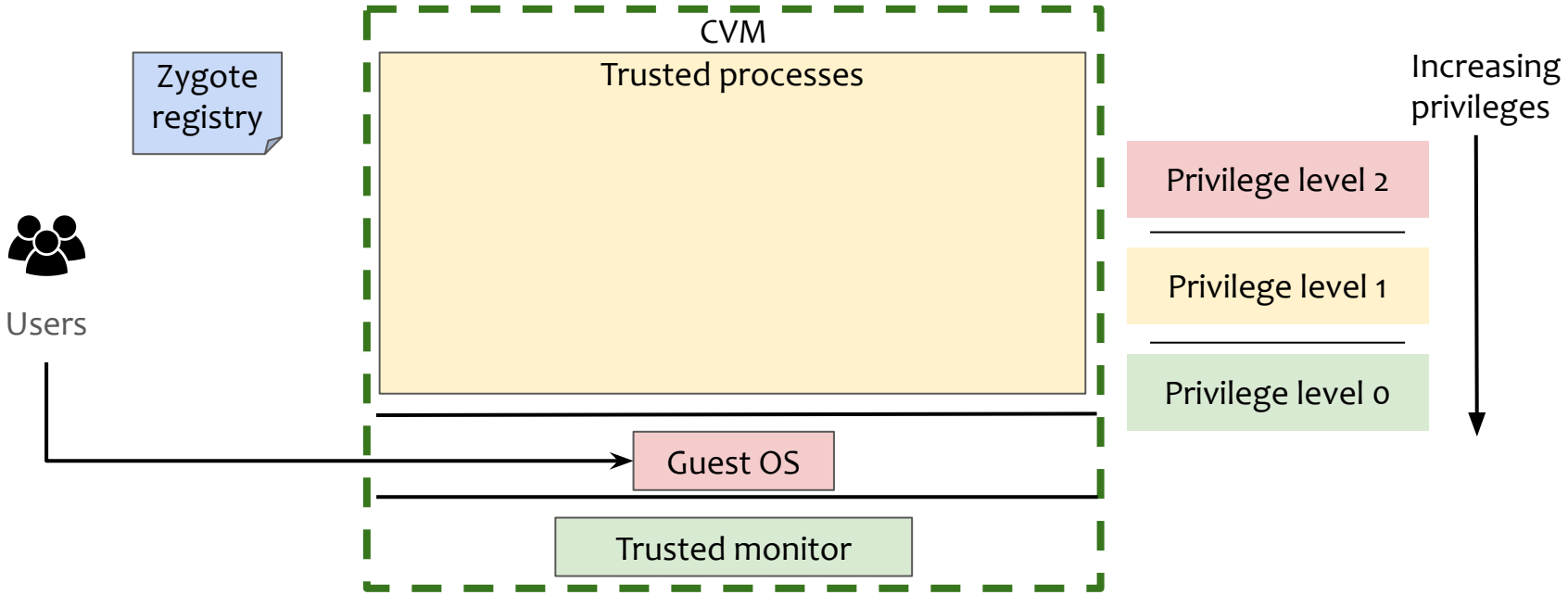

Deployment workflow - Trustlet

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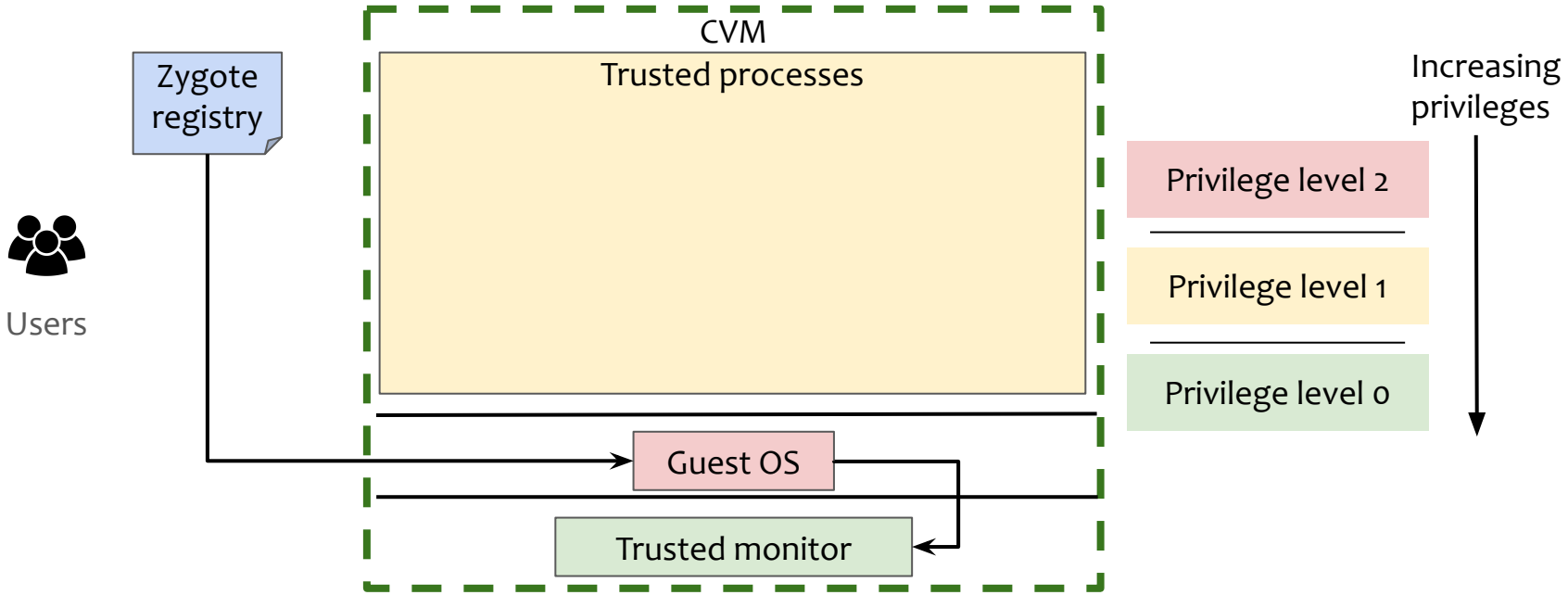

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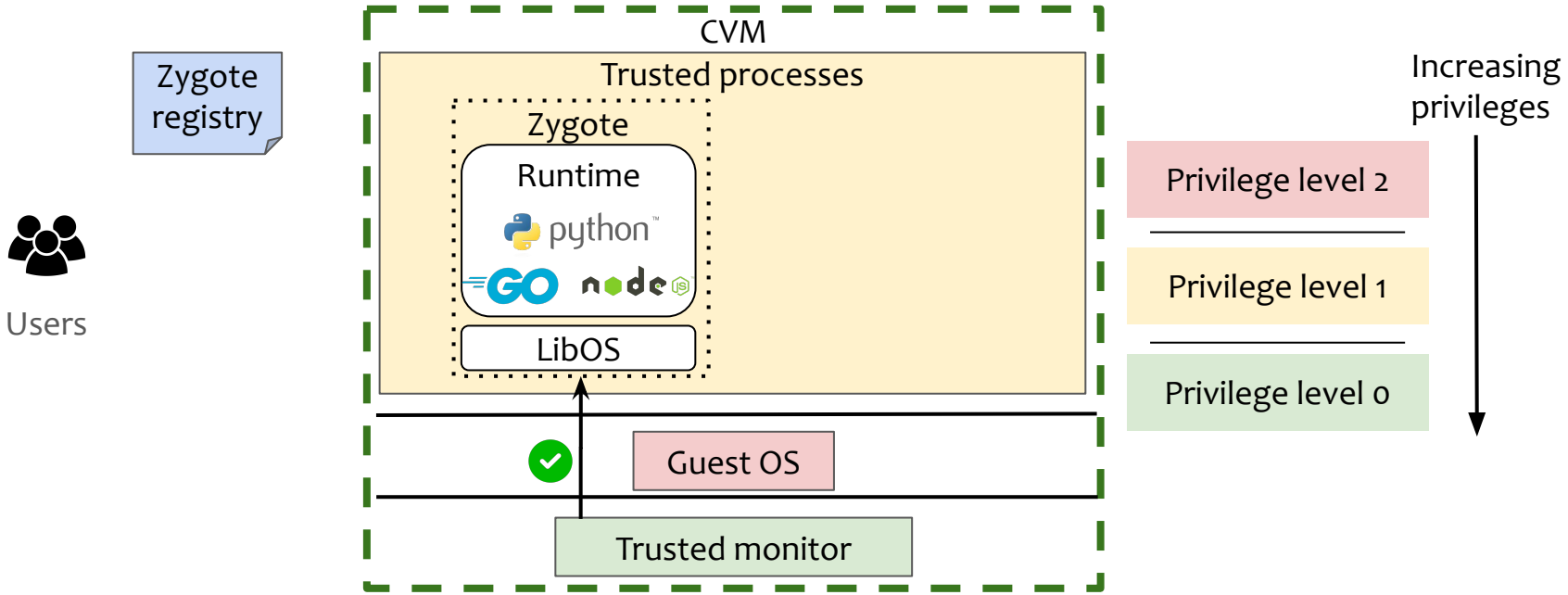
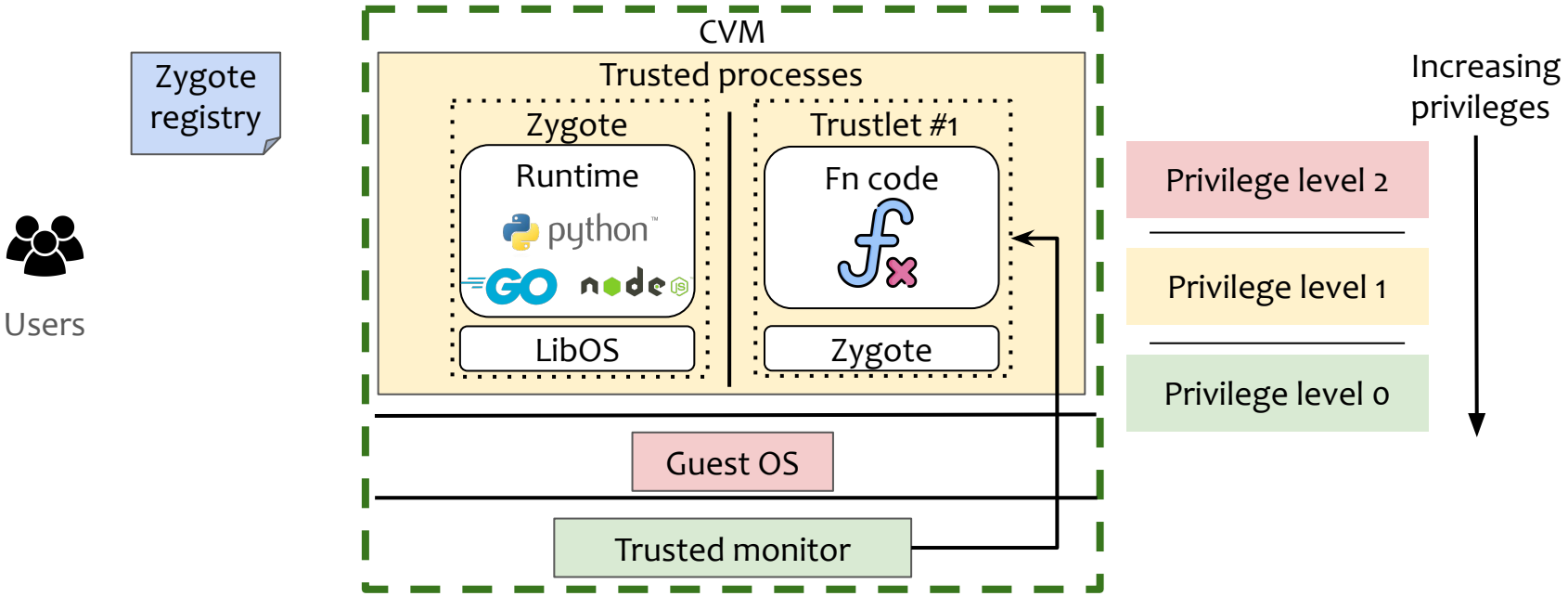


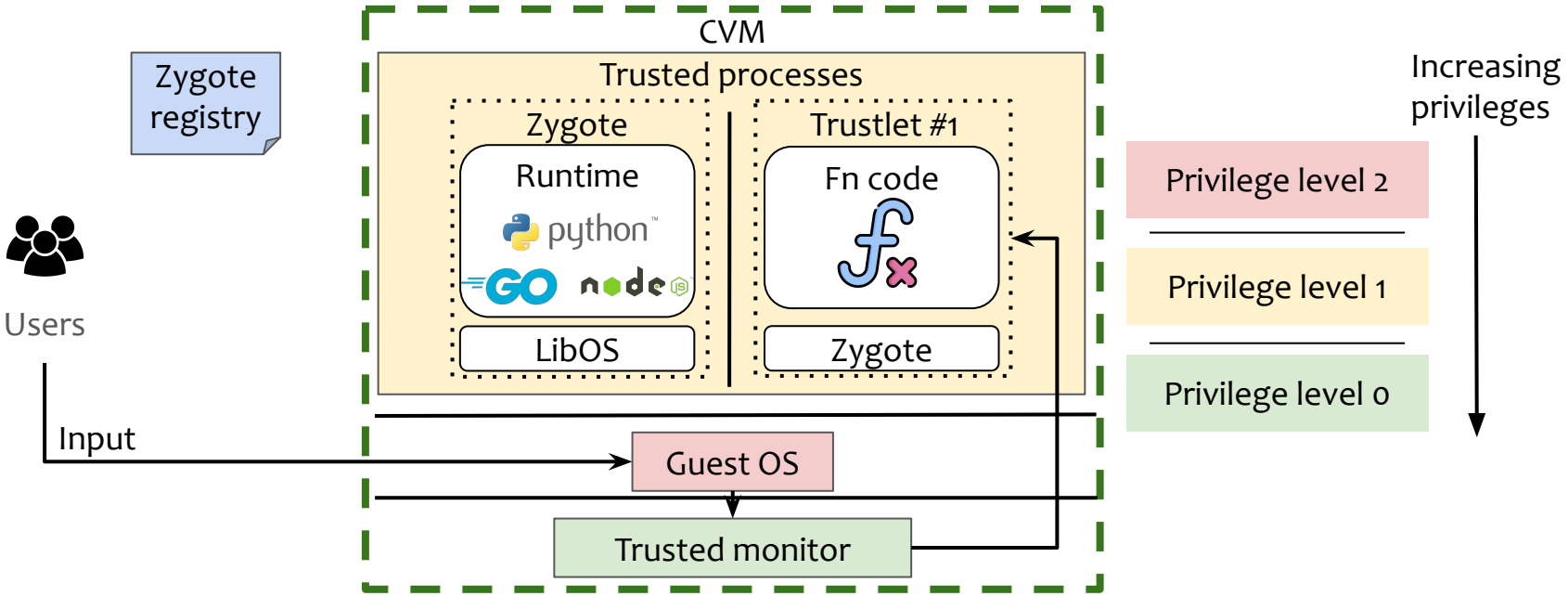
Deployment workflow - Trustlet

2. Create trustlet with function data (lukewarm start)



Deployment workflow - Trustlet

3. Invoke trustlet with user input (warm start)



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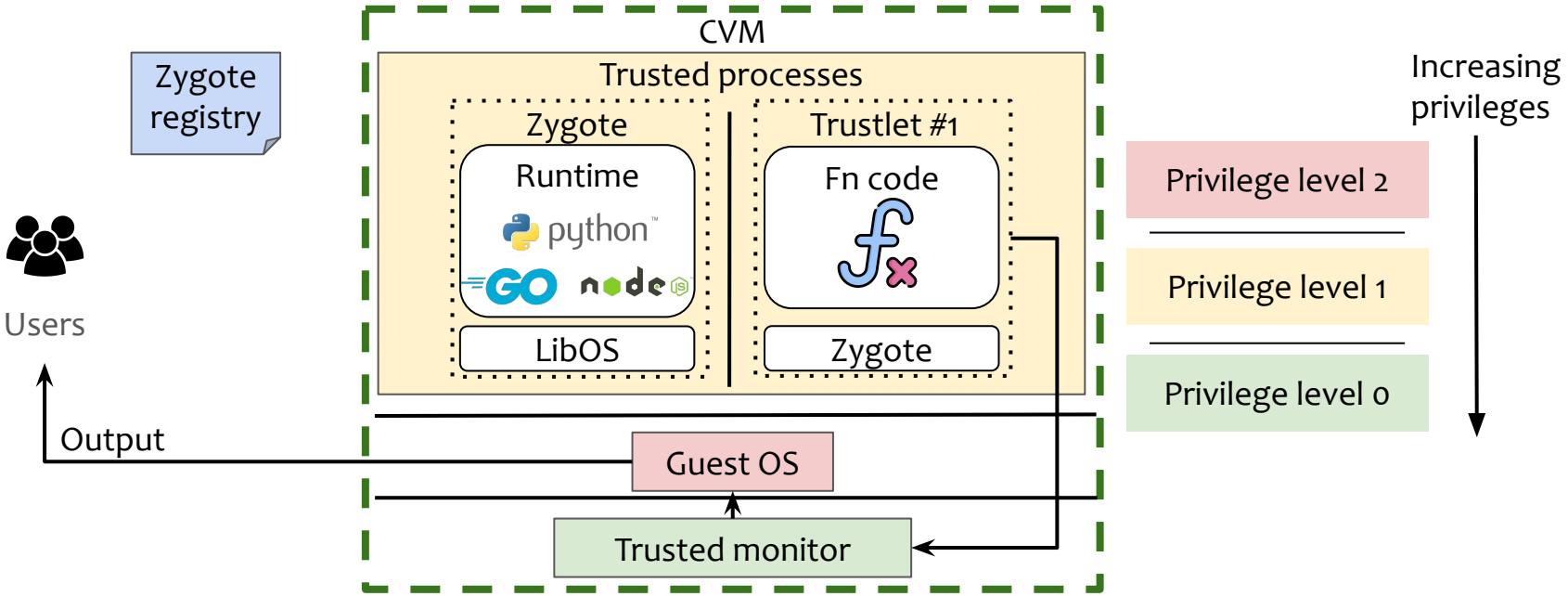
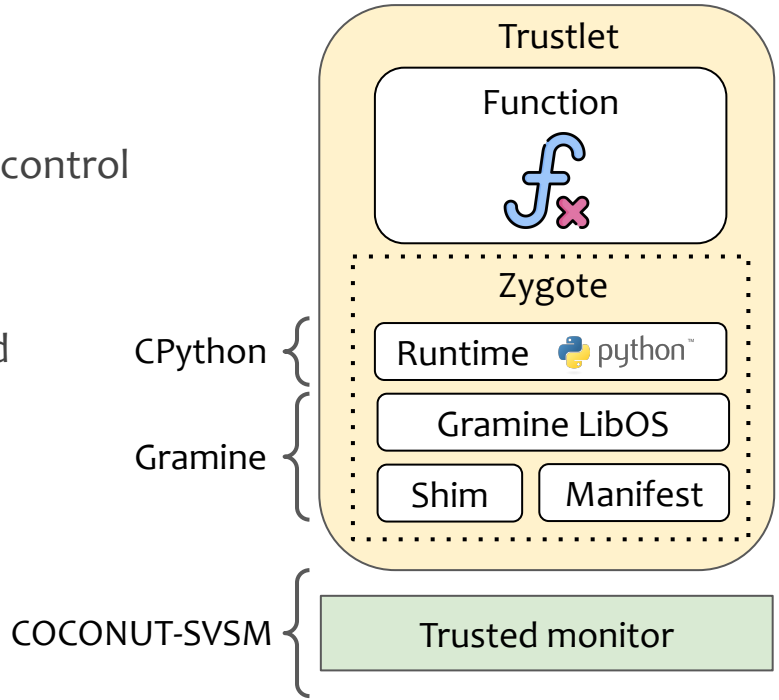


Outline

- ~~Motivation~~
- ~~Key idea~~
- ~~Design~~
- Implementation
- Evaluation

Implementation

- Monitor extends **COCONUT-SVSM**
  - New monitor and communication API calls
  - Interface for privilege-level-based process control
- **Gramine** as our chosen libOS
  - Bundle a static filesystem
  - Manifest specifies how application is called
- **CPython**-based runtime
  - Provides runtime via static filesystem



[1] Coconut-svsm: https://github.com/coconut-svsm/svsm
[2] Gramine: https://gramineproject.io/

Outline

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Evaluation

- Experimental setup:
  - AMD EPYC 7713P 64 cores
  - 1 TB DDR4 memory
  - Host & guest kernel: 6.8 & 6.5 with VMPL enhancements

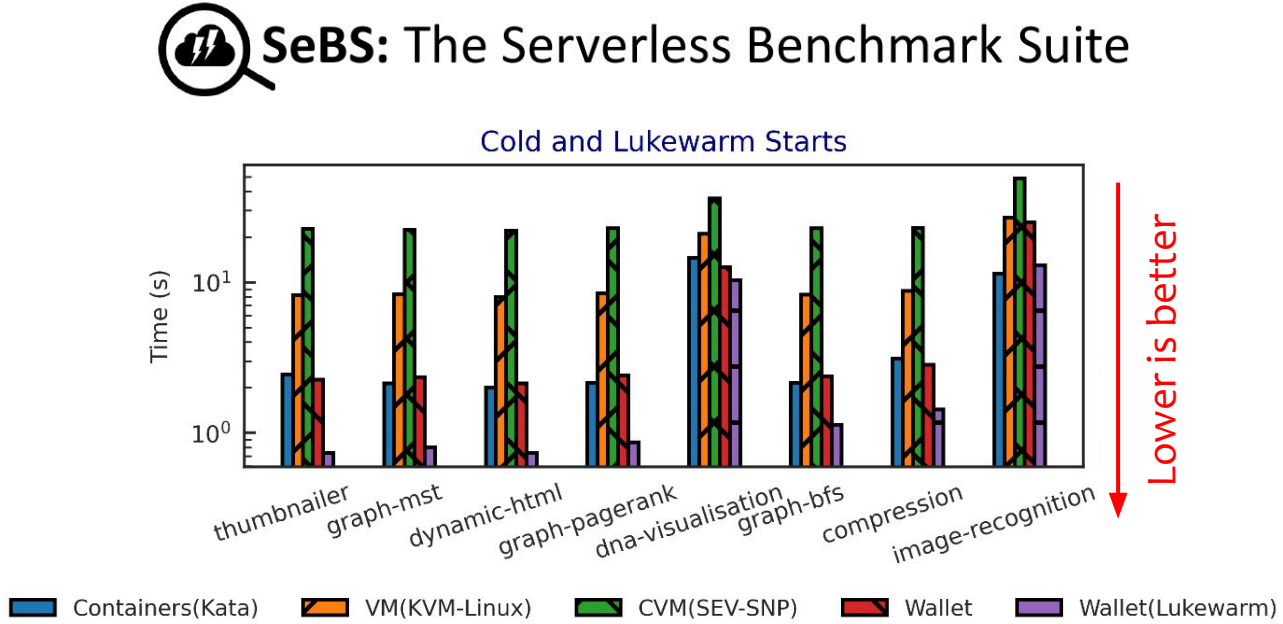
- Benchmarking variants:
  - **Container:** Kata Container runtime using Qemu
  - **VM:** Function in a standard VM with Linux kernel
  - **CVM:** Function in a AMD SEV-SNP VM with Linux kernel
  - **Wallet:** Execution of functions in Wallet framework (single CVM)

Evaluation

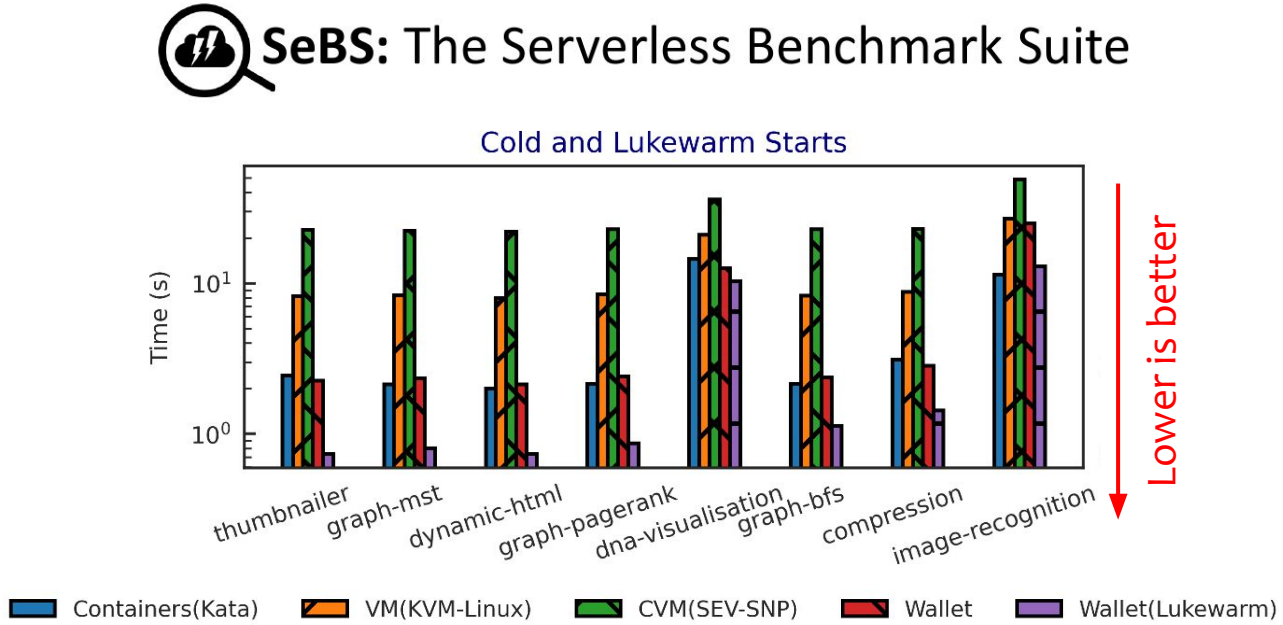
- Questions
  - What is Wallet's **end-to-end performance** in real-world serverless functions?
  - How does Wallet's communication mechanism perform with **function chaining**?
  - How does the Wallet's **Copy-on-Write** affect memory usage?

- For more results please refer to the paper

Performance



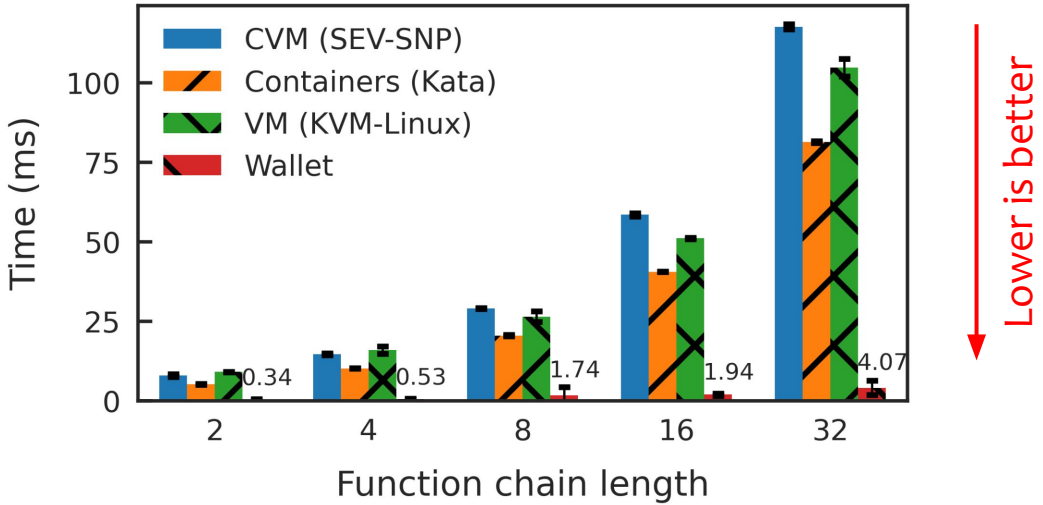
Performance



Wallet achieves lower end-to-end latencies compared to CVM deployments **(85%/93%)**

Communication channel performance

Latency of functions with fixed message size (16 kB) and increasing chain length



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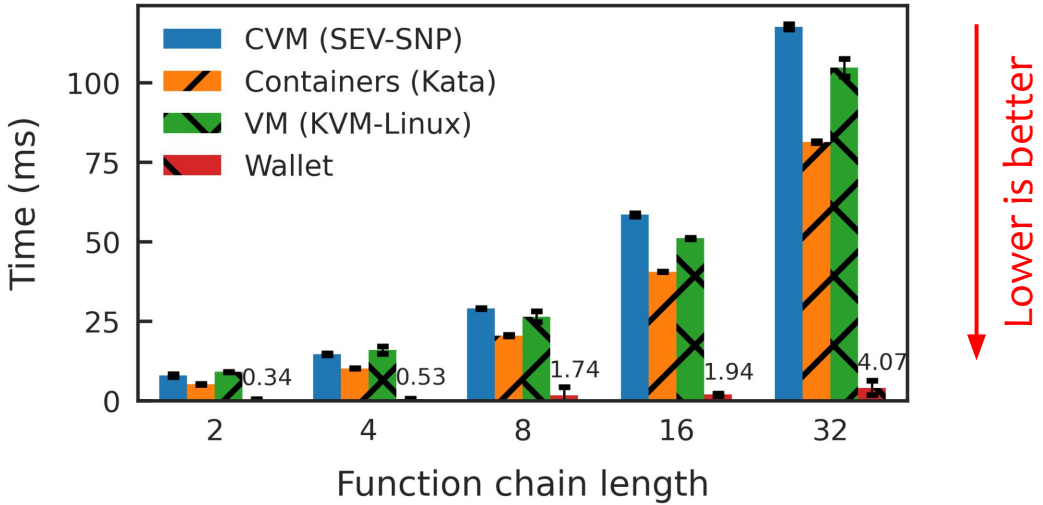
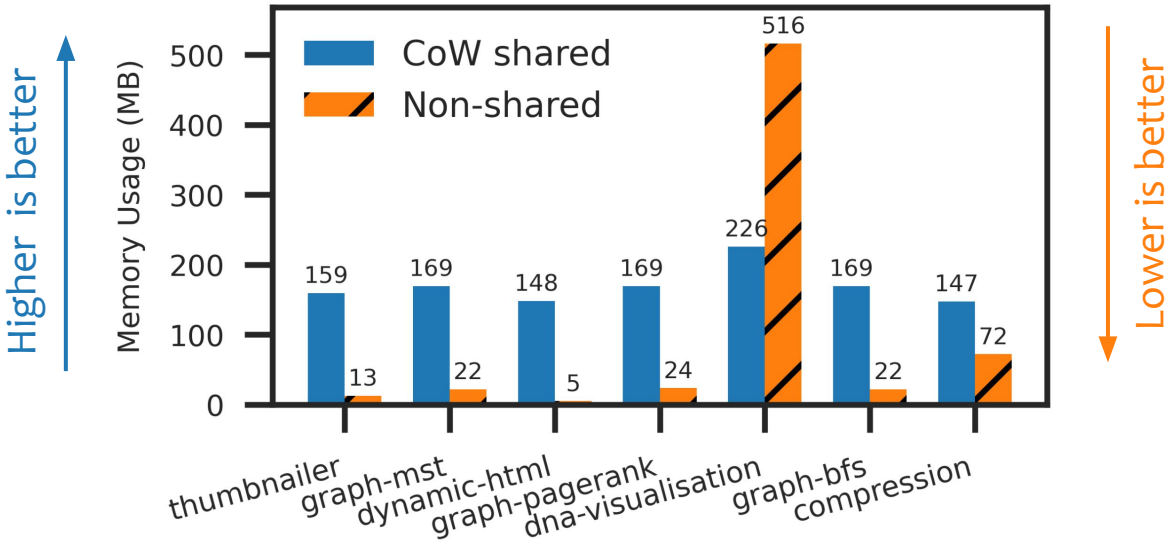


Wallet achieves low communication latency even with long chains (up to **30x**)

Copy-on-Write performance

Split between memory pages after trustlet execution



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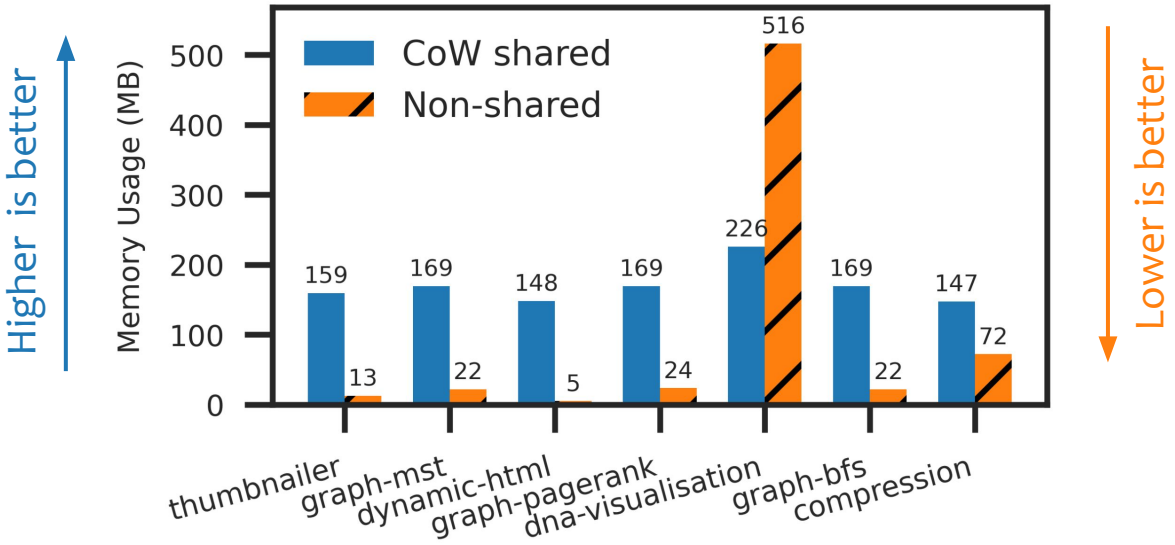

Wallet lowers memory requirements through its CoW mechanism (**78%** shared)

Summary

How do we enable **trustworthy serverless computing** in the cloud?

Wallet: Confidential Serverless Computing

- Small TCB and fast boot: Minimal trusted monitor, libOS-based functions
- Efficient function chaining: Direct shared-memory channels within a CVM
- Efficient resource utilization: Templated functions with CoW, privilege-level-based isolation

https://github.com/TUM-DSE/Wallet-VMPL