Aalto University

Research Institute for Collaborative Autonomous and Resilient Systems

UNIVERSITY OF WATERLOO

Trustworthy & Accountable Function-as-a-Service

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Function-as-a-Service (FaaS)

Recent instantiation of “serverless computing”

- Customer specifies the function
- Service provider manages runtime, scaling, load-balancing etc.

Differences to Infrastructure-as-a-Service (IaaS)

- Relatively short-running function invocations
- Stateless functions (storage provided by separate service)

Motivation

FaaS is available from established cloud providers

Usual security concerns of cloud computing still apply:

- Confidentiality of data
- Integrity of computation

Motivation

The Register®
Biting the hand that feeds IT

DATA CENTRE | SOFTWARE | SECURITY | **DEVOPS** | BUSINESS | PERSONAL TECH | SCIENCE | EMERGENT TECH | BOOTNOTES | LECTURES

DevOps

Whisk-y business: How Apache OpenWhisk hole left IBM Cloud Functions at risk of hijacking

Now-patched vulnerability let attackers overwrite code

By Shaun Nichols in San Francisco 24 Jul 2018 at 13:00 3 SHARE ▼

IBM has patched a critical vulnerability in its Cloud Functions platform that would have allowed miscreants to remotely overwrite customers' code – and execute malicious commands to hijack services.

https://www.theregister.co.uk/2018/07/24/apache_ibm_cloud_vulnerable/

Motivation

FaaS is available from established cloud providers

Usual security concerns of cloud computing still apply:

- Confidentiality of data
- Integrity of computation

More accurate resource usage measurements required:

- Sub-second compute time measurements

Currently achieved via existing reputational trust, but can we do better?

Motivation

FaaS can also be provided by non-traditional service providers

- Data centres with spare capacity
- Individuals with powerful PCs (e.g. gamers)

Open source frameworks available

https://openwhisk.apache.org/

Multiple start-ups in this space

https://golem.network/

https://ankr.com

Motivation

FaaS can also be provided by non-traditional service providers

- Data centres with spare capacity
- Individuals with powerful PCs (e.g. gamers)

Heightened security concerns:

- Service provider identity/location may be unknown
- Service provider may not have security expertise

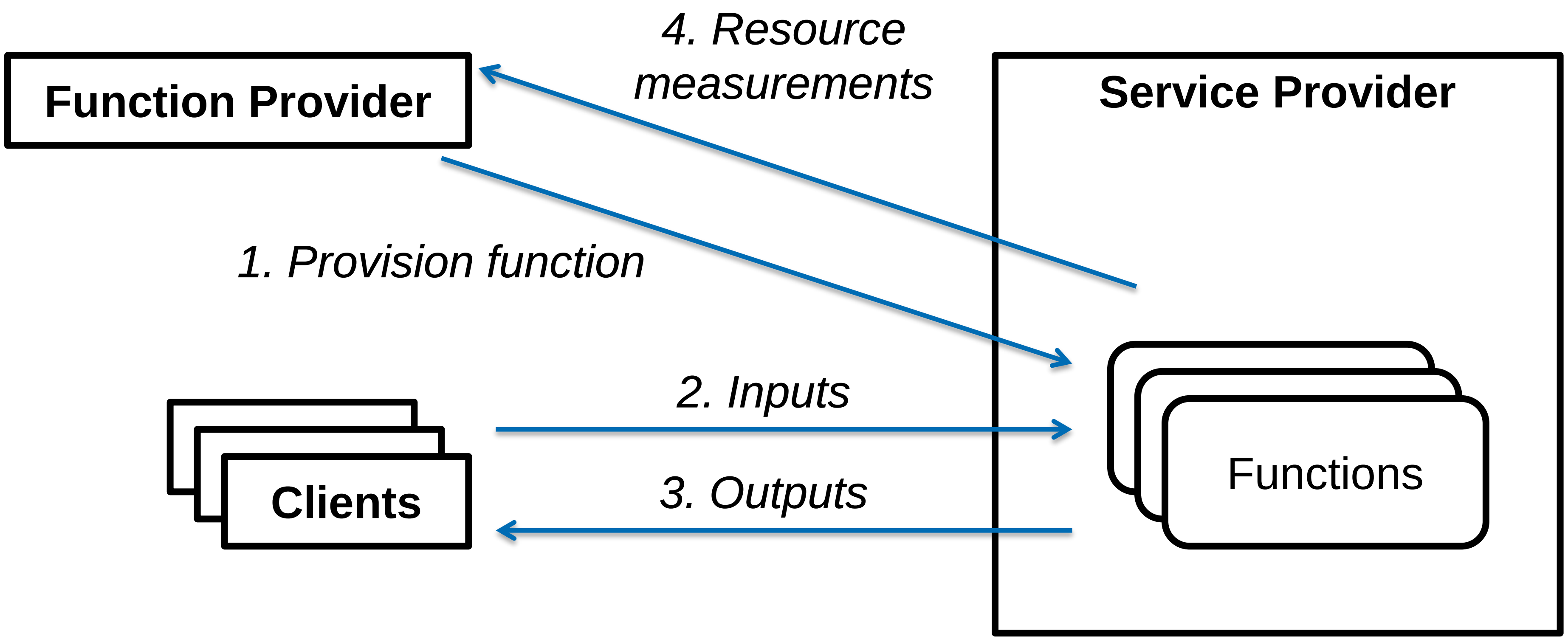
Very few disincentives for cheating:

- Malicious service provider might inflate resource usage measurements

No reputational trust has been established

System Model & Requirements

System model



Adversary model

Two types of adversaries:

Service provider

- Learn inputs and outputs of function invocations
- Modify inputs and outputs, or execute the function incorrectly
- Overcharge the function provider
  - Falsely inflate resource usage measurements
  - Create fake function invocations

Function provider

- Under-pay the service provider for resources used by the function

Requirements

R1 - Security

- Service provider cannot modify inputs or outputs of a function invocation
- Client assured that output is result of correct execution of intended function on supplied inputs

R2 - Privacy

- Service provider cannot learn inputs or outputs of a function invocation

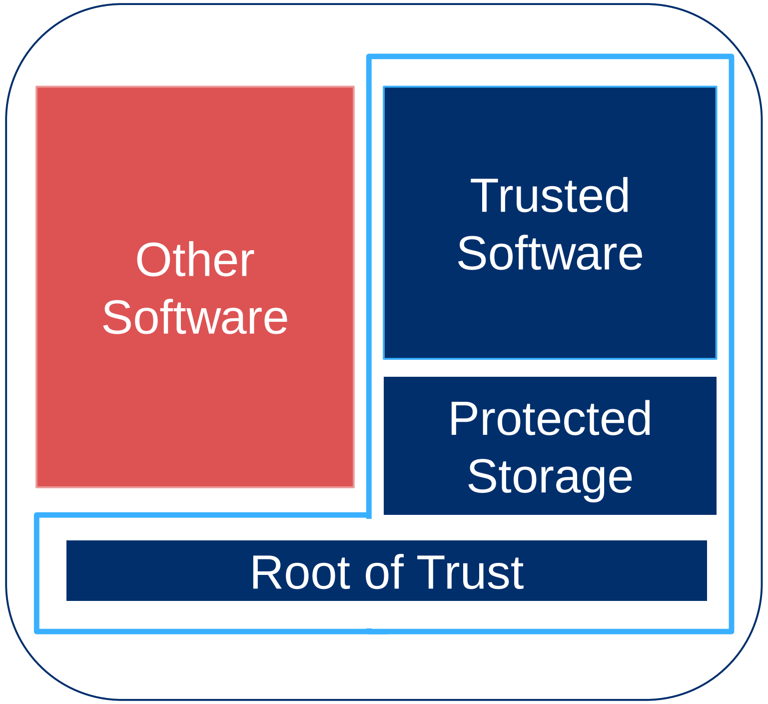
R3 - Measurement accuracy

- Resource measurements must have sufficient accuracy for FaaS billing

R4 - Measurement veracity

- All parties must be able to verify authenticity of resource measurements

Trusted Execution Environments



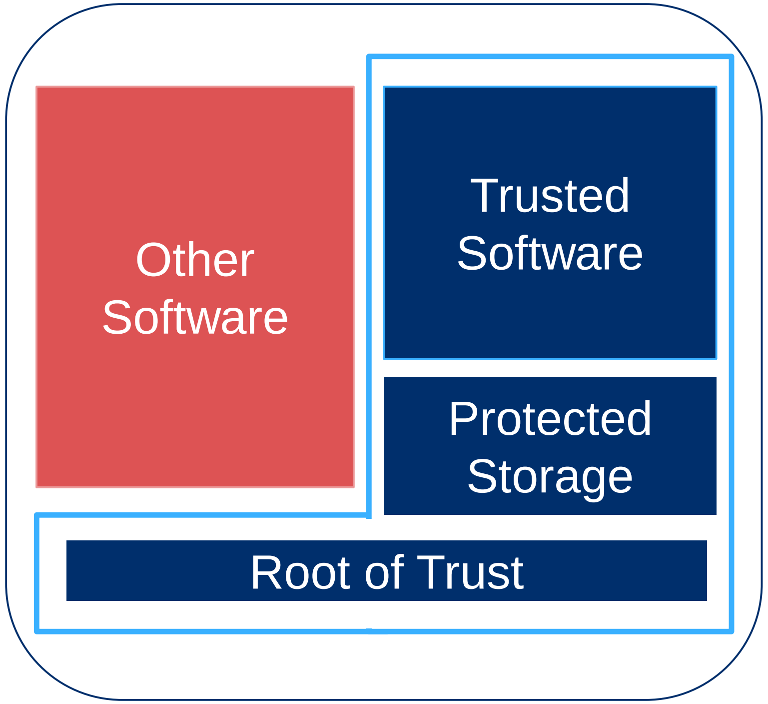
Hardware support for

- **Isolated execution: Isolated Execution Environment**
- **Protected storage: Sealing**
- **Ability to convince remote verifiers: (Remote) Attestation**

Trusted Execution Environments (TEEs)

Operating in parallel with “rich execution environments” (REEs)

Hardware-assisted TEEs are pervasive



Hardware support for

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Trusted Execution Environments (TEEs)

Operating in parallel with "rich execution environments" (REEs)

Cryptocards

https://www.ibm.com/security/cryptocards/

Trusted Platform Modules

https://www.infineon.com/tpm

ARM TrustZone

arm

https://www.arm.com/products/security-on-arm/trustzone

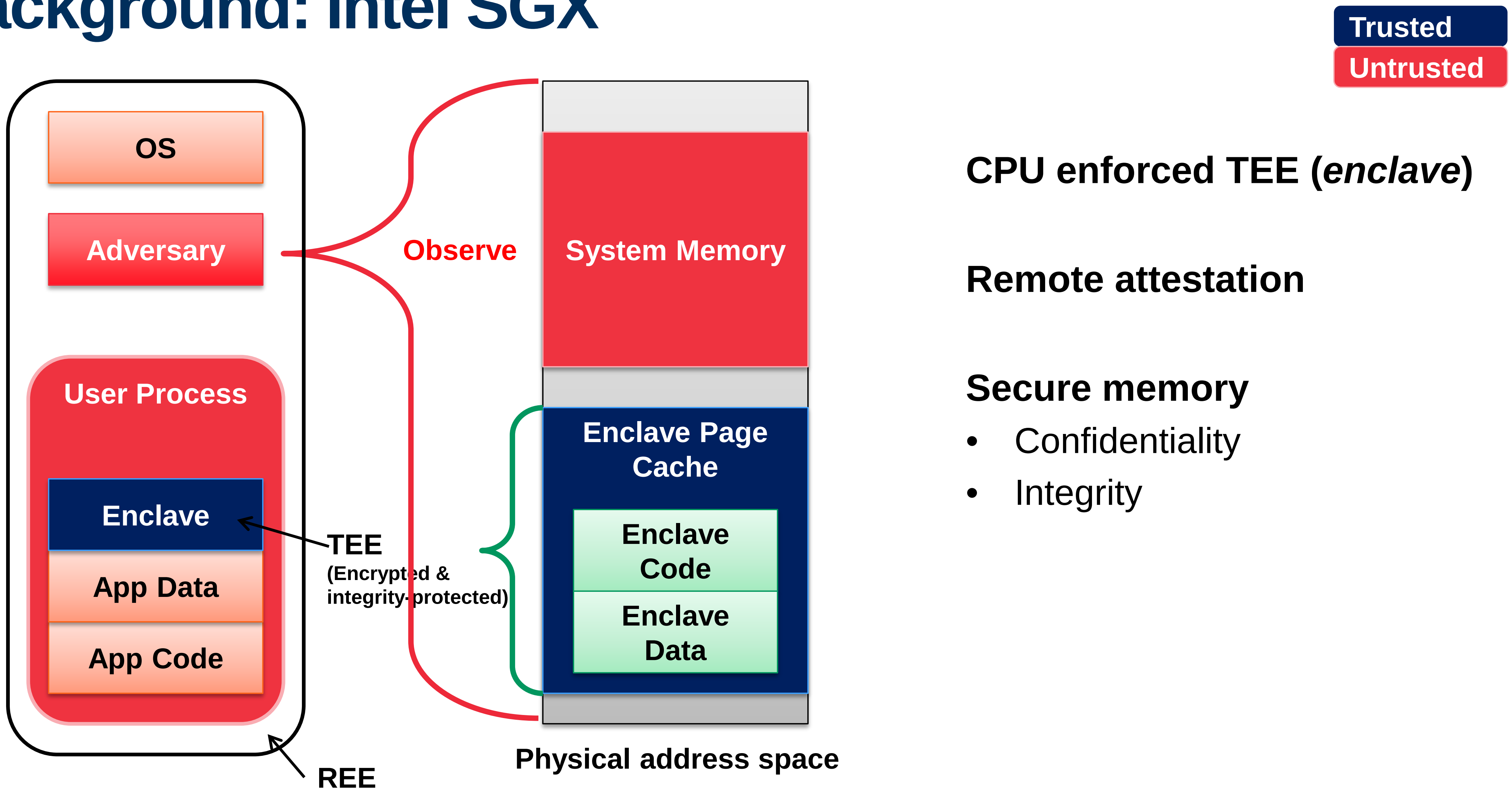
Intel Software Guard Extensions

intel

https://software.intel.com/en-us/sgx

[A+14] "Mobile Trusted Computing", Proceedings of the IEEE, 102(8) (2014)
[EKA14] "Untapped potential of trusted execution environments", IEEE S&P Magazine, 12:04 (2014)

Background: Intel SGX



CPU enforced TEE (*enclave*)

Remote attestation

Secure memory

- Confidentiality
- Integrity

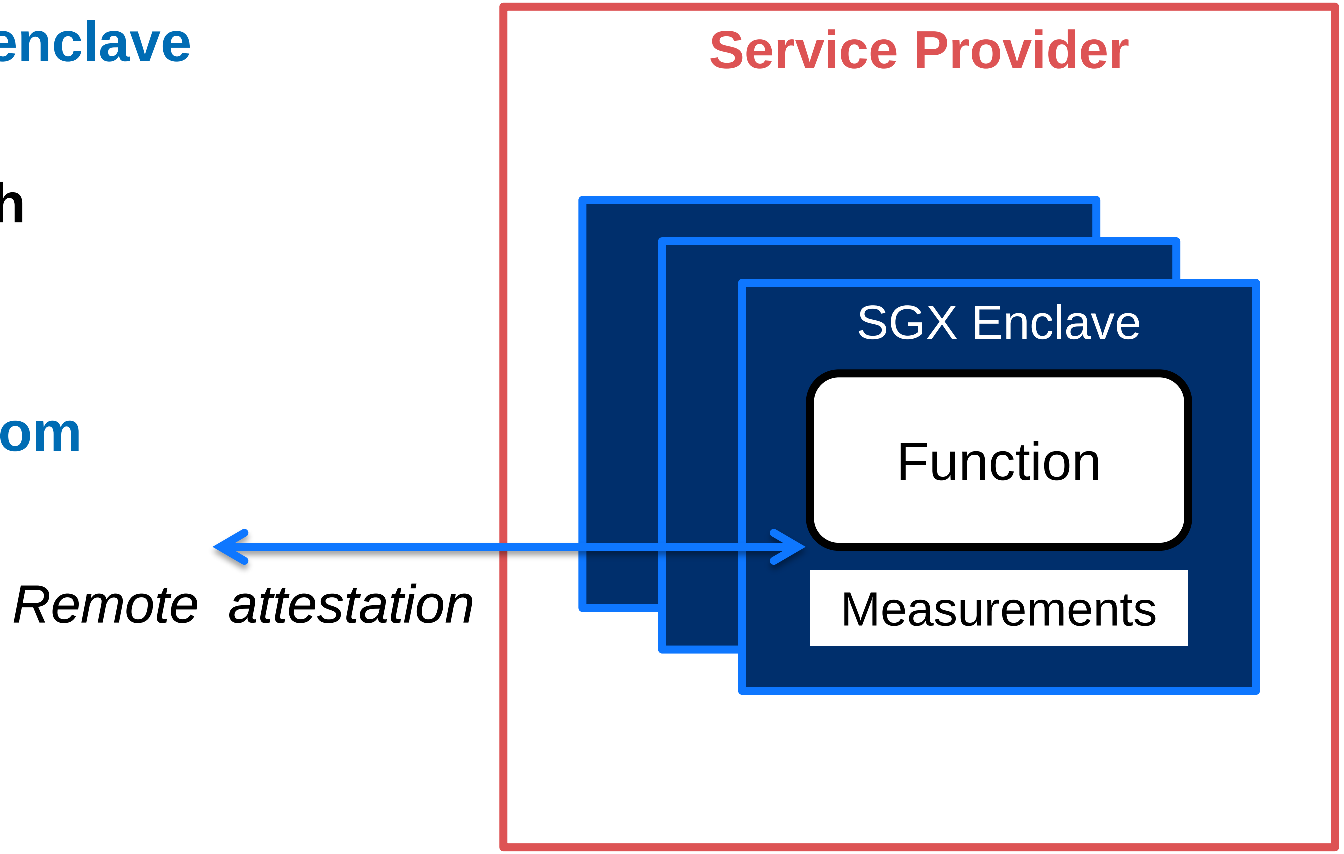
https://software.intel.com/sgx

Preliminary design

Execute each function in an SGX enclave

Use remote attestation to establish secure communication channels

Measure resource consumption from within the enclave

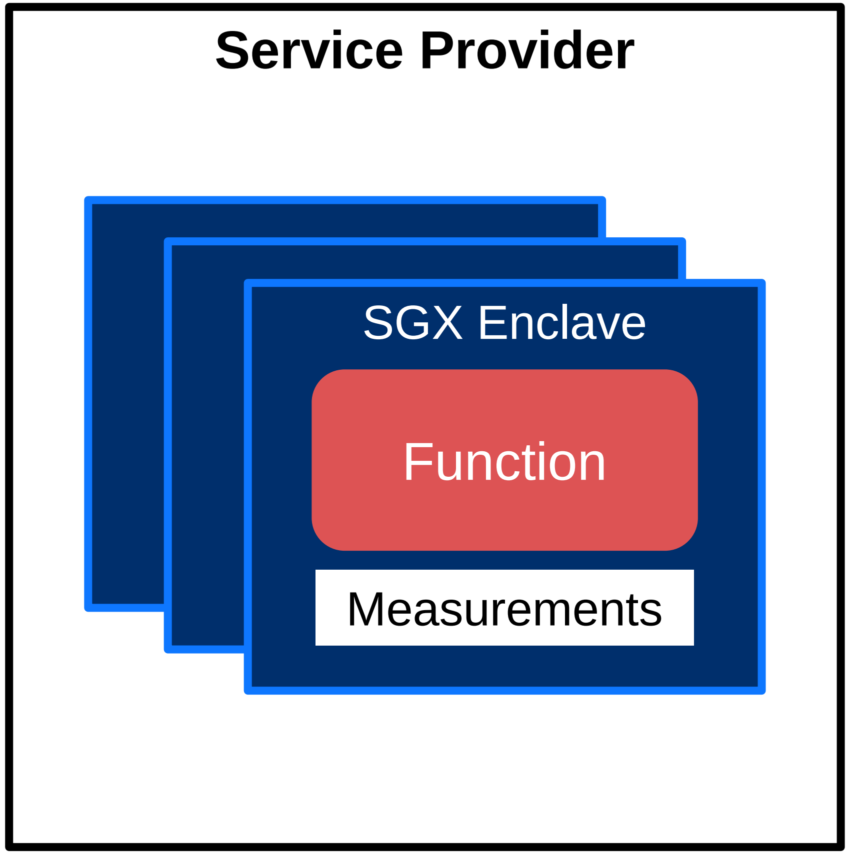


Design Challenges

Challenge: Sandboxing untrusted functions

Malicious function provider could attempt to reduce in-enclave measurements

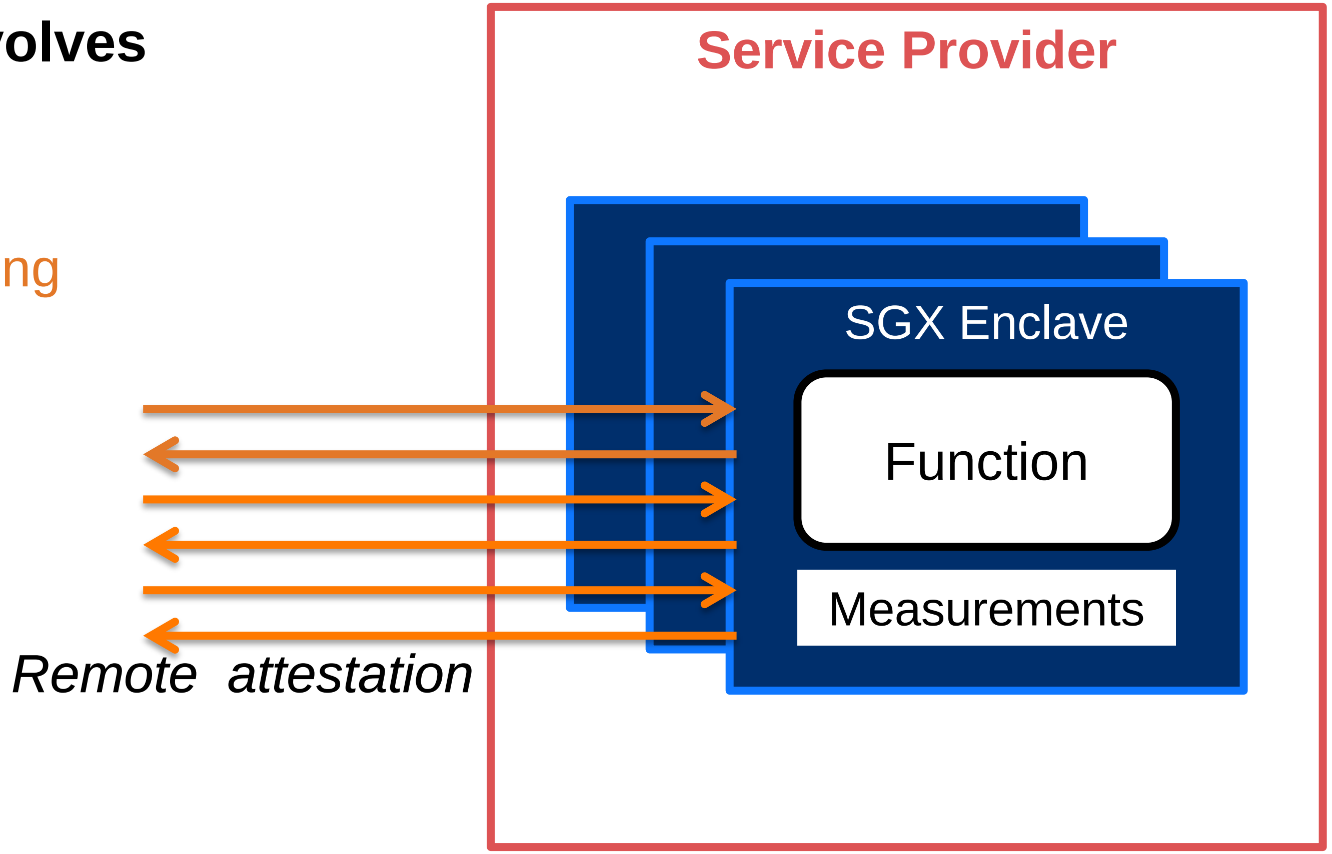
- No protection from code in the same enclave



Challenge: Attesting worker enclaves

Default SGX remote attestation involves multiple message round-trips

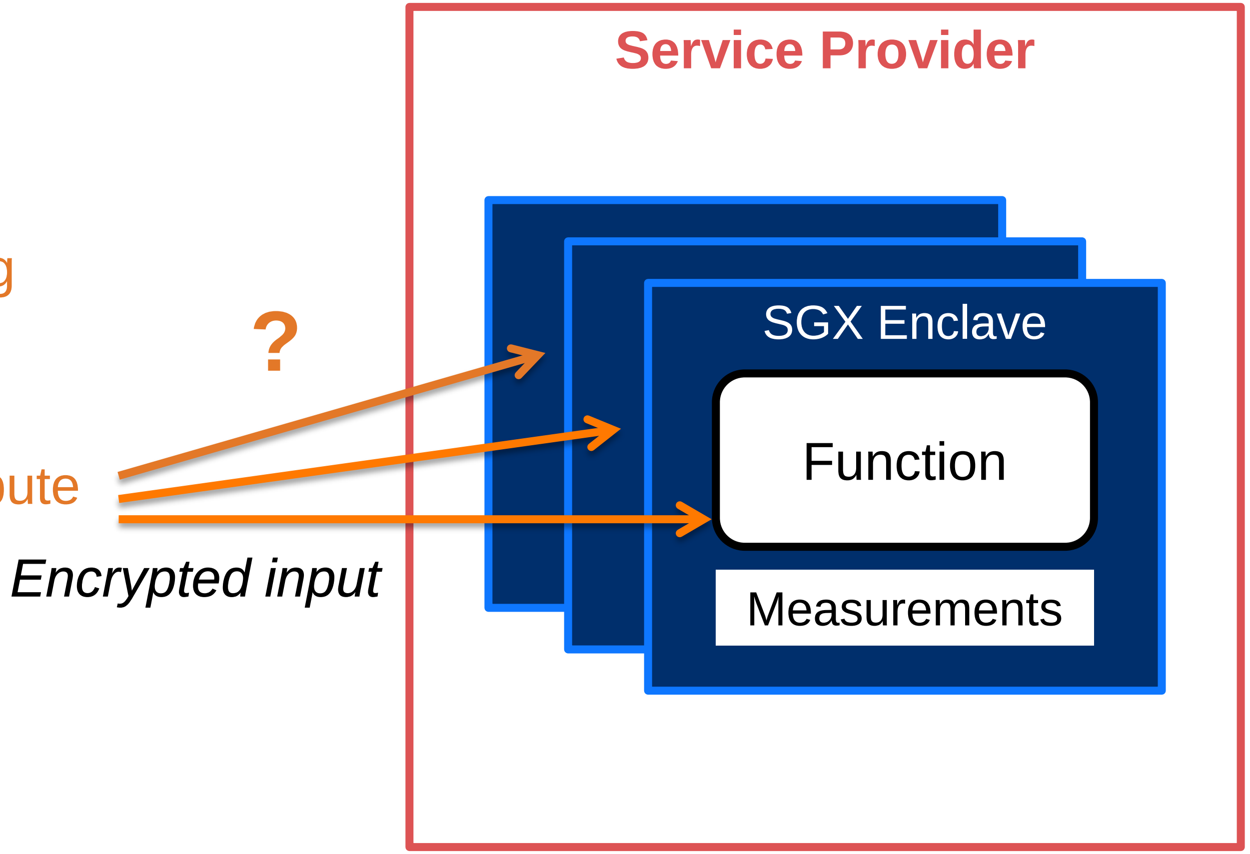
- Overhead and latency for short-running functions is too high
- Must be repeated for each enclave



Challenge: Encrypting client input

Function invocation is a one-shot message, including (encrypted) input

- Client must encrypt input *before* knowing which enclave will run the function
- Cannot rely on service provider to distribute keys to worker enclaves

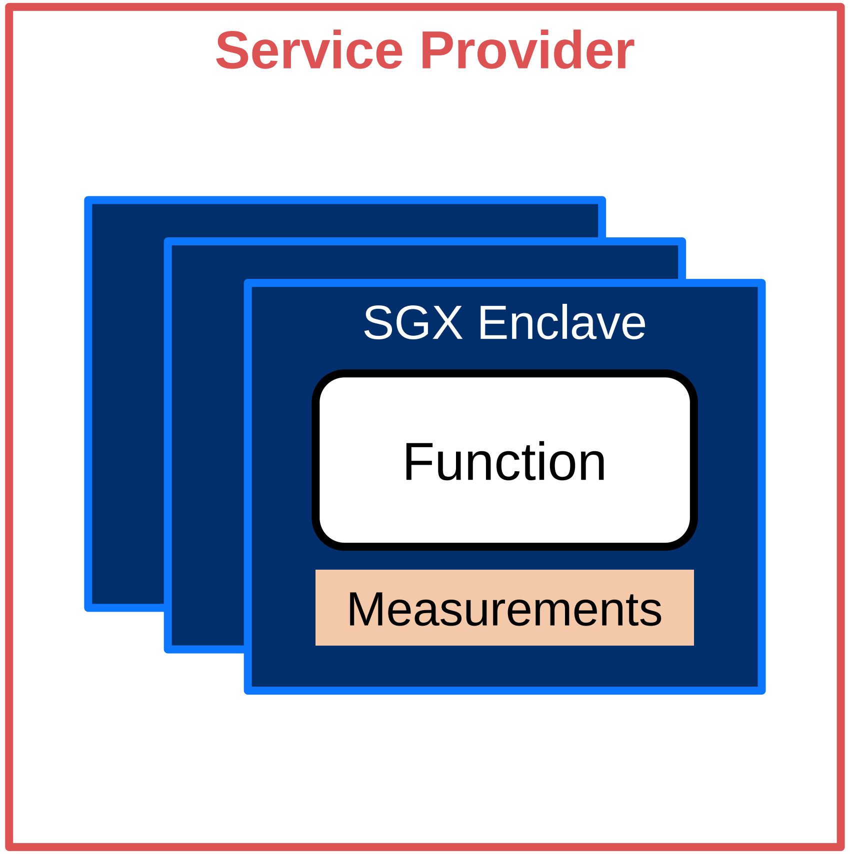


Challenge: Measuring time in enclaves

CPU instructions
RDTSC: read timestamp counter
AEX: asynchronous enclave exit
ERESUME: resume enclave

SGX enclave cannot reliably measure its own running time

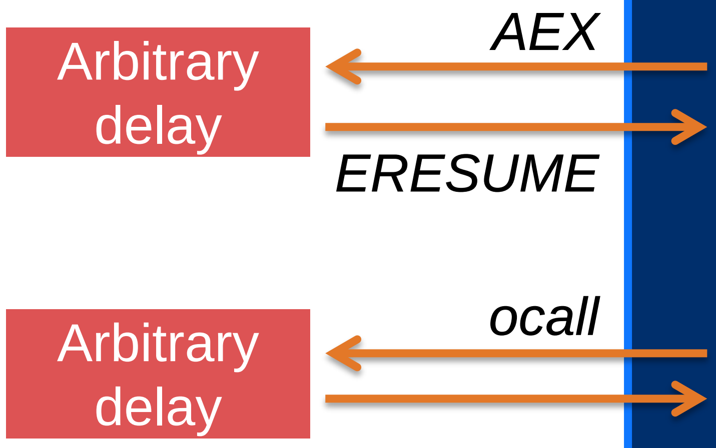
- `RDTSC` value can be manipulated by VMM
- `sgx_get_trusted_time()` can be arbitrarily delayed
- Enclaves can be transparently interrupted (AEX) and resumed (ERESUME)



Challenge: Measuring time in enclaves

VERICOUNT:

call `sgx_get_trusted_time()` at ecall start & end




```
ecall_to_measure()
{
    t1 = sgx_get_trusted_time();
          .
    [function code]
          .
          .
          .
          .
    t2 = sgx_get_trusted_time();
    time = t2 – t1;
}
```

Tople et al., "[VeriCount: Verifiable Resource Accounting Using Hardware and Software Isolation]()", ACNS 2018

S-FaaS Architecture

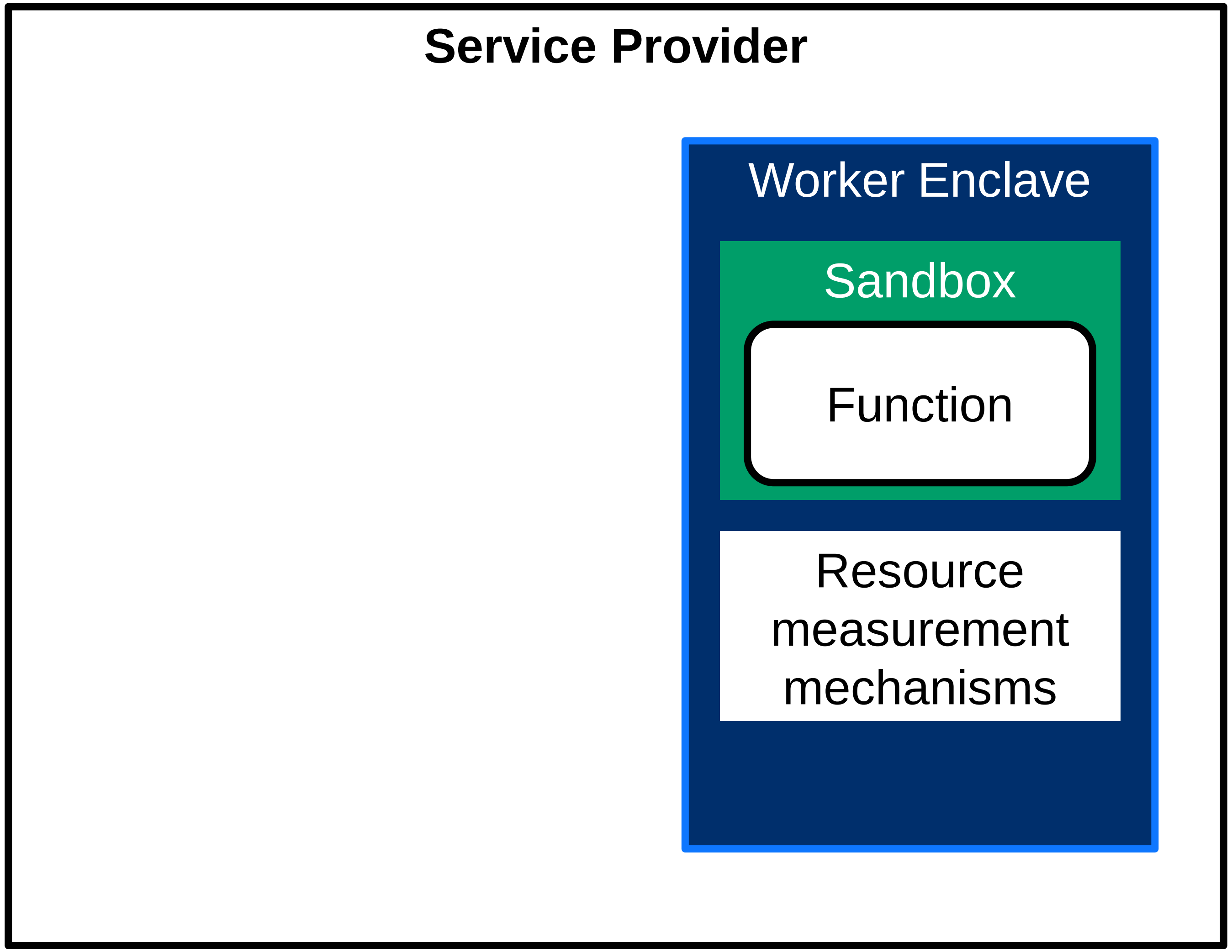
Architecture overview

Worker enclave runs function within a sandbox

- e.g. Ryoan
- sandboxing interpreters: e.g. for JavaScript

Challenges

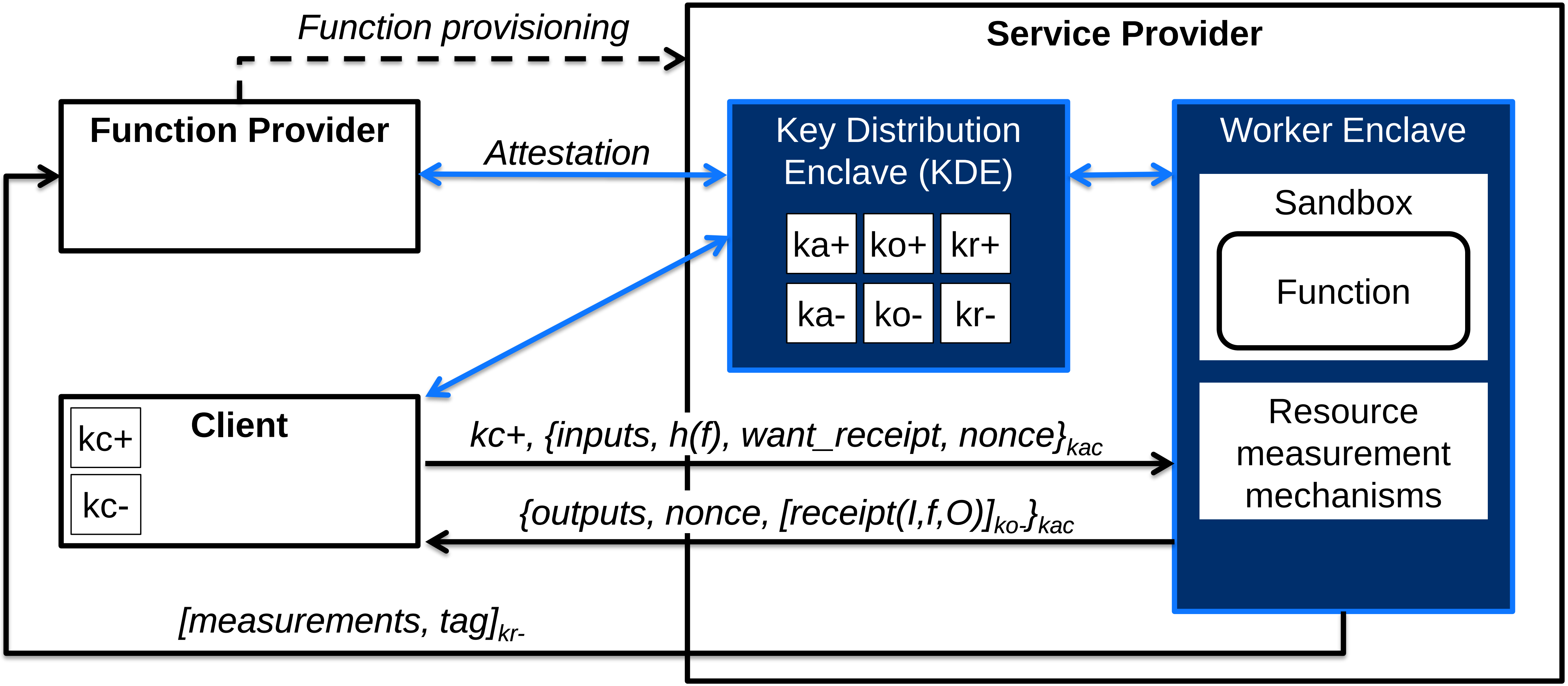
C1: Sandboxing
C2: Attesting enclaves
C3: Encrypting input
C4: Measuring time



Hunt et al., "[Ryoan: A Distributed Sandbox for Untrusted Computation on Secret Data](#)", OSDI 2016

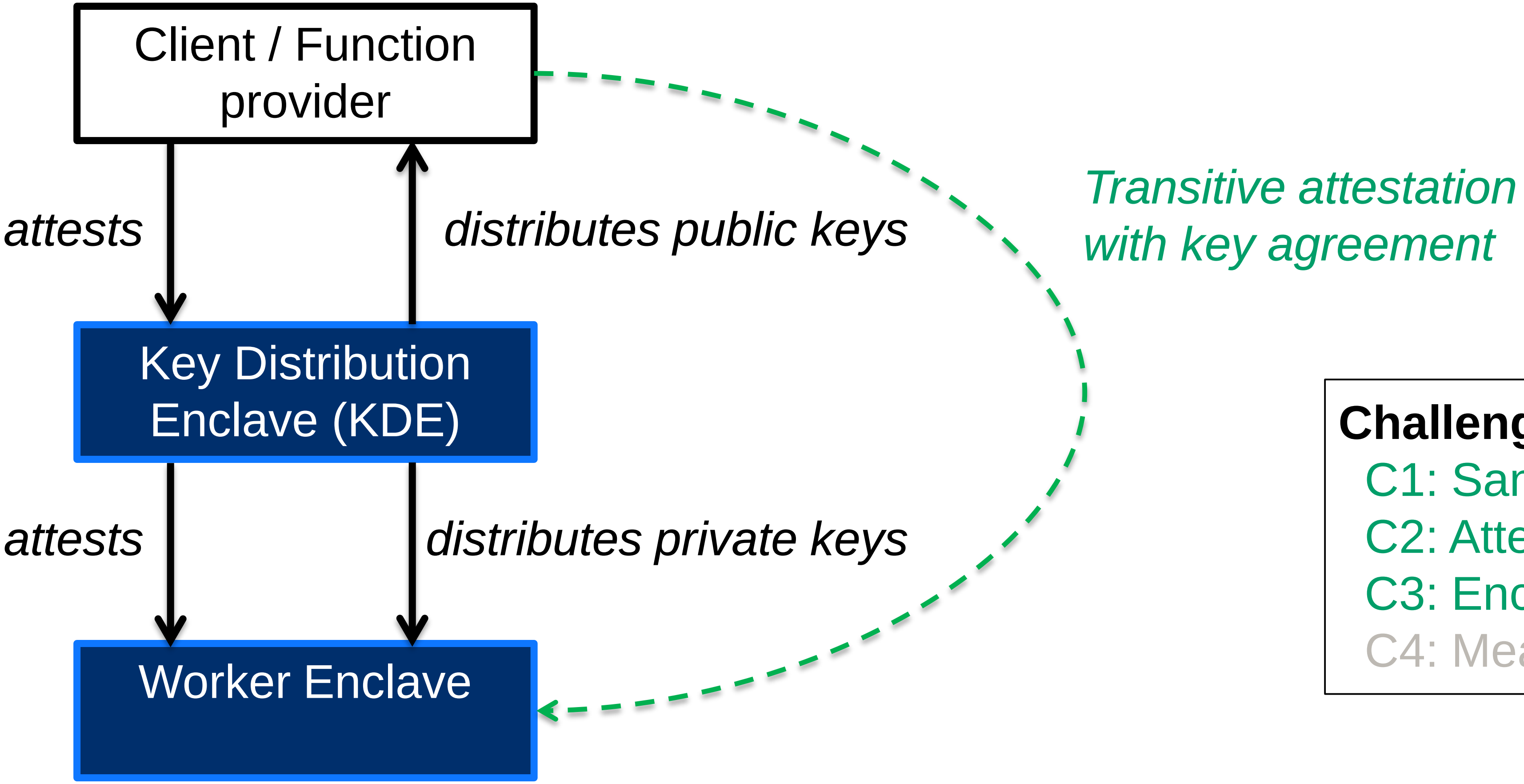
Architecture overview

ka: enclave's DH key
kc: client's DH key
ko: output key
kr: resource reporting key



Transitive attestation

Clients and function providers attest worker enclaves indirectly



Challenges

- C1: Sandboxing
- C2: Attesting enclaves
- C3: Encrypting input
- C4: Measuring time

Measuring Resource Usage in SGX

Motivation

FaaS is available from established cloud providers

Service	Invocations	Time (GHz-s)	Memory (GB-s)	Network (GB)
AWS Lambda	X	O	X	
Azure Functions	X	O	X	
Google Cloud Functions	X	X	X	X
IBM Cloud functions	X	O	X	

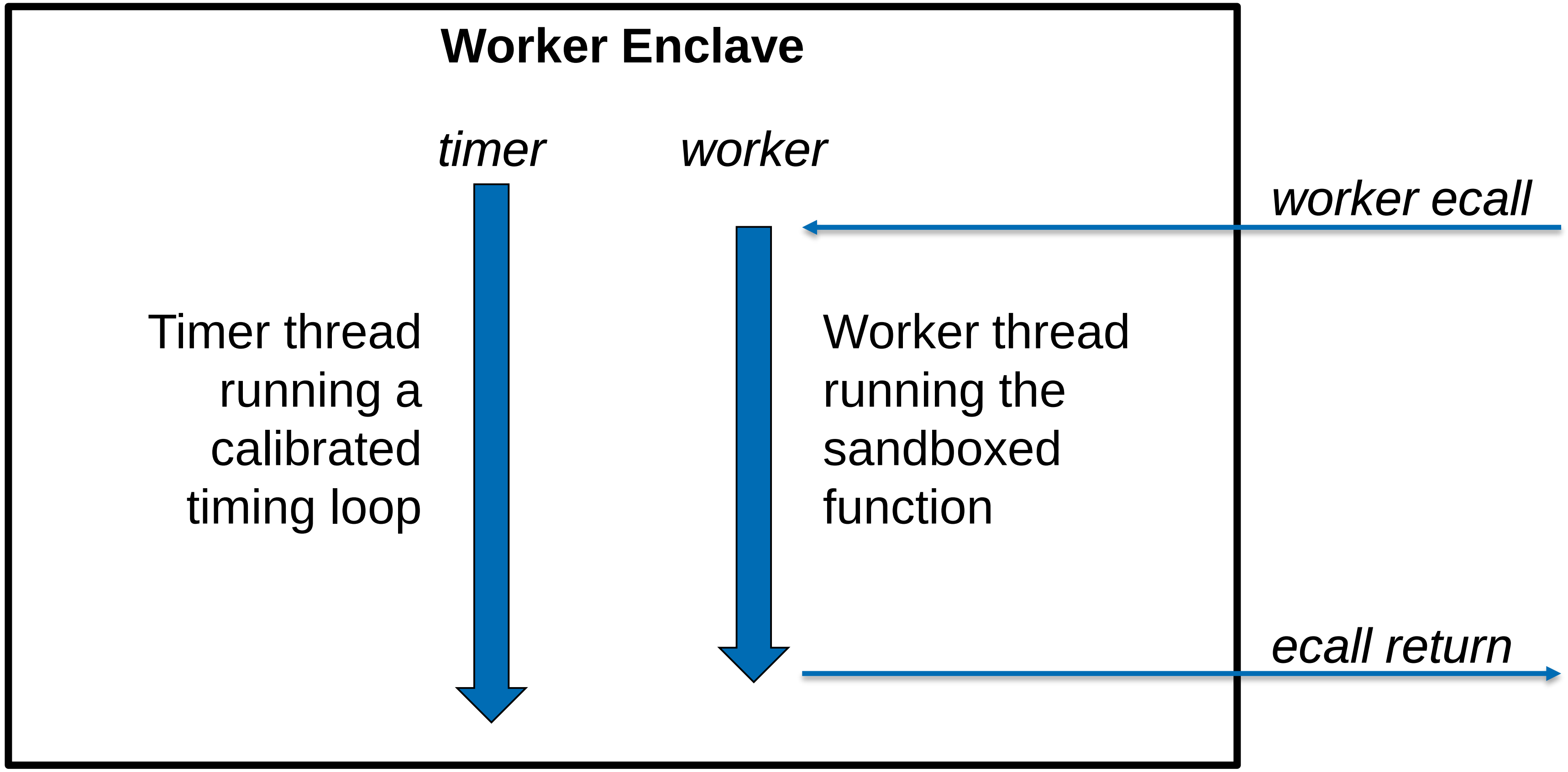
FaaS billing policies of established cloud providers *(X = explicit; O = implicit)*

Types of measurements

Symbol	Description	Units
t	Total compute time of the function	multiples of Ƭ
Ƭ	Duration of each tick in CPU cycles	GHz-s
$\mathbf{m_{int}}$	Time-integral of memory usage	GB-s
$\mathbf{m_{max}}$	Maximum memory used by the function	GB
net	Total number of network bytes sent and received	GB

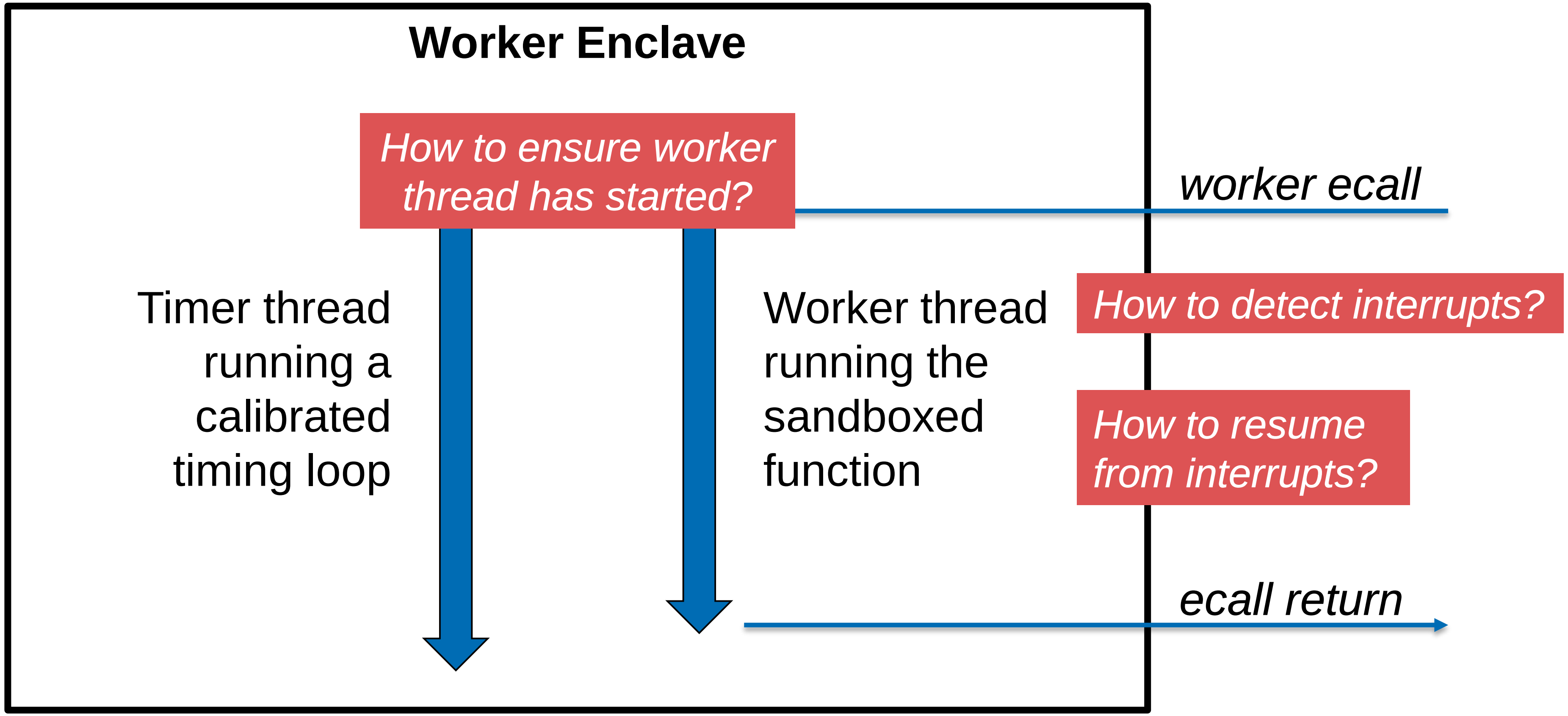
Measuring compute time

High level idea: two concurrent threads in the enclave (timer & worker)



Measuring compute time

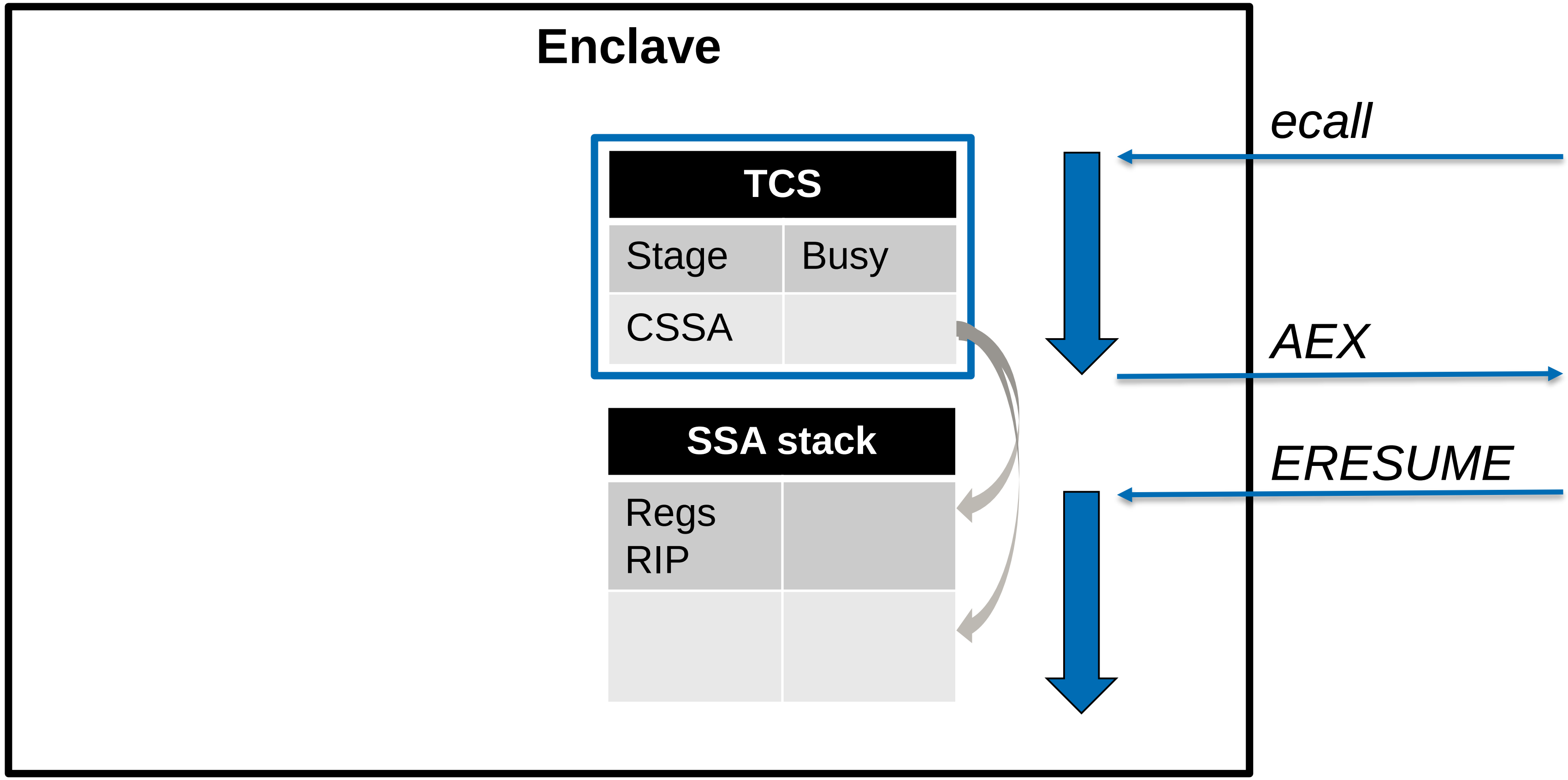
High level idea: two concurrent threads in the enclave (timer & worker)



Intel SGX internals

Enclave data structures
TCS: Thread Control Structure
(C)SSA: (Current) Save State Area

CPU Registers	
RAX	0xff…
RBX	
…	…
RSP	
RIP	0xff…



CPU Registers
RIP: Instruction Pointer
RSP: Stack Pointer

Intel Transactional Synchronization Extensions (TSX)

Special instructions enabling Hardware Lock Elision (HLE)

Read set

- Memory addresses read by the transaction (added upon access)
- Transaction will abort if address is concurrently written

Write set

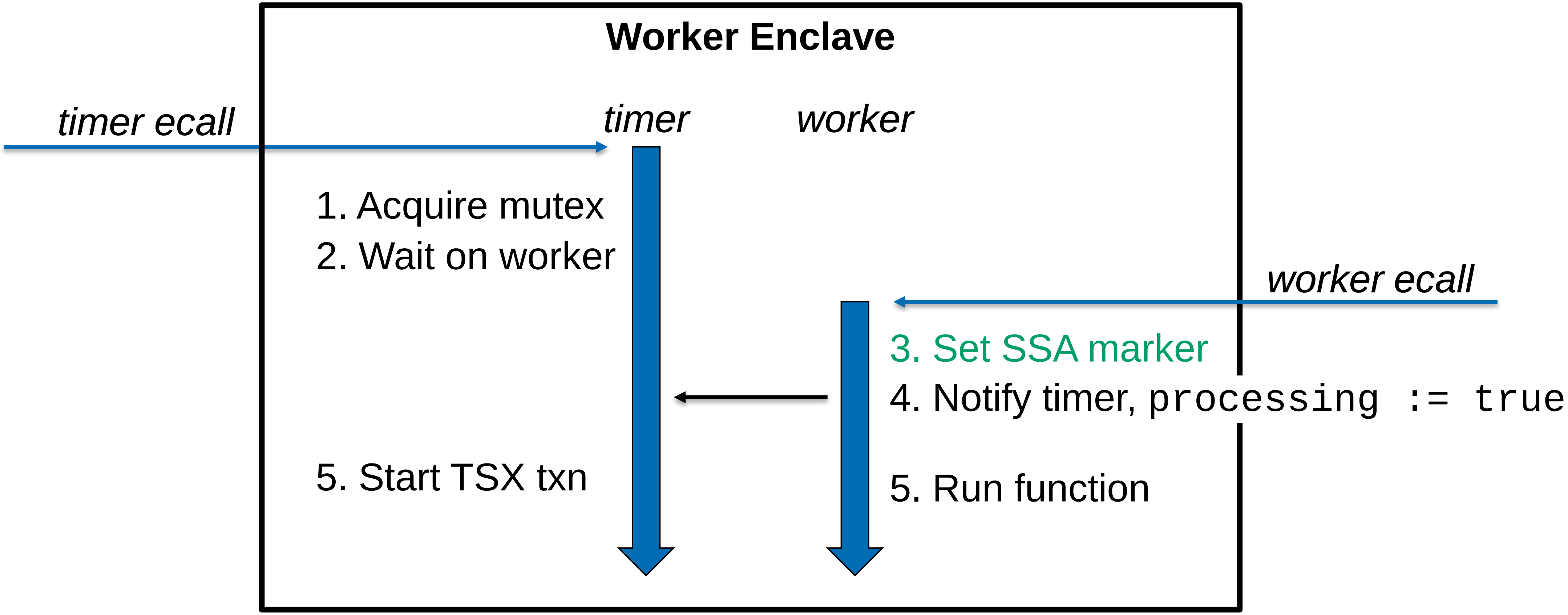
- Memory addresses written by the transaction
- Transaction will abort if address is concurrently read

Roll-back

- All operations since the beginning of the transaction are reverted

Starting a function

SSA stack	
Marker	0x12…

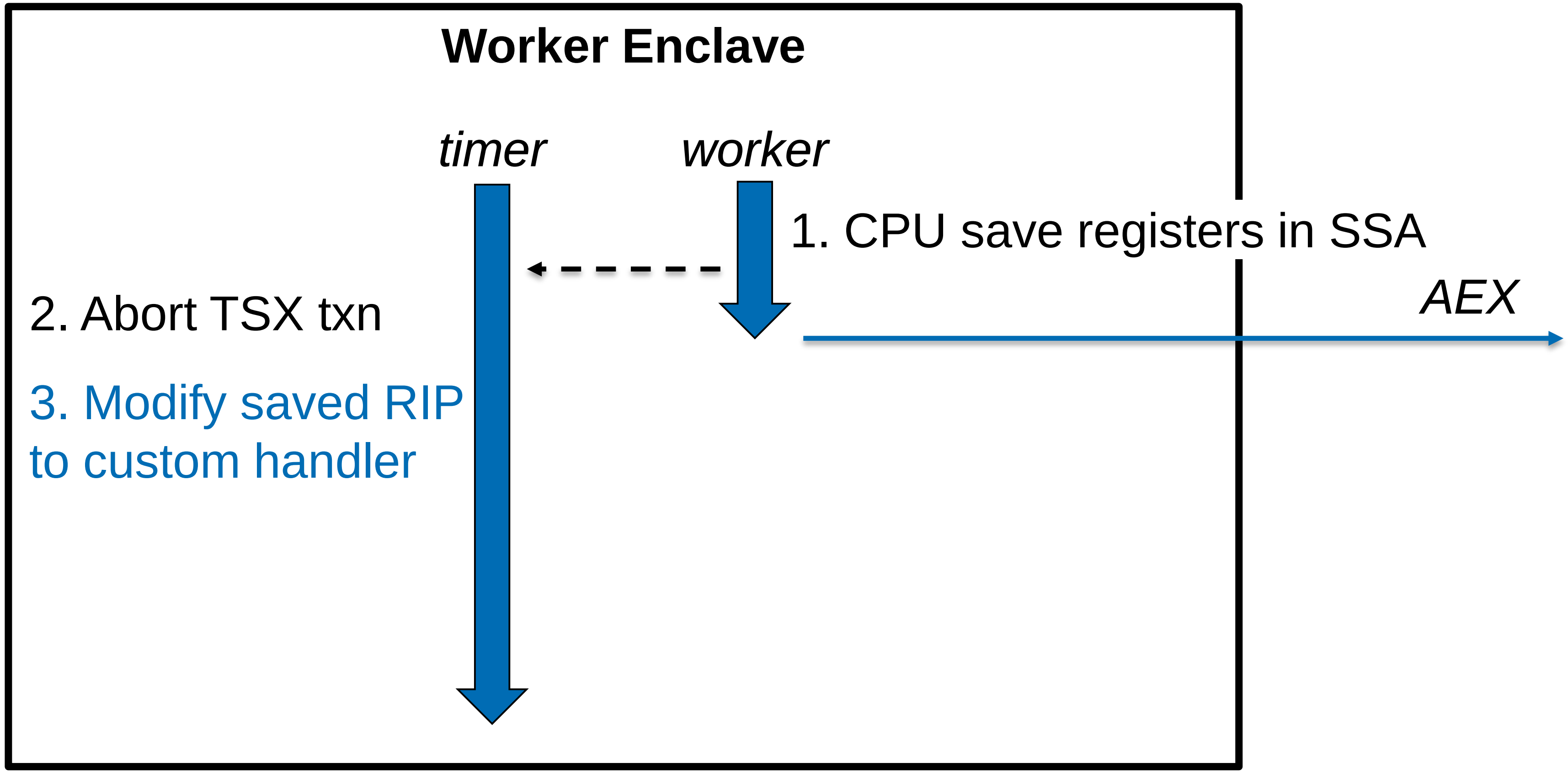


Timer thread algorithm

```
while(processing == true) {
    XBEGIN   // begin TSX txn
    if(worker.ssa == marker)  // add worker.ssa to txn read set
    {
        for(i=0; i<LOOP_COUNT; i++) // LOOP_COUNT depends on T
            nop;
        t_internal++;
    }
    XEND   // end TSX txn
    t_external = t_internal   // update external counter
}
```

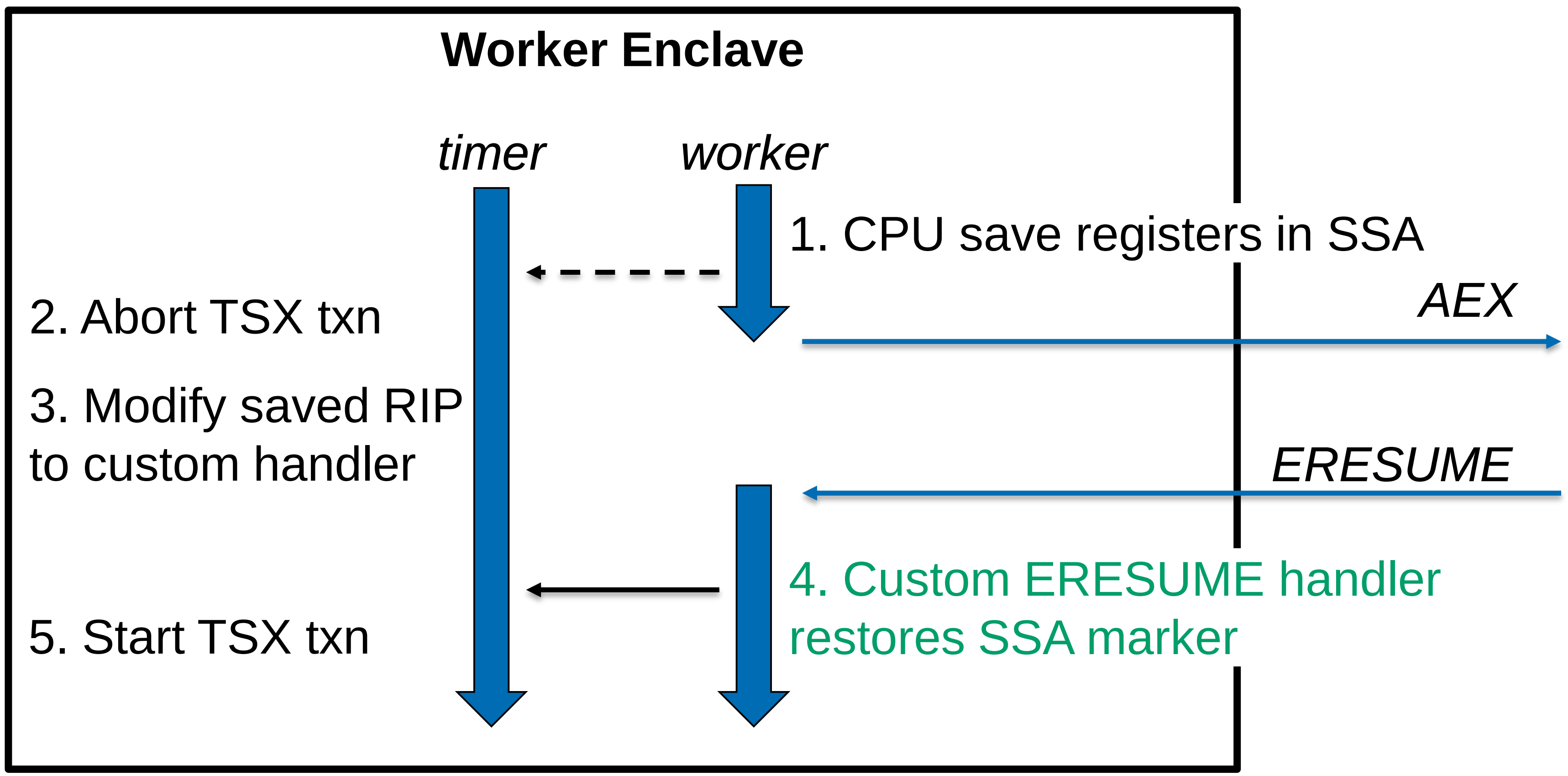
Worker thread interrupted

SSA stack	
Regs RIP	0x00… 0x89…



Worker thread resumed

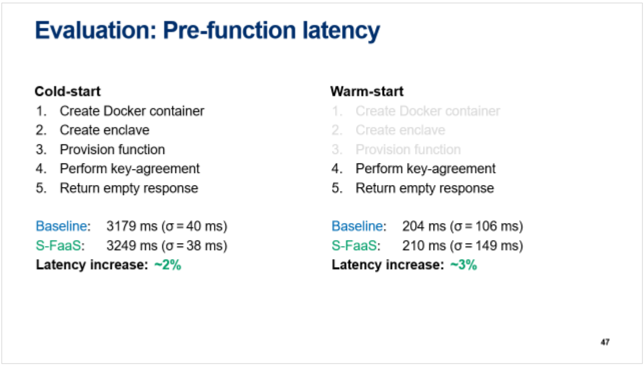
SSA stack	
Marker	0x12..

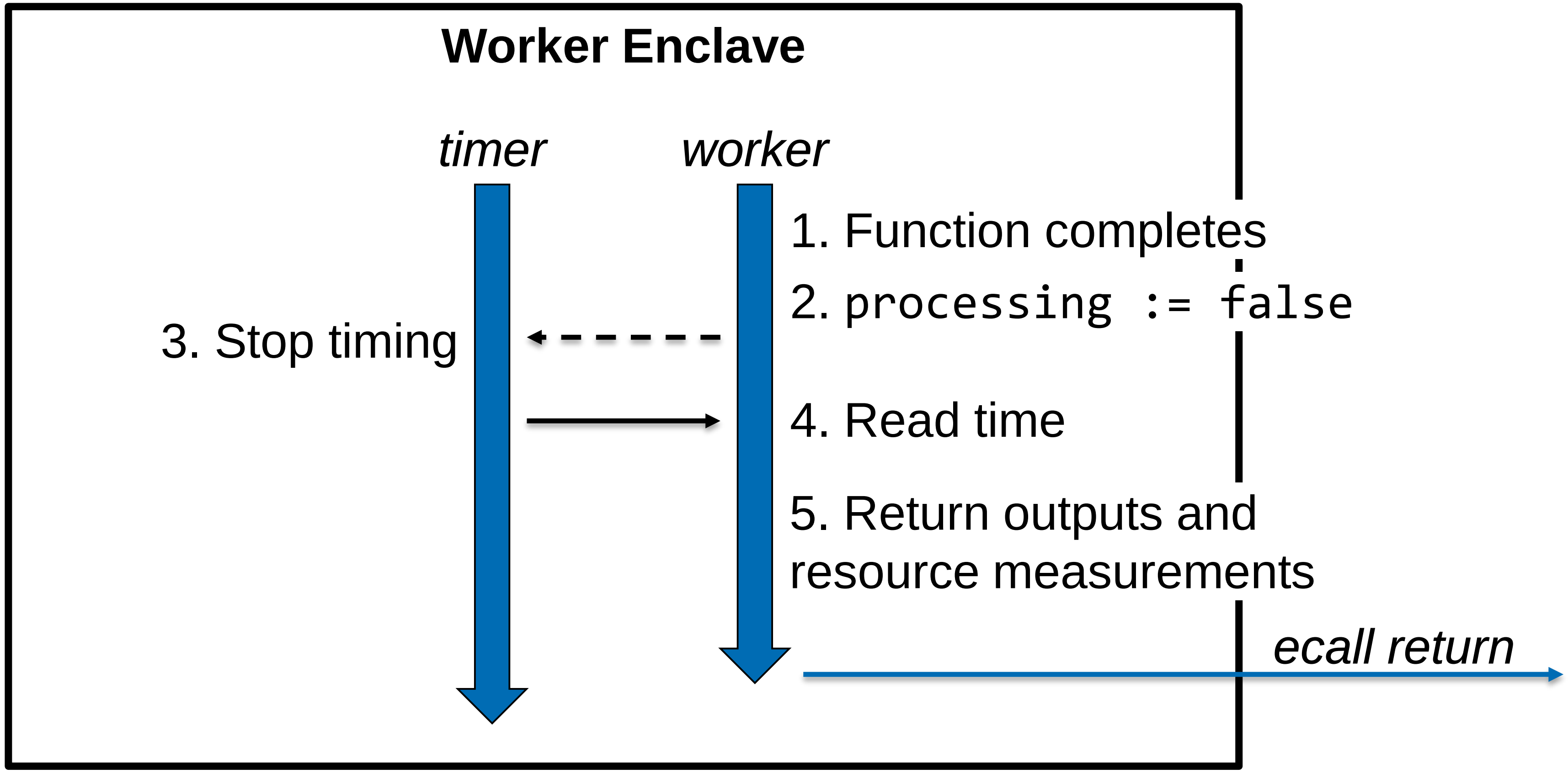


Custom ERESUME handler

```
    .text
    .globl custom_eresume_handler
    .type custom_eresume_handler,@function
    custom_eresume_handler:
        push %rax                            # Save registers
        push %rbx
        lea g_worker_ssa_gpr(%rip),%rax      # Load pointer
        mov (%rax),%rbx                      # Dereference pointer
        movl $12345,(%rbx)                   # Write SSA marker value
        pop %rbx                             # Restore registers
        pop %rax
        jmp *g_original_ssa_rip(%rip)        # Resume execution
```

Completing a function





Measuring Memory and Networking

Memory

- Instrumented allocators used by interpreter
- Measurements updated on every allocation/free

m_{int}	Time-integral of memory usage
m_{max}	Maximum memory used by the function

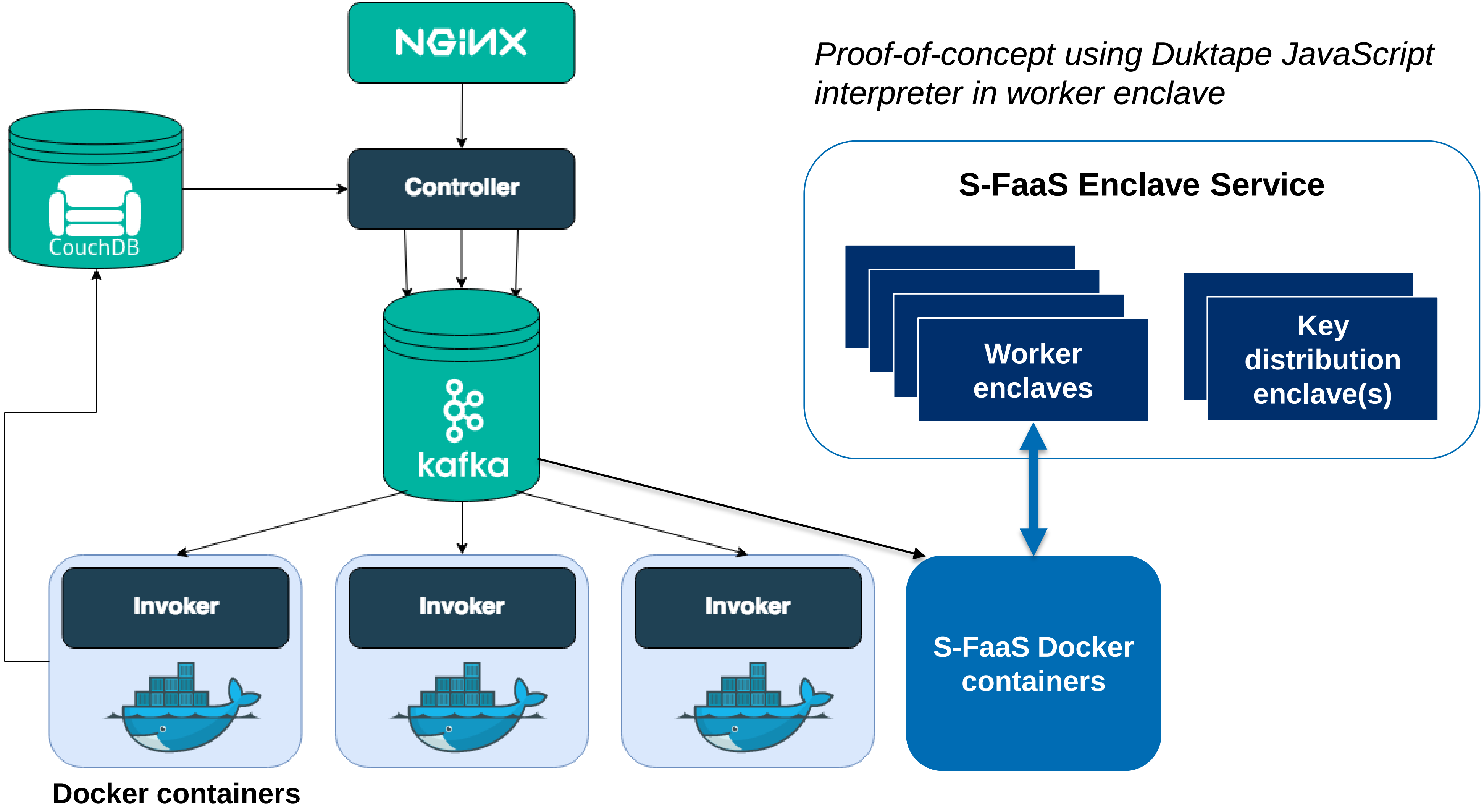
Network

- Payloads measured inside enclave

Integration with OpenWhisk

Integration with OpenWhisk

Proof-of-concept using Duktape JavaScript interpreter in worker enclave



https://openwhisk.apache.org/documentation.html

Evaluation

Evaluation: Accuracy

Synthetic function with well-defined compute and memory requirements

- `fibonacci(k)` calculates the first k numbers in the Fibonacci sequence

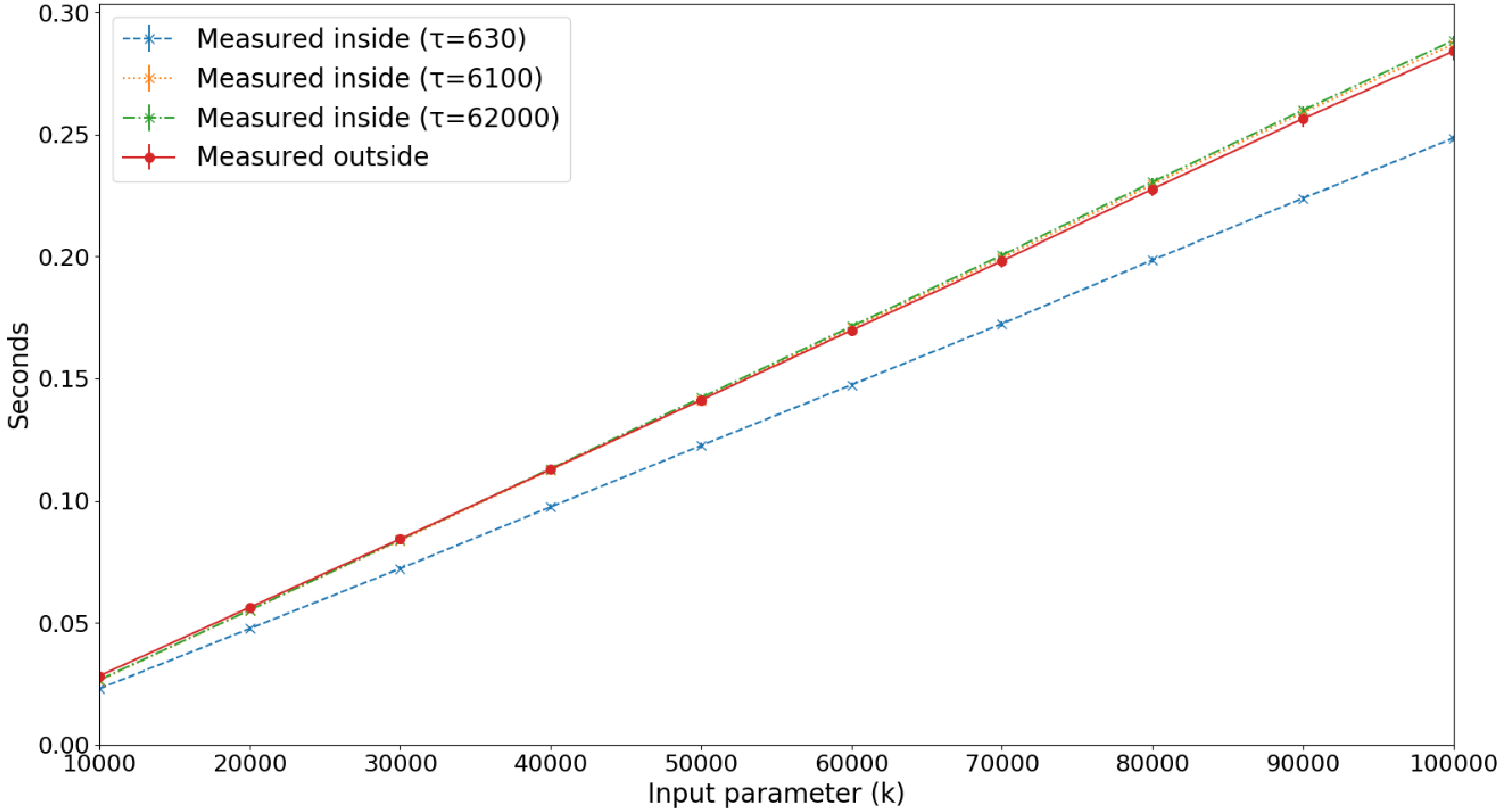
Compute time

- Expected to be linear in k
- Can be compared with measurement outside the enclave

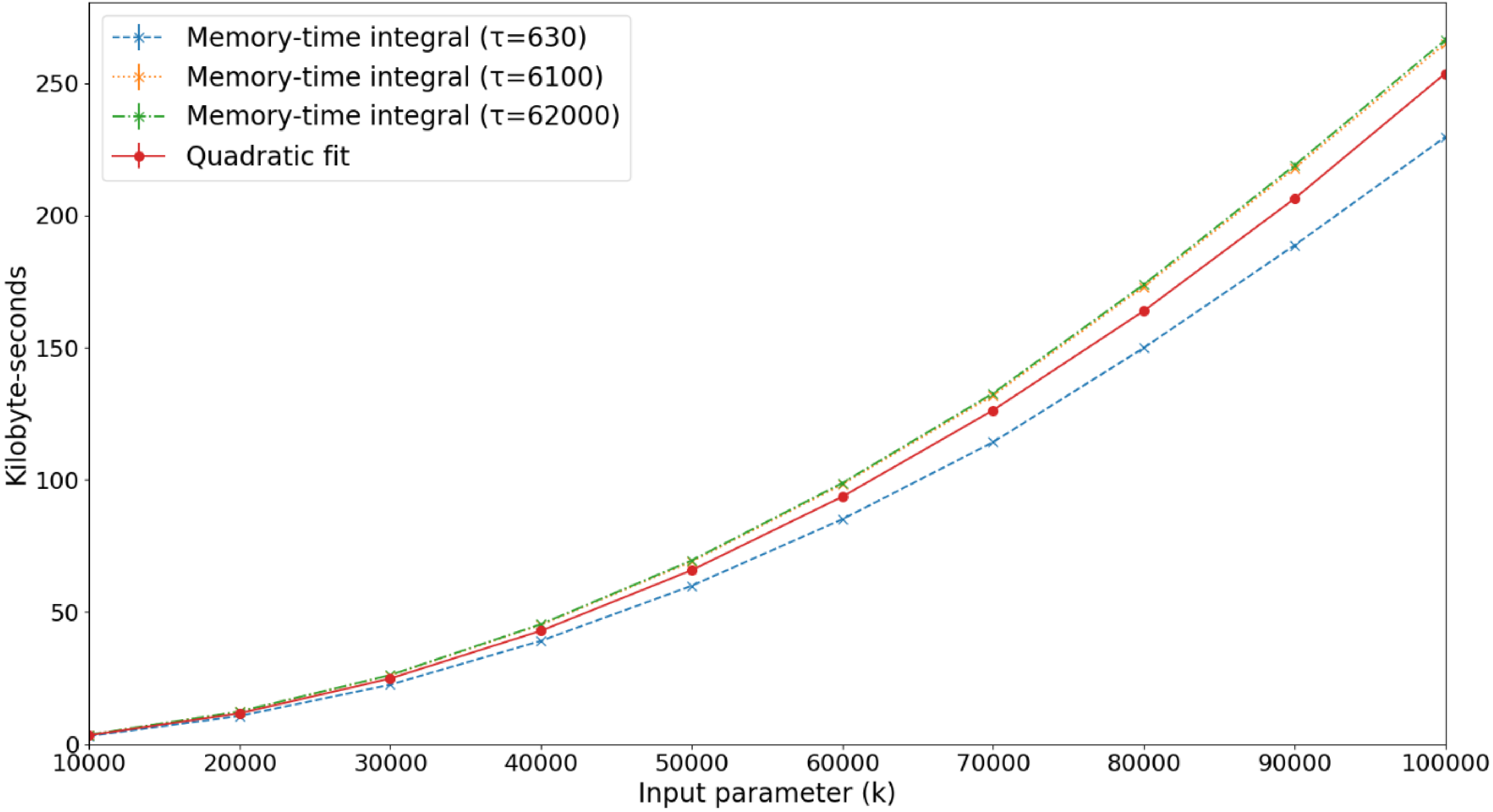
Memory time-integral

- Expected to be quadratic in k (k-element list pre-allocated at start of function)
- Harder to measure outside enclave

Evaluation: Accuracy



Evaluation: Accuracy



Evaluation: Performance

Pre-function latency

- Measure cold-start and warm-start latency
- Tested using an empty function to isolate pre-function latency
- Baseline: equivalent operation (same interpreter) without SGX

Resource measurement overhead

- Measure overhead of S-FaaS resource measurement mechanisms
- Octane JavaScript benchmarks (excluding graphical tests)
- Baseline: equivalent operation without resource measurement

Benchmark environment

- Core i5-6500, 8GB RAM, Ubuntu 16.04, Intel SGX SDK 2.2.1

Evaluation: Pre-function latency

Cold-start

1. Create Docker container
2. Create enclave
3. Provision function
4. Perform key-agreement
5. Return empty response

Baseline: 3179 ms ($\sigma = 40$ ms)
S-FaaS: 3249 ms ($\sigma = 38$ ms)
Latency increase: ~2%

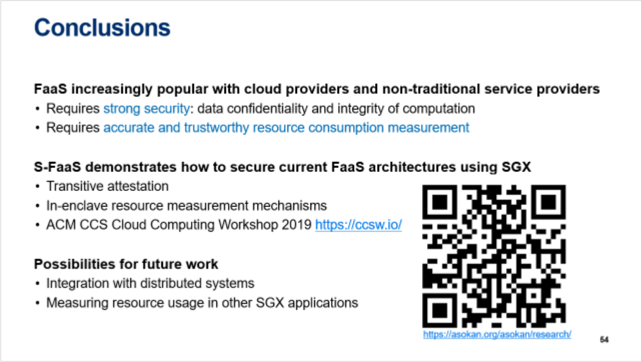
Warm-start

1. Create Docker container
2. Create enclave
3. Provision function
4. Perform key-agreement
5. Return empty response

Baseline: 204 ms ($\sigma = 106$ ms)
S-FaaS: 210 ms ($\sigma = 149$ ms)
Latency increase: ~3%

Evaluation: Resource measurement overhead

Function	Baseline	S-FaaS					
		No encryption		Encryption		Encryption & receipt	
Box2D	3.019	3.118	3.3%	3.121	3.4%	3.135	3.8%
DeltaBlue	1.446	1.524	5.4%	1.529	5.7%	1.537	6.3%
NavierStokes	4.155	4.418	6.3%	4.447	7.0%	4.473	7.7%
RayTrace	0.779	0.848	8.9%	0.850	9.1%	0.852	9.4%
Richards	1.719	1.767	2.8%	1.767	2.8%	1.799	4.7%
Overall	**-**		***5.3%***		***5.6%***		***6.3%***



Trade-offs and limitations

Need for an additional thread

- State-of-the-art SGX side-channel defences(*) require control of both sibling hyperthreads

Timing granularity

- Choice of T affects extent of under- or over-reporting
- S-FaaS service providers can specify T for each function

Architecture-specific calibration

- Timing loop must be calibrated for different CPU architectures

(*) SGX side-channel defenses:
Cloak: Gruss et al., "[Strong and Efficient Cache Side-Channel Protection using Hardware Transactional Memory]", Usenix SEC 2017
HyperRace: Chen et al., "[Racing in Hyperspace: Closing Hyper-Threading Side Channels on SGX with Contrived Data Races]", IEEE S&P 2018
Varys: Oleksenko et al., "[Varys: Protecting SGX enclaves from practical side-channel attacks]", Usenix ATC 2018

Suggested SGX enhancements

Secure tick counter

- Provide a trustworthy tick counter that can be accessed without leaving the enclave

Custom ERESUME handlers

- Allow enclaves to specify an in-enclave handler to be called on each ERESUME
- Could also be used to detect frequent AEX events indicative of side-channel attacks

Integration with distributed systems

Smart contracts to pay for outsourced computation

- S-FaaS function receipts and resource measurements can be verified in smart contracts
- Straight-forward integration with payment networks
  - Particularly beneficial to non-traditional service providers

Leader election based on useful work

- Similar to Resource-Efficient Mining for Blockchains (Zhang et al.)
- Uses “useful computation” to determine who mines next block

Zhang et al., “REM: Resource-Efficient Mining for Blockchains”, Usenix SEC 2017

Deployment considerations

Incremental deployment

- Initially, S-FaaS requires no changes on client-side (no client attestation or encryption)
- Clients can individually start to verify attestation and/or encrypt inputs

Implementations with other TEEs

- S-FaaS could be ported to e.g. ARM TrustZone
- TrustZone secure world still requires functions to run in a suitable sandbox, but timing would be simpler because secure world cannot be arbitrarily paused

Conclusions

FaaS increasingly popular with cloud providers and non-traditional service providers

- Requires strong security: data confidentiality and integrity of computation
- Requires accurate and trustworthy resource consumption measurement

S-FaaS demonstrates how to secure current FaaS architectures using Intel SGX

- ACM CCS Cloud Computing Workshop 2019 https://ccsw.io/

https://asokan.org/asokan/research/

Code available on GitHub

https://github.com/SSGAalto/sfaas

What if SGX is broken?

Back to current state of FaaS security and resource measurement

- **TEEs useful in two kinds of settings:**
  1. improving security
  2. improving other attributes while preserving security

  S-FaaS is Type 1. TEE compromise is a bigger concern in Type 2

- **Application-specific ways of detecting / mitigating effects of TEE compromise, e.g.,**
  - post-mortem auditing of signed receipts
  - statistical mechanisms like in PoET and Zhang et. al.