Technische Universität Braunschweig

Institute of Operating Systems and Computer Networks

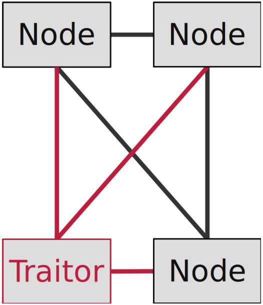
Resilient Byzantine Fault-Tolerance

Using Multiple Trusted Execution Environments

Markus Becker, October 14, 2021

Byzantine Agreement

- Goal: Reach consensus across multiple machines
- Application: State-Machine Replication (SMR)
  - Agree & Order requests
  - Execute deterministic operation



Byzantine Failures

- Malicious party exhibits arbitrary behaviour

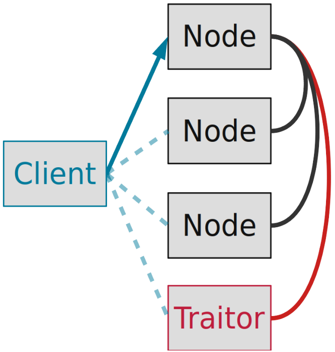
Fault Tolerant Systems

- Resilient against Byzantine Failures
- Operates correctly despite faults

Byzantine Fault Tolerant (BFT) Protocols

Example protocol: PBFT M. Castro and B. Liskov '99

1. Replicated nodes act as servers
2. Client sends request
3. Communication rounds between replicas
   - Ordering and agreement
   - Requires $n \geq 3f + 1$ for f faults
4. Client receives responses
5. Client performs voting on results



BFT Protocol Deployment

Usage in permissioned Blockchains

- BFT for ordering and agreement
- BaaS: Nodes & Infrastructure by cloud provider
  - Amazon Managed Blockchain
  - Azure Blockchain Service
- Agreement using specific protocol

But we do not want to have to trust the cloud provider!

Trusted Execution

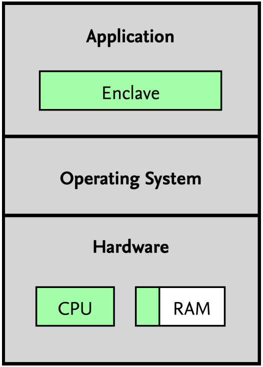
Features of most Trusted Execution Environments (TEEs):

- Execution of signed code on third parties machine
  - Local and remote attestation
- Confidentiality over host
  - Fully hardware-encrypted memory
- Reduced the chance of bugs
  - Small TCB

But we still have to assume Byzantine failures!

Intel Secure-Guard-Extensions (SGX)

- Trusted Execution Environment
- Extension of x86
- Exclusively on Intel CPUs
- Transparently encrypted memory
- Ring-3 only execution
- (Remote) Attestation



But enclaves can still contain bugs (or have other weaknesses) [1]

[1] Weichbrodt et al., AsyncShock: Exploiting Synchronisation Bugs in Intel SGX Enclaves, (ESORICS'16)

Robustness

Reduce chance that practical BFT system enters irreparable state.

Ordinary

- Increase number of replicas
- Use safe programming strategies / frameworks
- Diversification (Lazarus'19)
  - Code & OS
  - Hardware
  - Passwords
  - Admins
- Rejuvenation

Invasive

- Trusted Execution
  - No golden bullet
  - Small *validated* TCB
  - Interface with OS needed
- Separation by functionality
  - Logically
  - Physically

BFT Partitioning

Naïve Solution:

- Entire protocol in TEE

Problem:

↯ Attacks on enclave

Solution:

- Separate agreement protocol

↯ Attacker in enclave $\Rightarrow$ liveness

↯ Attacker in f enclaves $\Rightarrow$ safety & liveness

- Depend on quorum decisions for safety

Thesis Goals

Combination of robustness features as SplitBFT

- Trusted Execution (SGX) in stronger fault model
- Separating into independent compartments

Goals

- Improve safety & resilience using TEEs
  - Tolerate up to f faults per compartment type
- Keep confidentiality as long as possible
  - Sensitive data in only one compartment type

Requirements for SplitBFT

Split PBFT into small protocol units for compartments:

Performance

- Efficient memory management
- Avoiding SGX overhead
- Efficient shim

Safety

- Independent compartments
- Security-sensitive functions isolated
- Eliminating shared state

Compartmentalization

Splitting State-Machine-Replication

- SMR is often physically split into Clients and Replicas
- Replicas are logically split into Agreement and Execution (SOSP'03)

We recognise further opportunity to split based on **quorum decisions**:

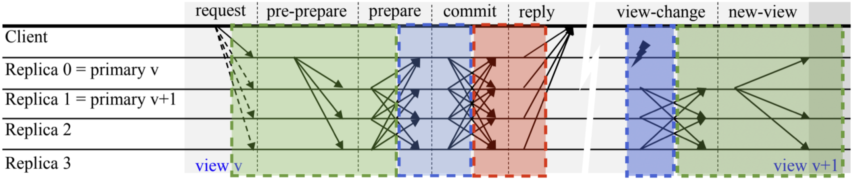
$$\text{BFT} \longrightarrow \text{Clients} + \text{Replicas}$$

$$\text{Replica} \longrightarrow \text{Agreement} + \textbf{Execution}$$

$$\text{Agreement} \longrightarrow \textbf{Preparation} + \textbf{Confirmation}$$

SplitBFT: Normal Operation

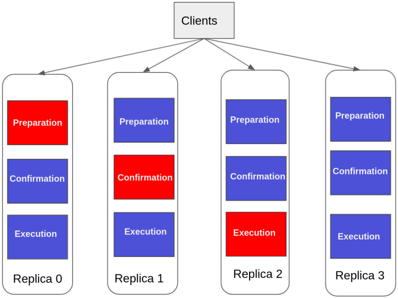
Preparation, Confirmation, Execution



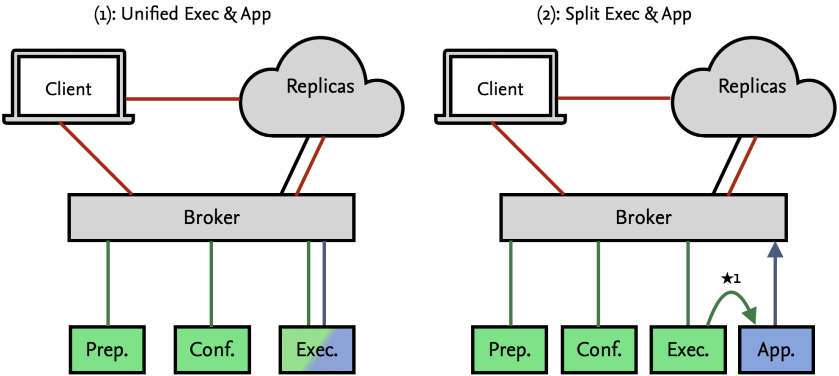
1. Collect symmetrically encrypted operations in untrusted memory
   - Only client and execution compartment can decrypt
2. Liveness decisions outside of compartments
3. Verify fine-grained asymmetric signatures in compartments
4. Follow PBFT-like operation

Compartment's responsibilities

1. Preparation:
   - $\Leftarrow$ Receive requests, pre-prepares
   - ☐ Order requests
   - $\Rightarrow$ Send pre-prepares, prepares
2. Confirmation:
   - $\Leftarrow$ Receive $\geq 2f$ prepares
   - $\Rightarrow$ Send commits
3. Execution:
   - $\Leftarrow$ Receive $\geq 2f + 1$ commits
   - ☐ Execute requests
   - $\Rightarrow$ Send replies



Option: Execution & Application split



Checkpointing and View-Changes

Design consideration:

- Independence
- Safety based on quorums

Garbage-collection & liveness:

- Checkpoints
  - Application state only in Execution compartments
  - Allows removing old messages
- View-Changes
  - View *required* in all compartments
  - Cannot trust a global variable or even local “View-Compartment”

$\Rightarrow$ New-View messages are broadcast to all compartments

Fault Model

- Faulty enclave escapes to replica
- Faulty replica cannot enter enclave
- Independent faults in enclaves
- Require quorum to advance protocol

$\Rightarrow$ Integrity as long as at most f faults per enclave type

$\Rightarrow$ Confidential as long as execution compartments non-faulty

Themis

- IBR's own BFT Framework!
- Written in Rust: memory-safe, systems language
- Protocols:
  - PBFT
  - Railchain
- Implemented applications:
  - Benchmark-Counter
  - YCSB-KVS

Implementation

1. Setup for Teaclave SGX SDK
2. Integration into Themis
   - Dependencies, dependencies, dependencies
3. Structured communication between TCB and Themis
4. Applications

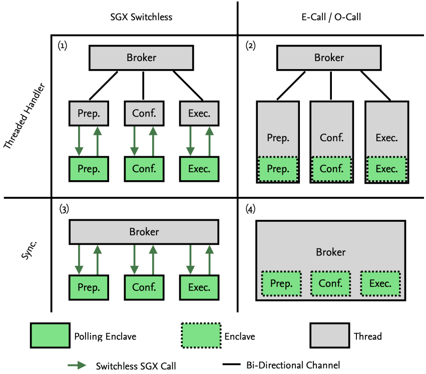
Setup

- Rust `nightly-2021-02-17`
- Themis `@master`
- Teaclave SGX SDK >`1.1.3`
  - `1.1.3` incompatible with Themis
  - `master` incompatible with `SGX World`

⇒ Own `SGX World` forks & docs + wiki
  - `bytes-sgx`, `ring-sgx`, `serde-sgx`, `msgpack-rust-sgx`, ...

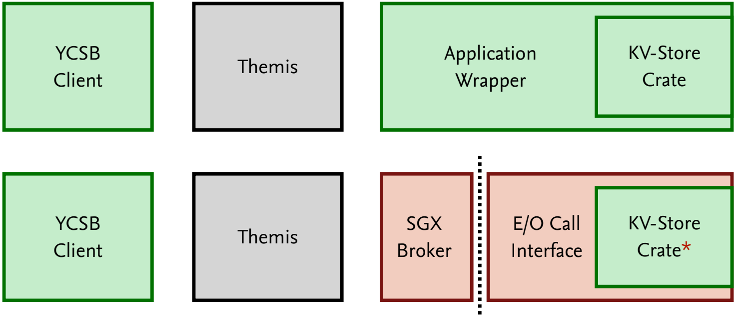
SGX Broker Layer

- Compatible management structure for enclaves
- Efficient memory management
- Minimize SGX overhead
- Translation layer between Themis and TCB
- Deciding asynchronous/synchronous operation



Adaptation of KV-Store implementation

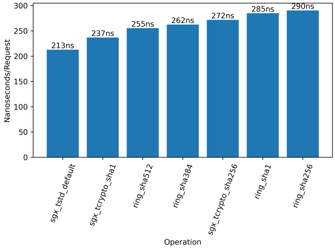
Writing TCB to allow swapping of non-SGX and SGX SMR without changing the client:



Wrapping for transparent interation with Themis is non-trivial

Evaluation

- Benchmarking `#[no_std]` crates in SGX
- Deploying and measuring integration tests
- Measure with benchmark application
- Measure with YCSB-KVS application



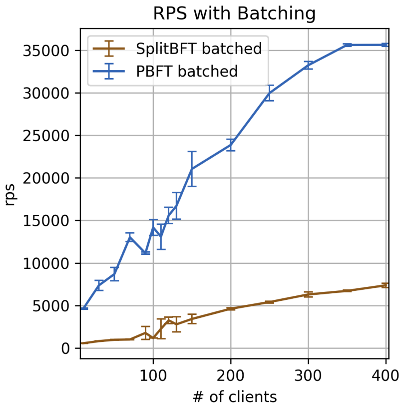
Example benchmark of hashing inside enclaves.

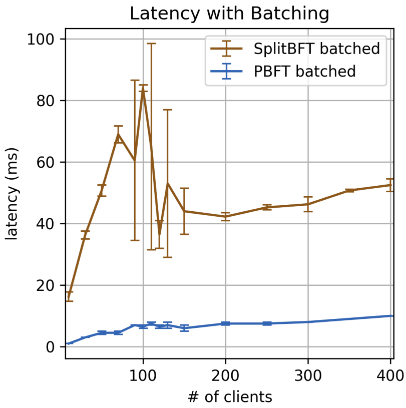
Benchmark Application

Compare PBFT against SplitBFT

- Replicated on ssgx machines
  - 4× Intel Xeon E3-1230 v5
  - 1 Gbps
  - 32 GB RAM
  - 94.5 MiB EPC Size
- Threaded clients on dsgx machines
  - 4× Intel Core i7-6700
  - 1 Gbps
  - 24 GB RAM

Benchmark Application





Benchmark Application Evaluation

- Cost of ECalls and OCalls spread across requests when batching
  - Performance bottleneck: Sending replies

PBFT replying to batch

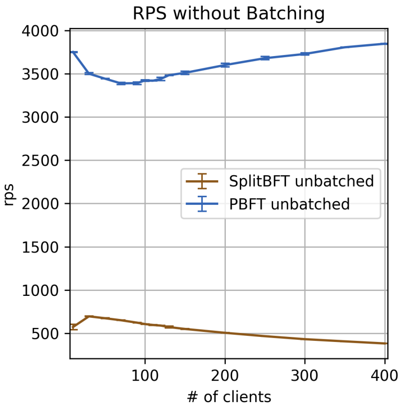
1. Create reply & sign
2. Network send (serialize)

SplitBFT replying to batch

1. Create reply & sign
2. *Batch with other replies*
3. *Serialize batch*
4. *Perform OCall*
5. *Deserialize OCall batch*
6. Network send (serialize)

Benchmark Application Evaluation

Comparison without Batching
ECalls and OCalls of ordering each request individually dominate performance.



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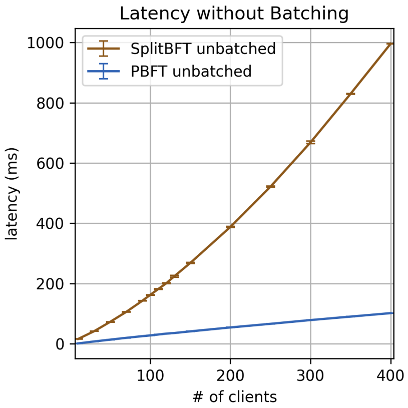


YCSB-KVS Application

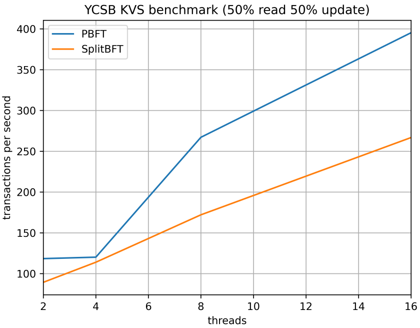
Distributed benchmark

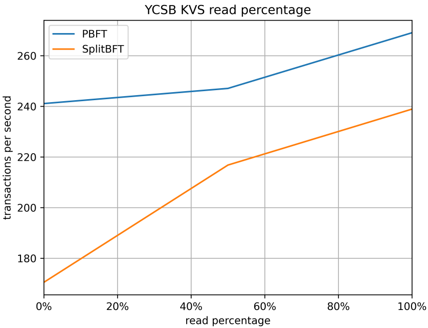
- Data store benchmark
  - Realistic access patters (SoCC '10)
- SplitBFT vs. PBFT in Themis
- Application is in-memory KVS

Workload

1. Load phase
   - Insert data
2. Run phase
   - Reads & Updates

YCSB-KVS Evaluation





Conclusion

- Design and implementation of SplitBFT in Themis
- SGX broker and enclave maintainable and exchangeable
- Distributed evaluations in hardware mode against PBFT

Future Work

- More applications in SplitBFT
- Further optimizations and fast-tracks