Aalto University

Common-sense applications of hardware-based TEEs

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Multi-party Computation is useful and popular

Client-server, cloud computing, outsourced computing, …

Raises various security and privacy issues

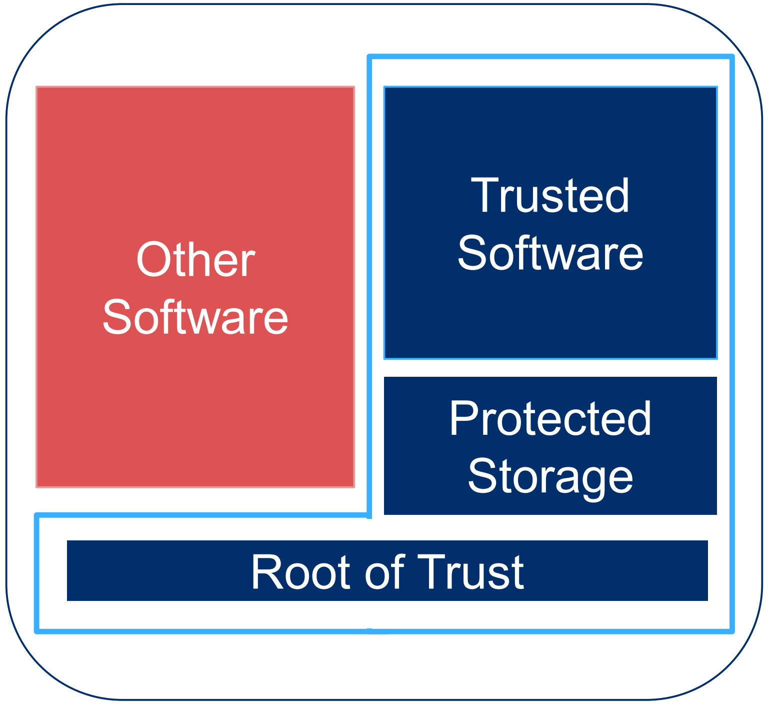
- How to keep sensitive information confidential?
- How to ensure the integrity of computation?

Cryptographic primitives are increasingly practical

- Secure MPC, homomorphic encryption, …

But may still be too expensive and/or difficult to use

Hardware-security mechanisms are pervasive



Hardware support for

- **Isolated execution: Isolated Execution Environment**
- **Protected storage: Sealing**
- **Ability to report status to a remote verifier: Remote Attestation**

Trusted Execution Environments (TEEs)

Cryptocards

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

Trusted Platform Modules

https://www.infineon.com/tpm

ARM TrustZone

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

Intel Software Guard Extensions

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)

Common-sense applications of TEEs

Practical applications to address everyday security/privacy needs of end users

- **Private membership test for malware scanning, private contact discovery, …**

  [TLPEPA17] Circle Game, ACM ASIACCS 2017 https://arxiv.org/abs/1606.01655

- **Protection of password-based web authentication**

  [KKPMA18] SafeKeeper, WWW 2018, https://ssg.aalto.fi/research/projects/passwords/

- **Secure accounting for function-as-a-service (FaaS) settings**

  [AAKPS18], S-FaaS, in submission 2018, https://export.arxiv.org/abs/1810.06080

- **…**
- ***Blockchains and cryptocurrencies***

Concerns with TEEs: flaws

TPM Reset Attack

50,012 views

Evan Sparks
Published on Jun 18, 2007

A demonstration of a vulnerability in the TCG architecture v
running TPM without restarting the platform.

http://www.cs.dartmouth.edu/~pkilab/sparks/ (2007)

CLKSCREW: Exposing the Perils of Security-Oblivious Energy Management

Authors:
Adrian Tang, Simha Sethumadhavan, and Salvatore Stolfo, *Columbia University*
Distinguished Paper Award Winner!

https://www.usenix.org/conference/usenixsecurity17/technical-sessions/presentation/tang (2017)

Foreshadow (security vulnerability)

From Wikipedia, the free encyclopedia

This article is about the security vulnerability. For other uses, see Foreshadow (disambiguation).

Foreshadow is a vulnerability that affects modern microprocessors that was first discovered by two independent teams of researchers in January 2018, but was first disclosed to the public on 14 August 2018.[1][2][3][4][5][6][7][8][9][10][11][12][13][14][15][16] The vulnerability is a speculative execution attack on Intel processors that may result in the loss of sensitive information stored in personal computers, or third party clouds.[1] There are two versions: the first version (original/Foreshadow) (CVE-2018-3615) targets data from SGX enclaves; and the second version (next-generation/Foreshadow-NG) (CVE-2018-3620 and CVE-2018-3646) targets Virtual Machines (VMs), hypervisors (VMM), operating system (OS) kernel memory, and System Management Mode (SMM) memory.[1] Intel considers the entire class of speculative execution side channel vulnerabilities as “L1 Terminal Fault" (L1TF).[1] A listing of affected Intel hardware has been posted.[10][11]

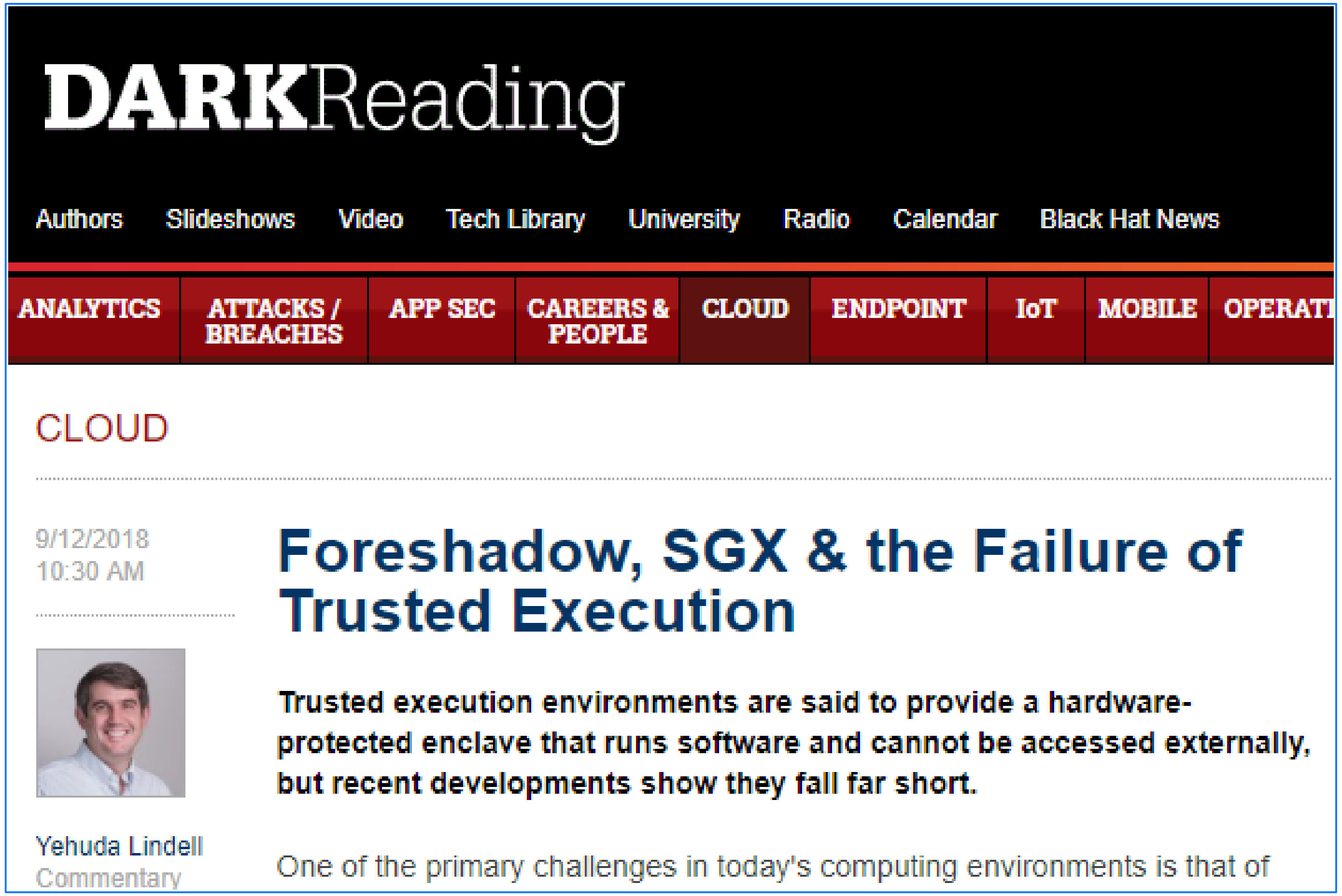
Foreshadow is similar to the Spectre security vulnerabilities discovered earlier to affect Intel and AMD chips, and the Meltdown vulnerability that also affected Intel.[6] However, AMD products, according to AMD, are not affected by the Foreshadow security flaws.[6] According to one expert, "[Foreshadow] lets malicious software break into secure areas that even the Spectre and Meltdown flaws couldn't crack".[15] Nonetheless, one of the variants of Foreshadow goes beyond Intel chips with SGX technology, and affects "all [Intel] Core processors built over the last seven years".[2]

Foreshadow may be very difficult to exploit,[2][6] and there seems to be no evidence to date (15 August 2018) of any serious hacking involving the Foreshadow vulnerabilities.[2][6] Nevertheless, applying software patches may help alleviate some concern(s), although the balance between security and performance may be a worthy consideration.[5] Companies performing cloud computing may see a significant decrease in their overall computing power; individuals, however, may not likely see any performance impact, according to researchers.[9] The real fix, according to Intel, is by replacing today's processors.[5] Intel further states, "These changes begin with our next-generation Intel Xeon Scalable processors (code-

FORESHADOW
A logo created for the vulnerability, featuring a lock with a shadow

https://en.wikipedia.org/wiki/Foreshadow_(security_vulnerability) (2018)

Flaws in hardware security: no hope?


DARKReading

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CLOUD

9/12/2018
10:30 AM

Yehuda Lindell
Commentary

Foreshadow, SGX & the Failure of Trusted Execution

Trusted execution environments are said to provide a hardware-protected enclave that runs software and cannot be accessed externally, but recent developments show they fall far short.

One of the primary challenges in today's computing environments is that of

https://www.darkreading.com/cloud/foreshadow-sgx-and-the-failure-of-trusted-execution/a/d-id/1332733 (2018)

Cost-effective hardware isolation is unlikely?

(Is cost-effective secure software likely?)

Concerns with TEEs: suspicions of motives

Software

MS Palladium protects IT vendors, not you – paper

Anderson gives us the FAQs

By John Lettice 28 Jun 2002 at 10:27 SHARE ▼

https://www.theregister.co.uk/2002/06/28/ms_palladium_protects_it_vendors/ (2002)

Problem: Third-party uncertainty about your software environment is normally a feature, not a bug

https://www.eff.org/wp/trusted-computing-promise-and-risk (2003)

Trusting Intel – Next Generation of Backdooring?

We have seen that SGX offers a number of attractive functionality that could potentially make our digital systems more secure and 3rd party servers more trusted. But does it really?

The obvious question, especially in the light of recent revelations about NSA backdooring everything and the kitchen sink, is whether Intel will have backdoors allowing "privileged entities" to bypass SGX protections?

http://theinvisiblethings.blogspot.fi/2013/09/thoughts-on-intels-upcoming-software.html (2013)

Possible motivations for widespread deployment

Vendor lock-in

Restriction of digital rights

…

Regulatory requirements

Protection of end-user data

…

Example: regulatory compliance

The IMEI shall not be changed after the ME's final production process. It shall resist tampering, i.e. manipulation and change, by any means (e.g. physical, electrical and software).

NOTE: This requirement is valid for new GSM Phase 2 and Release 96, 97, 98 and 99 MEs type approved after 1st June 2002.

3GPP TS 42.009, 2001

Secure storage of RF configuration parameters

Early TEEs for mobile phones
(ca. 2001)

TrustZone®
Security Foundation by ARM®

[KREA11] "Old, new borrowed, blue: a perspective on the evolution of mobile platform security architectures", ACM CODASPY (2011)
[EKA14] "*Untapped potential of trusted execution environments*", IEEE S&P Magazine, 12:04 (2014)

Aalto University

Can blockchains be made better using hardware-assisted security?

Lachlan J. Gunn, N. Asokan

What is a Blockchain?

A (public) ledger whose integrity is guaranteed

Each block is a set of transactions, cryptographically linked to the previous block

- Acceptance of one block implies agreement on entire history

Problem: How to reach consensus on what transactions get included in a block?

Choose who decides what transactions are included in a block

Devise a way for everyone to agree on the sequence of blocks

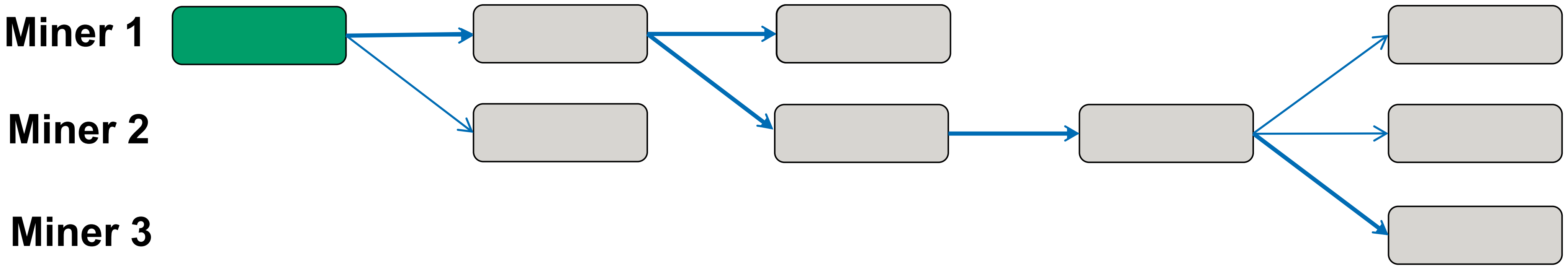
Proof of Work + “longest chain” rule

Bitcoin, Ethereum, etc. all use Proof of Work to agree on the next block:

Miners decide which transactions include in their proposal for the next block

Proof of Work: use computation power to solve a puzzle; winner proposes next block

- Chance of success proportional to amount of computation (work) performed
- Fair: any miner expending the same amount of work has the same chance of winning



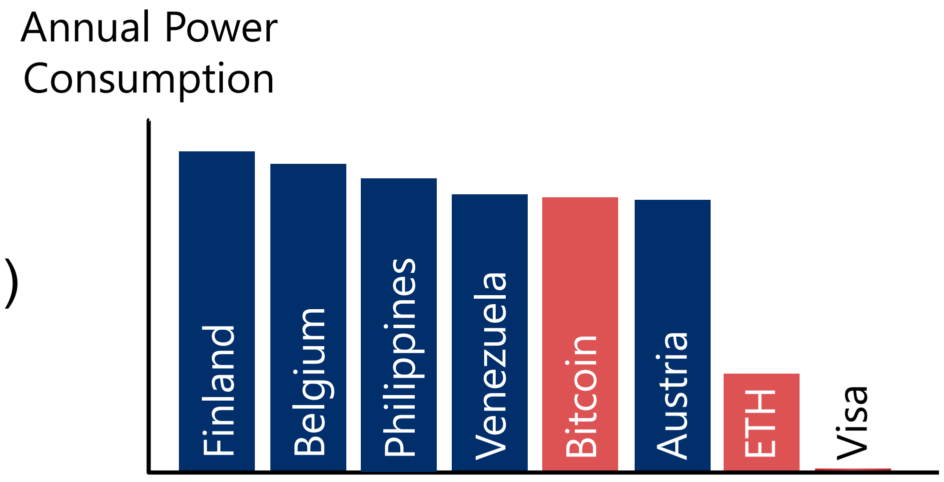
- Everyone follows the longest valid chain (chain with largest CPU power wins eventually)

What's wrong with Bitcoin, anyway?

The luxury of not trusting anyone does not come for free:

All transactions need to be online
Slow: long confirmation time, low throughput

Wasteful (energy expended on puzzle solving)
Probabilistic finality
Extremely scalable



Data: Digiconomist, CIA World Factbook

Outline

Can hardware-assisted security improve blockchains?

Example approaches

- **Changing the “business process”**
- **Replacing consensus (“longest chain” rule)**
- **…**

What challenges arise?

Changing the process

Fast off-chain transactions with TEEs

Offline

Fast

Bitcoin payments are made from/to cryptographic keys

TEE can enforce how a key is used and attest to such usage

1. Online (on-chain): transaction to transfer money to a TEE-protected key
   Proves initial balance using the blockchain
2. Offline: payment message + TEE-provided attestation: key used in only one outgoing payment

Fast, offline payment to any payee who

- is guaranteed instantaneously that double-spending is not possible!
- but must wait for on-chain confirmation before using the money with anyone!

Gopinath Nirmala, "Improving the Security and Efficiency of Blockchain-based Cryptocurrencies", MSc thesis @Aalto, 2017

Dmitrienko et al., "Secure Wallet-Assisted Offline Bitcoin Payments with Double-Spender Revocation", ASIACCS '17

Teechan: Net settlement with TEEs

Offline
Fast

TEEs can use attestation to create a secure channel between them

1. Decide how much you trust the TEE. Set a credit limit
2. Create a secure channel between the TEEs
3. Transaction made via this channel: TEEs keep track of net transfer value
4. Either TEE can close the channel and perform net settlement

Fast, offline series of payments between two designated parties:

- guaranteed instantaneously that double-spending is not possible!
- can reuse the money for transactions with peer immediately
- but must wait for on-chain confirmation before using the money with anyone else

Lind et al. "Teechan: Payment Channels Using Trusted Execution Environments", Bitcoin '17

Efficient

Proof of Elapsed Time

Proof of Work:

First miner to solve puzzle wins (gets to proposes next block)

Work ~ Exp (difficulty)

Proposals can be made at a rate proportional to computational power

Proof of Elapsed Time:

TEE issues attestation after waiting (idly) for a while; First miner to get the attestation wins

Idle wait time ~ Exp (difficulty)

Proposals can be made at a rate proportional to the number of idle CPUs

Intel, Hyperledger Sawtooth Documentation, 2015

Replacing Consensus

Byzantine Consensus

Slow
Probabilistic
Wasteful

Goals of classical Consensus schemes:

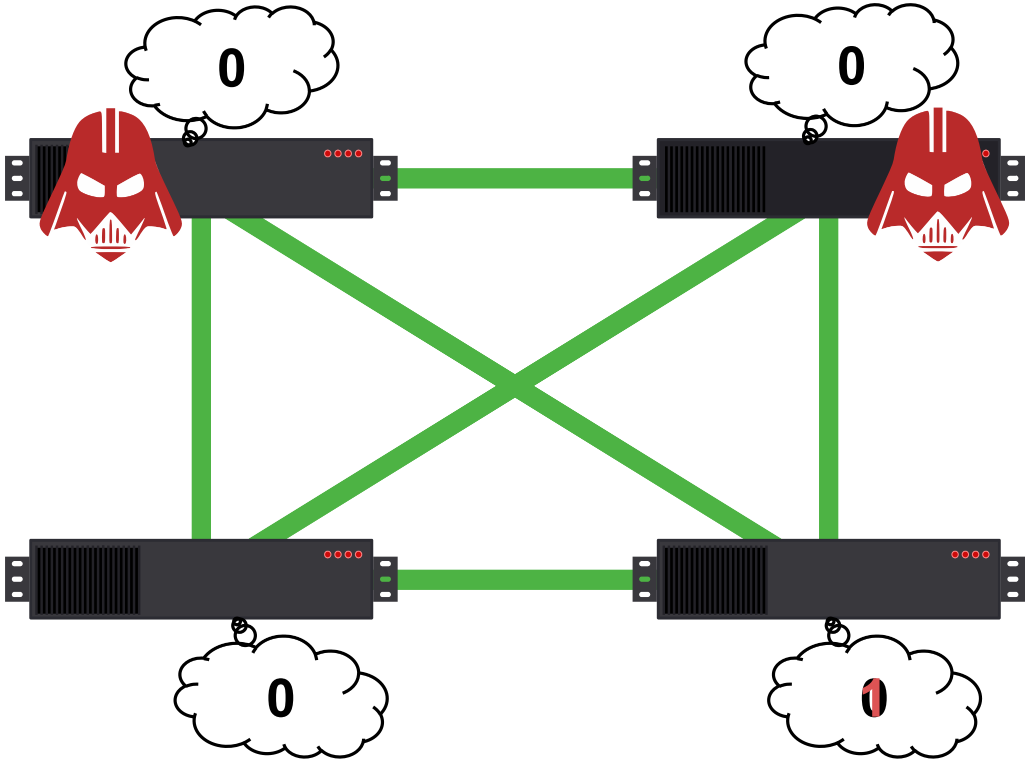
- Liveness: all (honest) nodes produce output
- Safety: all (honest) nodes output same value
- Finality: output values are definitive

Adversary model:

- Adversary can compromise some nodes
- Goals hold despite *f* compromised nodes

Limits:

- No protocol can tolerate more than a third of nodes being compromised

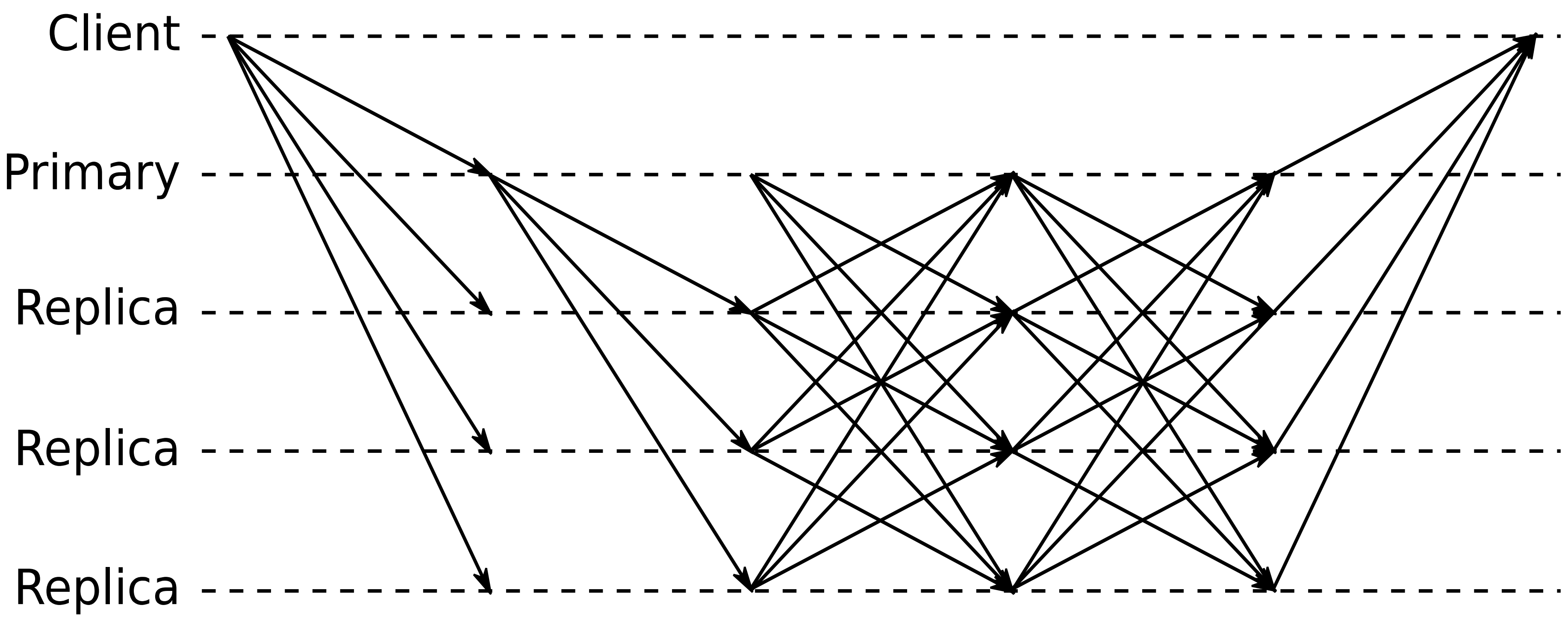


PBFT

Fast
Deterministic
Efficient
Scalable

The first practical protocol for Byzantine fault tolerance

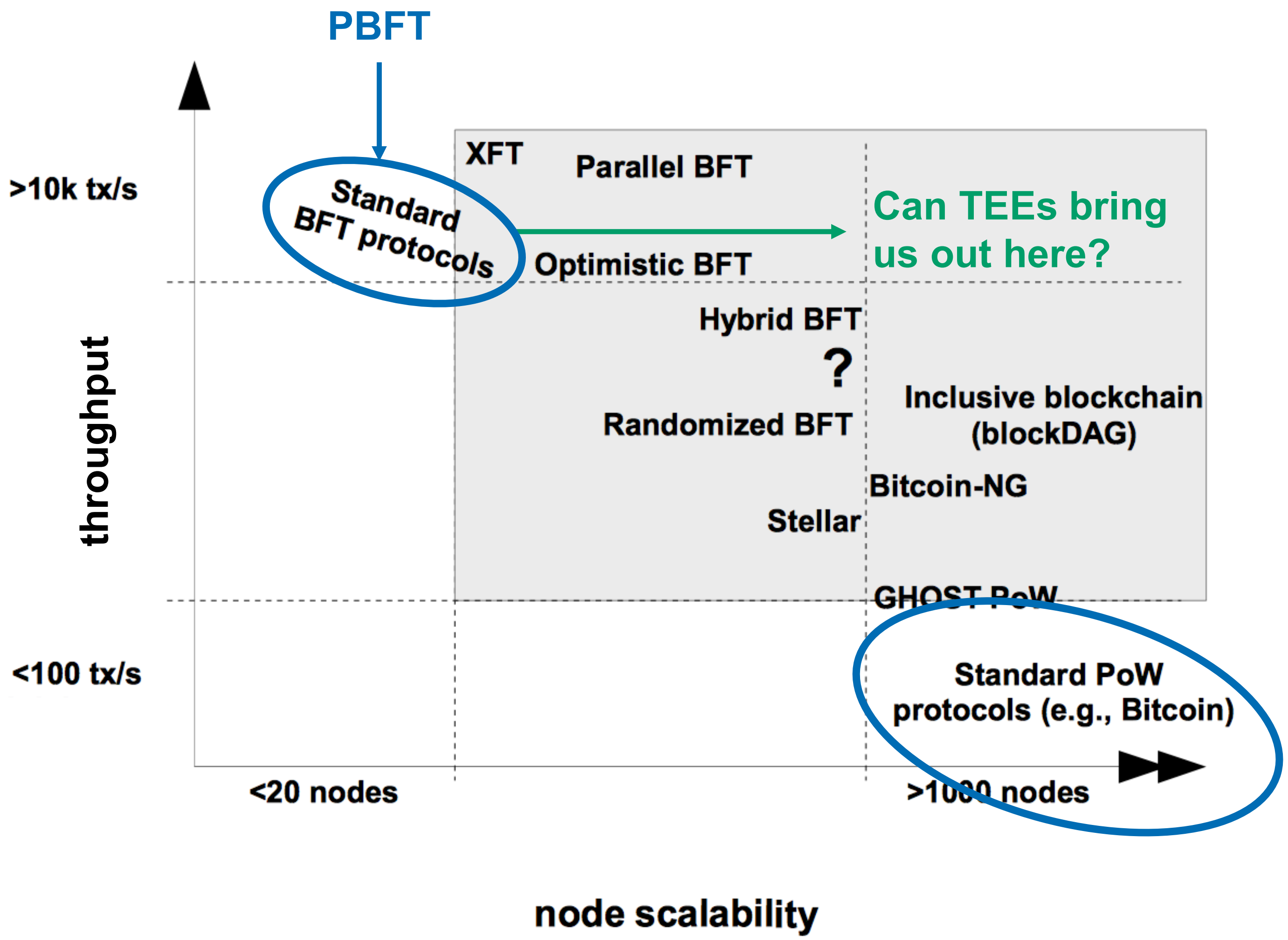
Less scalable than Proof of Work.



O(n^2) messages, $n = 3f + 1$

Castro & Liskov, "[Practical Byzantine Fault Tolerance]", OSDI'99

The landscape of consensus mechanisms



Adapted from Marko Vukolić, "[The quest for scalable blockchain fabric: Proof-of-work vs. BFT replication]" International Workshop on Open Problems in Network Security. Springer International Publishing, 2015

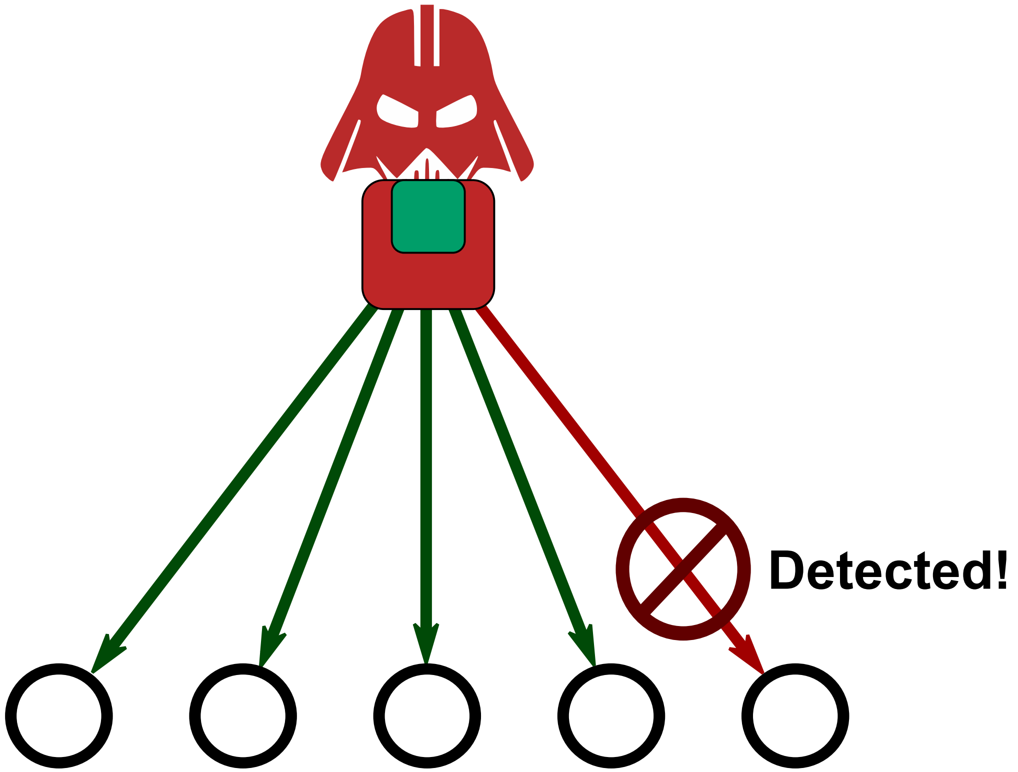
How can TEEs help design scalable consensus?

Problem: Compromised nodes can equivocate

Solution: Use attestation to prevent equivocation!

- Tolerate faults in ½ of the nodes

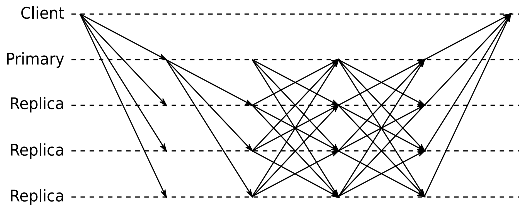
Applicability limited to permissioned settings



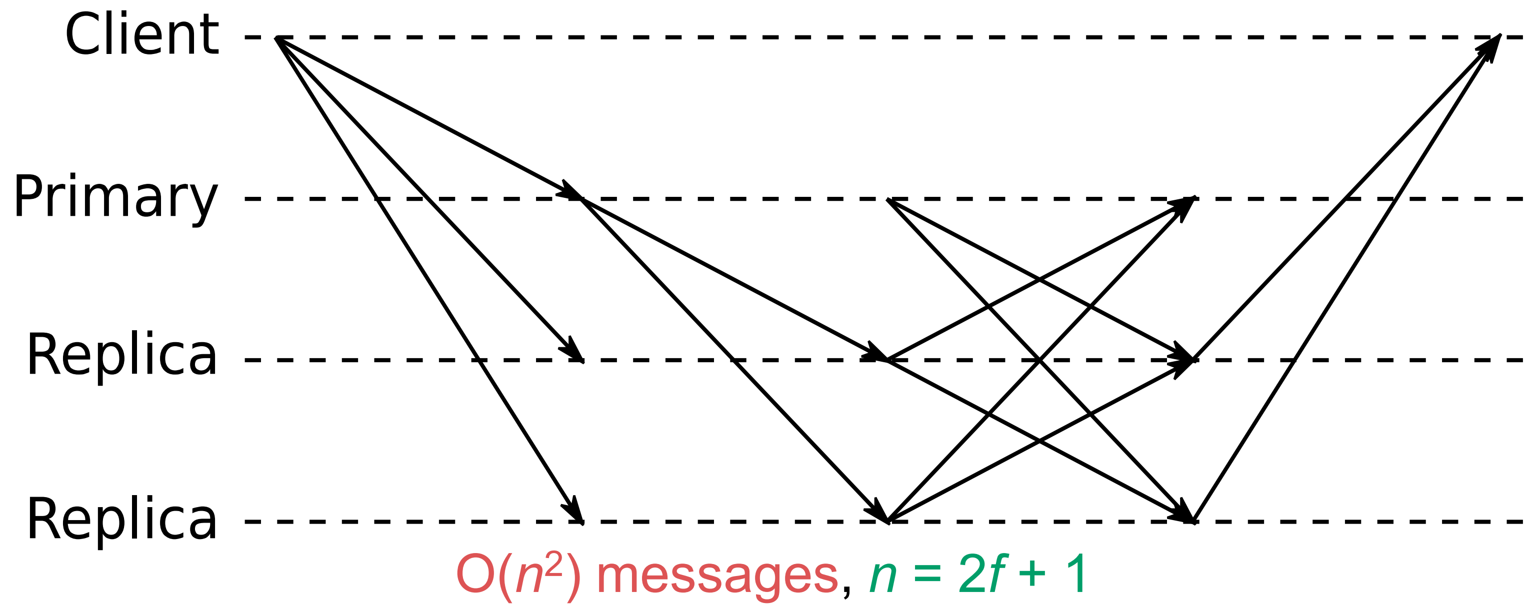
Chun et al., "Attested append-only memory: making adversaries stick to their word", SOSP '07

MinBFT

PBFT

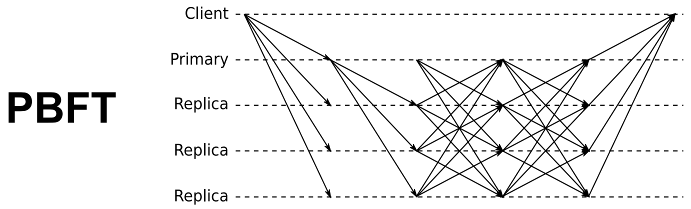


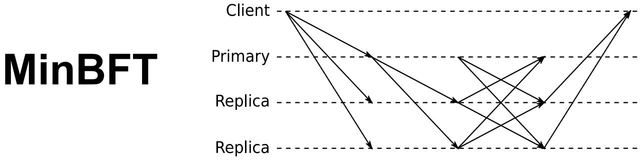
Hardware-based monotonic counters
→ increase fault-tolerance



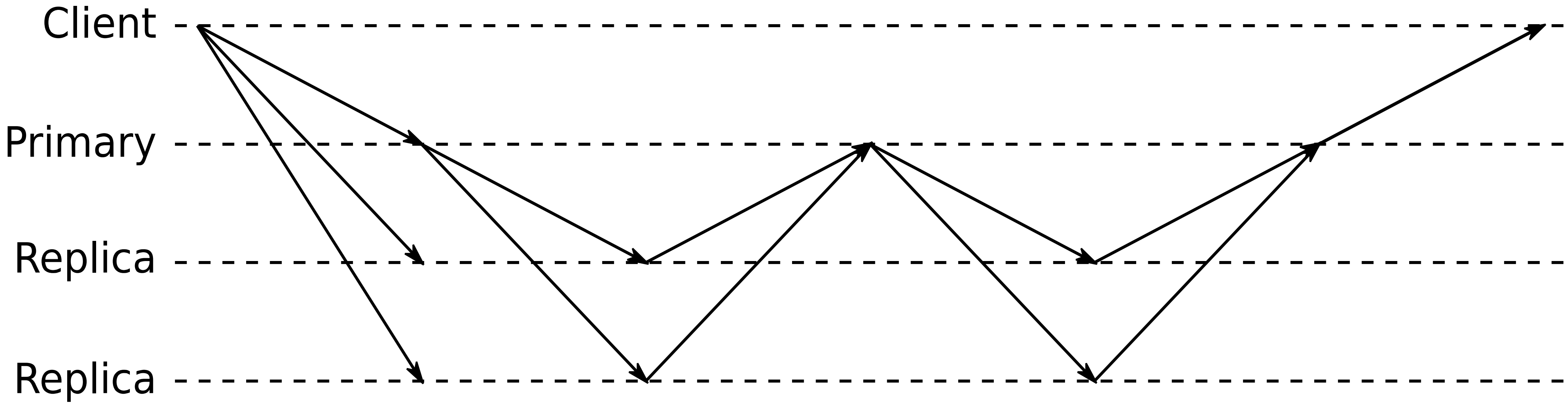
Veronese et al., "Efficient Byzantine fault-tolerance." IEEE Trans. Computers 62.1 (2013): 16–30

FastBFT





TEE-protected secret sharing, message aggregation
→ increase throughput

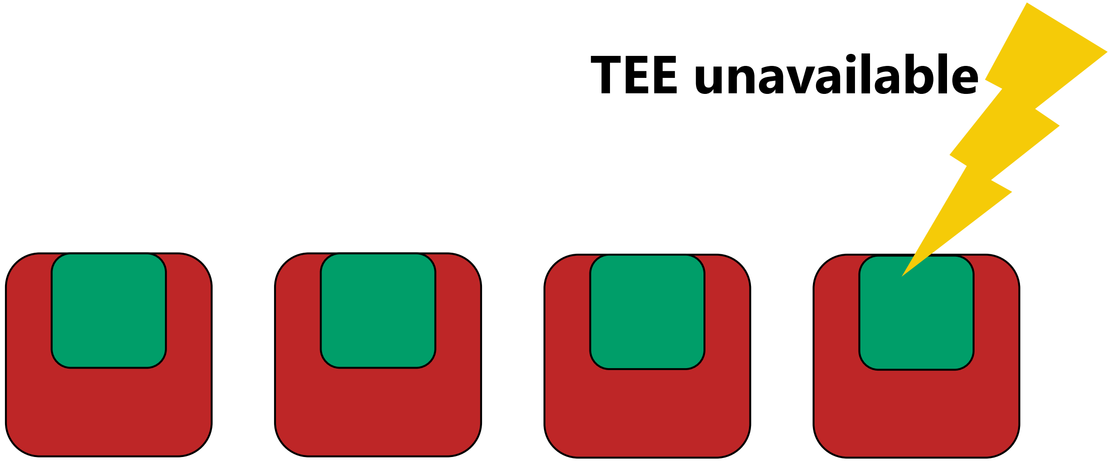


$O(n)$ messages, $n = 2f + 1$

[LLKA18]., "Scalable Byzantine Consensus via Hardware-assisted Secret Sharing", IEEE Trans. Computers (2018)

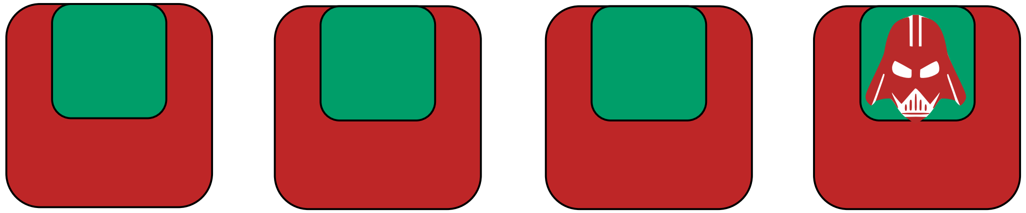
Challenges

Challenges in relying on hardware-assistance



TEE Availability:

- TEEs will not be universally available:
  - Gradual rollout
  - Obsolescence
  - Revocation



TEE Compromise:

- Compromising some TEEs should not completely break the system

Example: Dealing with TEE availability in consensus

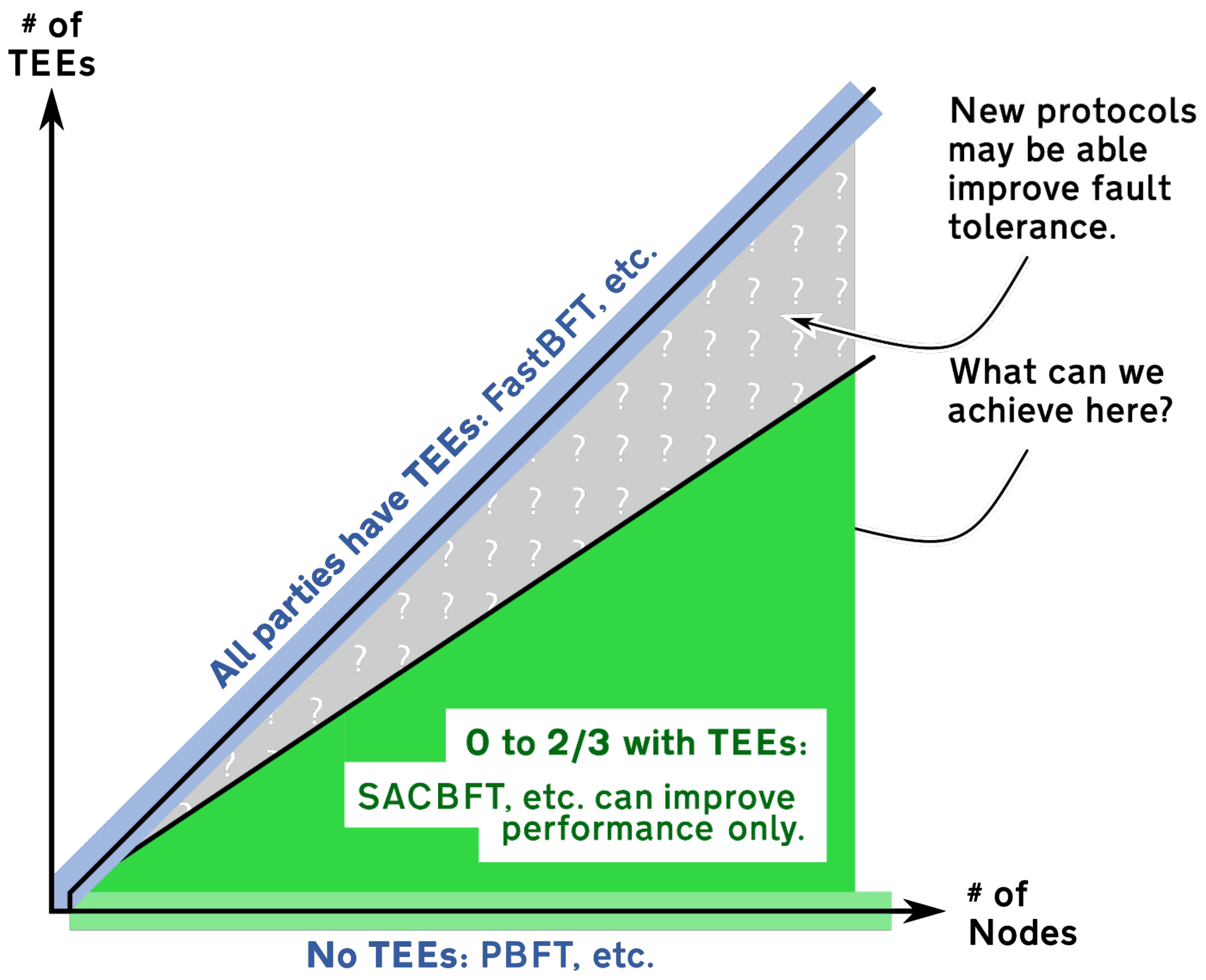
Question: Can we improve consensus protocols by adding only a few TEEs?

Answer*:

- can increase throughput if
  #TEEs > 1
- but fault tolerance cannot be increased if
  (#TEEs / #Nodes) ≤ 2/3

Open question: How can we optimally increase fault tolerance when

2/3 < (#TEEs / #Nodes) < 1



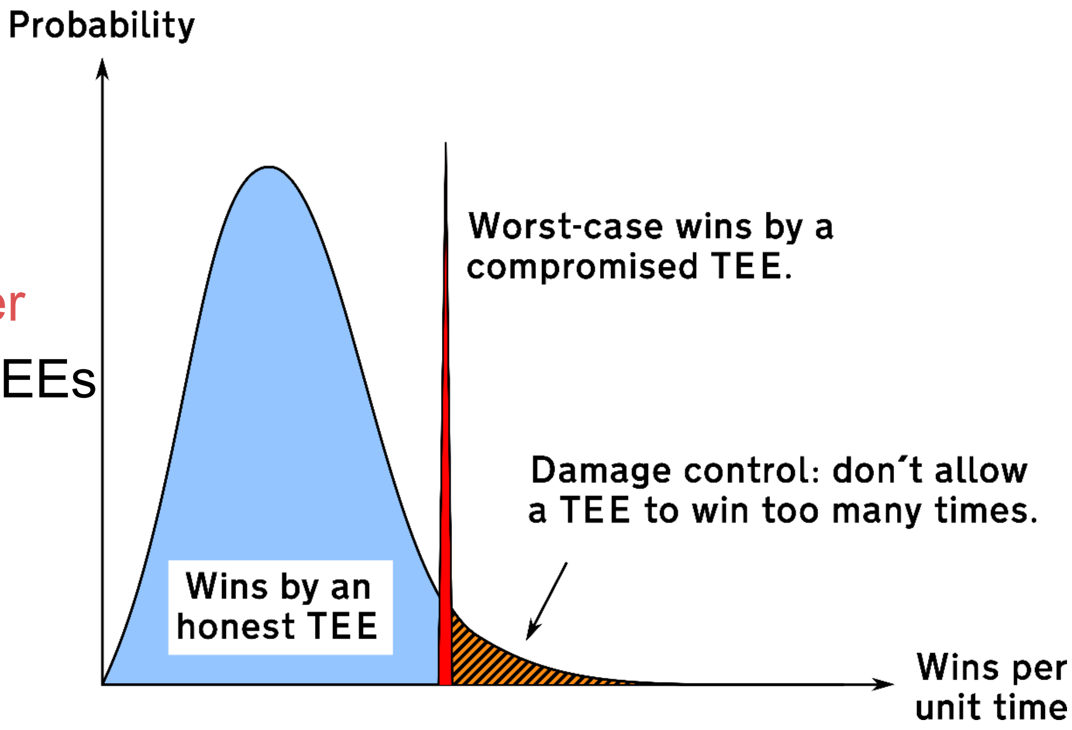
(* Forthcoming research report)

Example: Dealing with TEE compromise in PoET

Problem: A compromised TEE can win every block

Statistical solution: refuse blocks from machines that have won too many times

- Before: compromised TEEs give attacker unlimited power
- After: attacker power proportional to # of compromised TEEs



Open question: How can TEE-using applications detect/mitigate effects of TEE-compromise?

Intel, [Hyperledger Sawtooth Documentation](#) (2015).

Chen et al., "[On Security Analysis of Proof-of-Elapsed-Time (PoET)](#)", SSS 2017.

Summary

Concerns with applicability of hardware-supported TEEs remain

But compelling common-sense applications exist

be practical; protect end-users; address everyday needs

Solutions must incorporate mitigations for TEE unavailability or compromise

application- or system-level mitigations possible

https://ssg.aalto.fi/research/projects/bcon/
BCon project, Academy of Finland

http://www.icri-cars.org/
ICRI-CARS, Intel

On dealing with TEE compromise

Two types of settings where TEEs are useful:

1. Improving functionality without compromising security: e.g., PoET
2. Improving security (esp. where none exists today): e.g., SafeKeeper

TEE compromise is a major concern in Type 1 settings

In Type 2 settings, TEE compromise implies returning to current situation