Giving State to the Stateless:

Augmenting Trustworthy Computation with Ledgers

Gabriel Kaptchuk, Matthew Green, and Ian Miers

JOHNS HOPKINS
UNIVERSITY

JOHNS HOPKINS
UNIVERSITY

JOHNS HOPKINS
UNIVERSITY

JOHNS HOPKINS
UNIVERSITY


Now that we have SGX, all security problems are trivial. Security research is officially over!
HERE BE

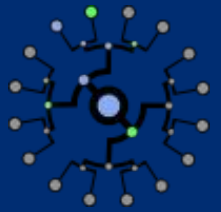
BEWARE!

HERE BE SGX!

JOHNS HOPKINS
UNIVERSITY

Why care about the bogeymen?

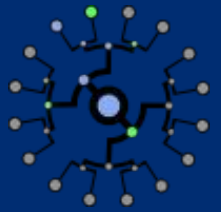
- Ledgers exist *in practice* and they aren't going away
  - Blockchains
  - Google Certificate Transparency Log



- Trusted Execution Environments exist *in practice*

Why care about the bogeymen?

- Ledgers exist *in practice* and they aren't going away
  - Blockchains
  - Google Certificate Transparency Log



- Trusted Execution Environments exist *in practice* … kinda?

Why care about the bogeymen?

- Ledgers exist *in practice* and they aren't going away
  - Blockchains
  - Google Certificate Transparency Log

- Trusted Execution Environments exist *in practice* … kinda?
  - Intel SGX and ARM Trustzone
  - Software only obfuscation
  - FPGA style hardware with burned keys

How can TEE's augment ledgers?
vs
How can ledgers augment TEE's?

Rewind Protection

Is the password “1234”?

Nope! You have 9 more attempts!

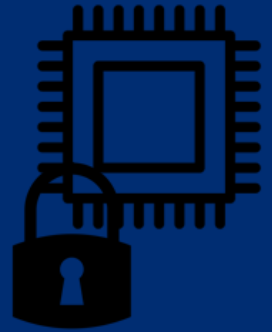
Rewind Protection

Is the password “1234”?

10 Guesses , Is the password “1234”?

9 Guesses , = KDF_k (“1234”)

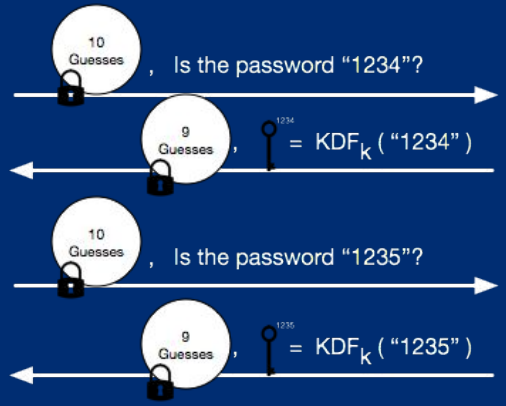
Decryption Failure! 9 more attempts!

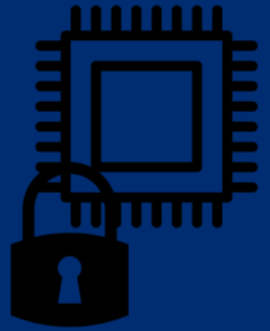


Rewind Protection

Is the password “1234” or “1235”?

Decryption Failure! 9 more attempts!





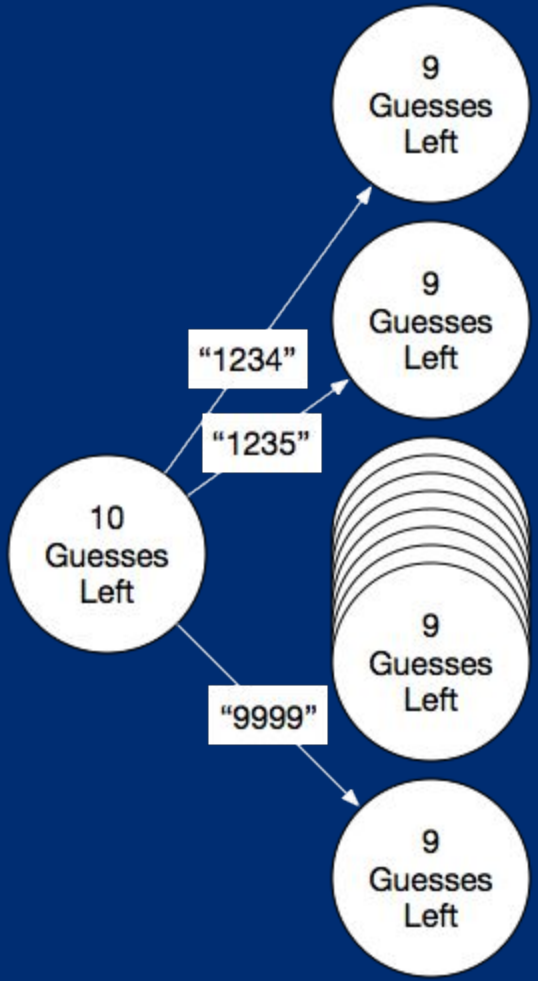
Rewind Protection

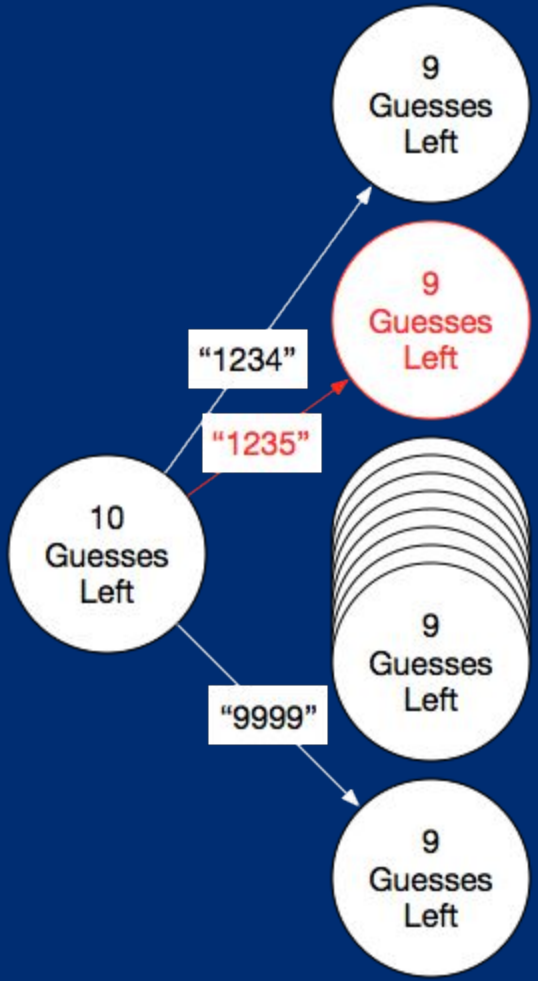
- Hardware based TEE's require NVRAM for protection
  - Scale poorly, expensive, and require special considerations for power fluctuations
  - Prior Work: Memoir [PLDMM11]

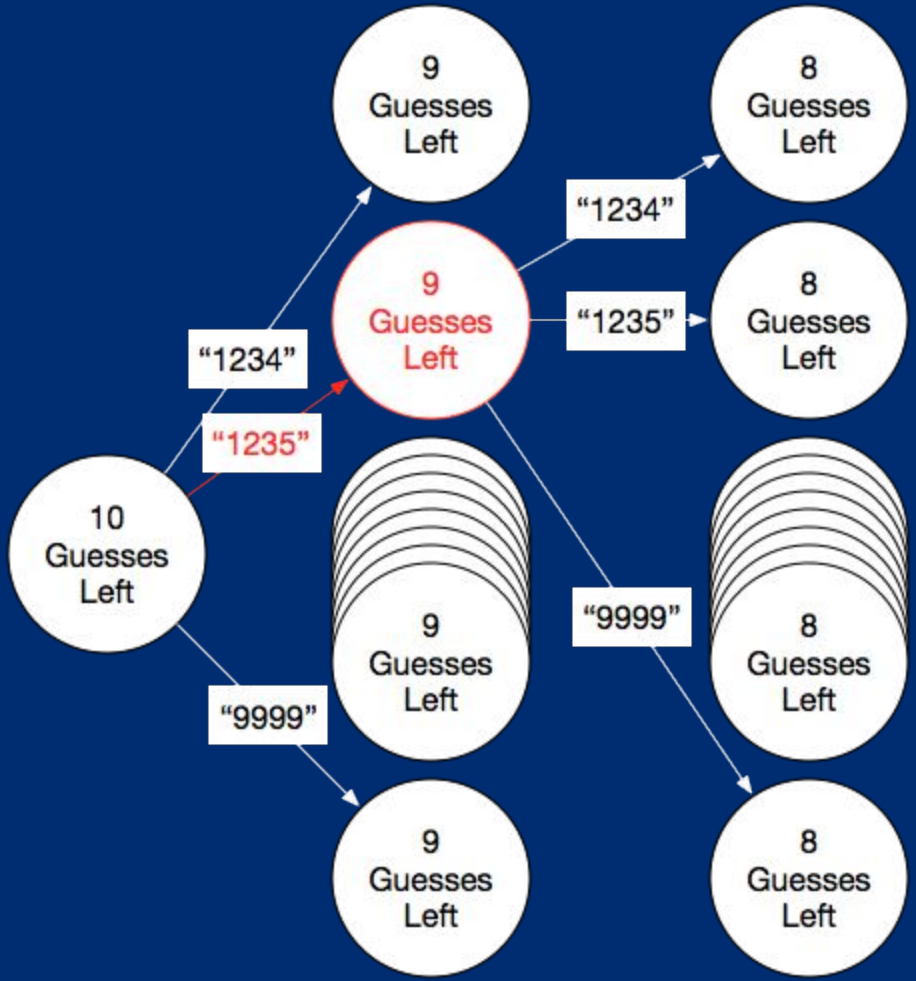
- Software only obfuscation can't get hardware-back protections
  - Prior Work: Goyal and Goyal [GoyGoy17] get one time programs from Ledgers + Obfuscation

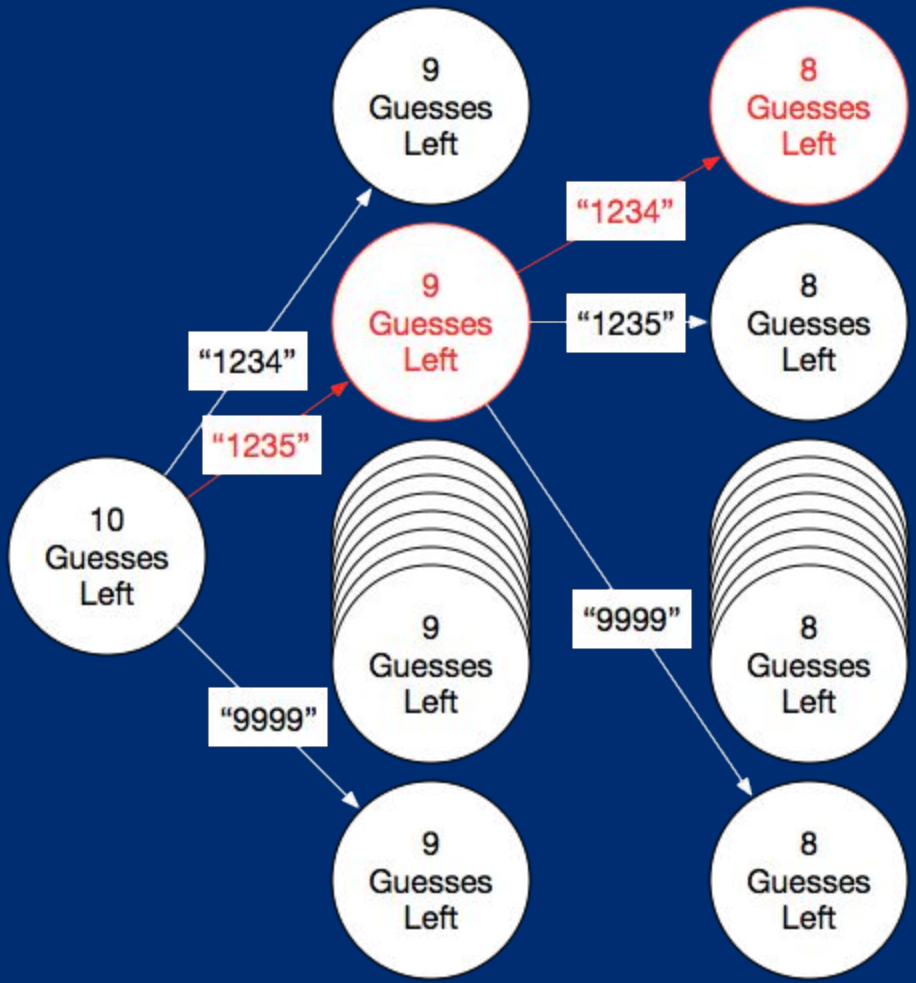
- This problem is *real*

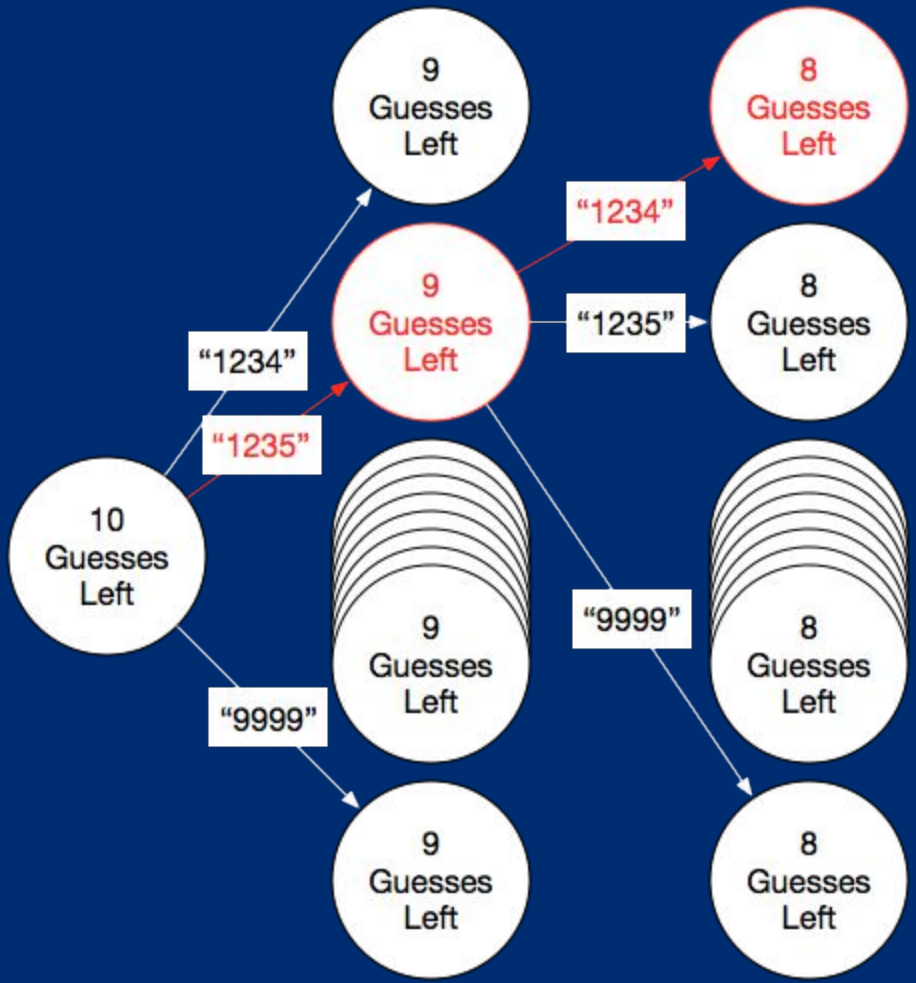
JOHNS HOPKINS UNIVERSITY





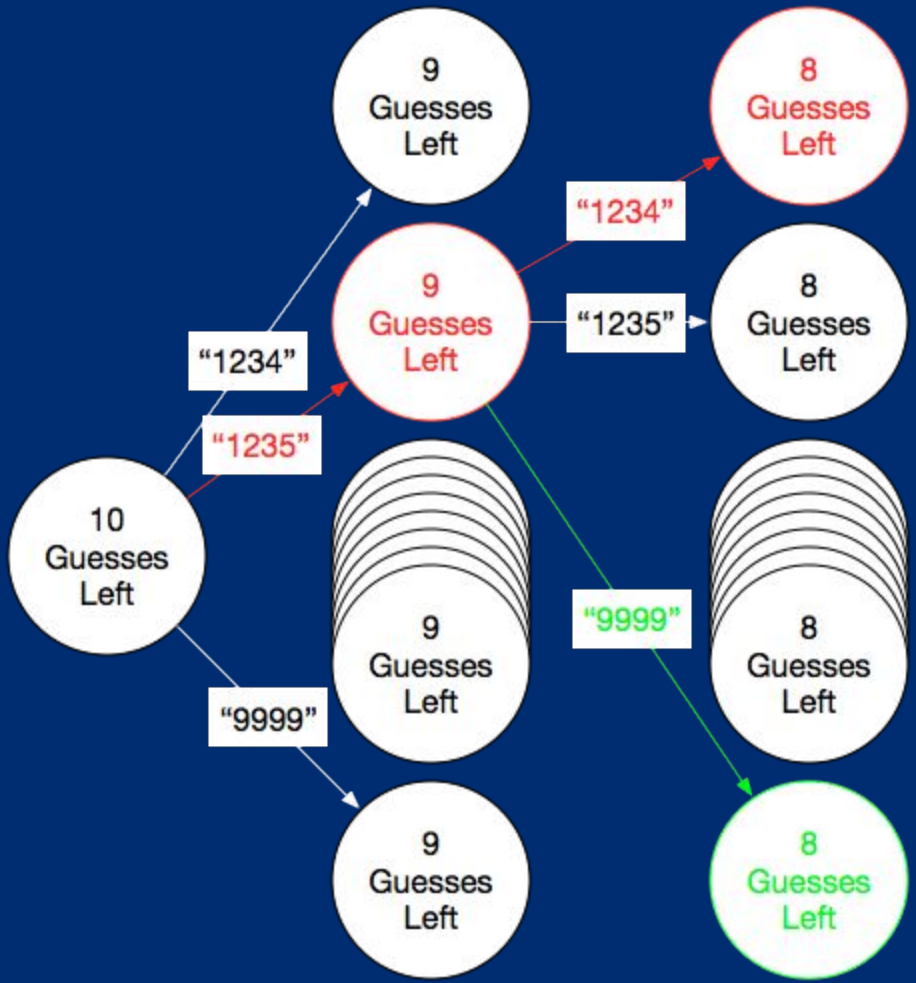






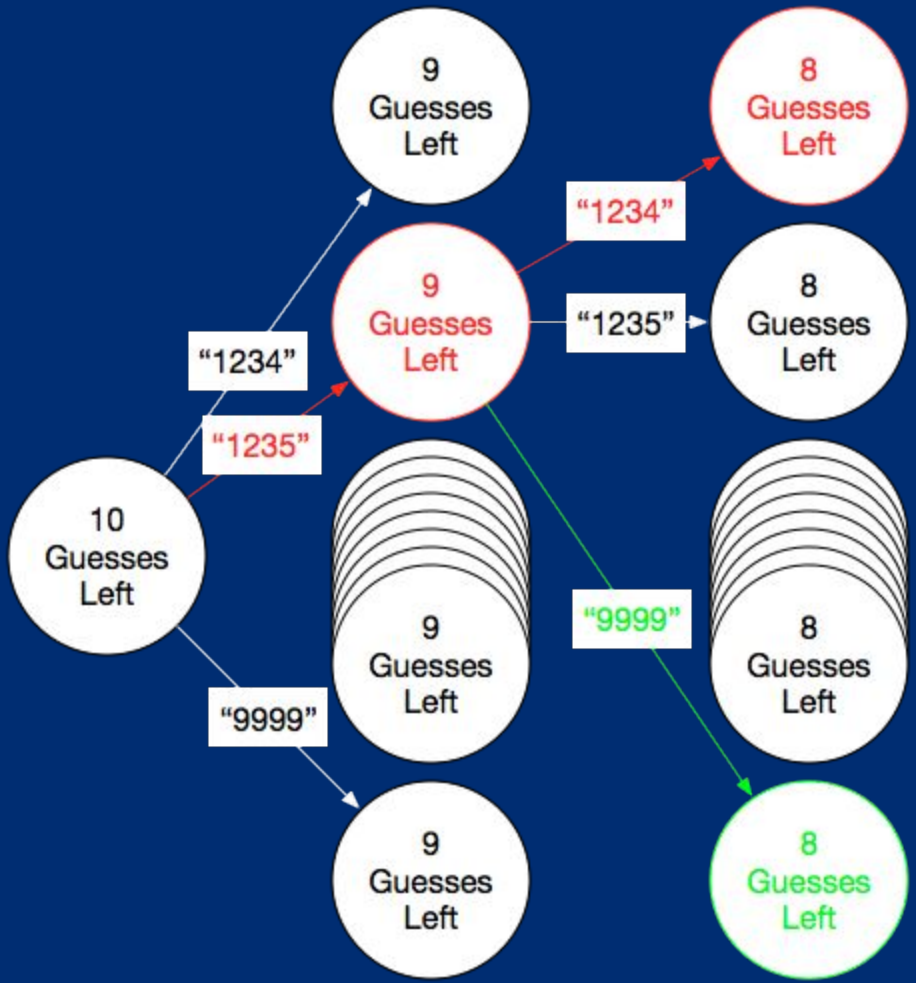
Repeated Execution

- Re-execution of a path doesn't cause a vulnerability
  - Derive the same key repeatedly
  - Starting again generates new master key



Repeated Execution

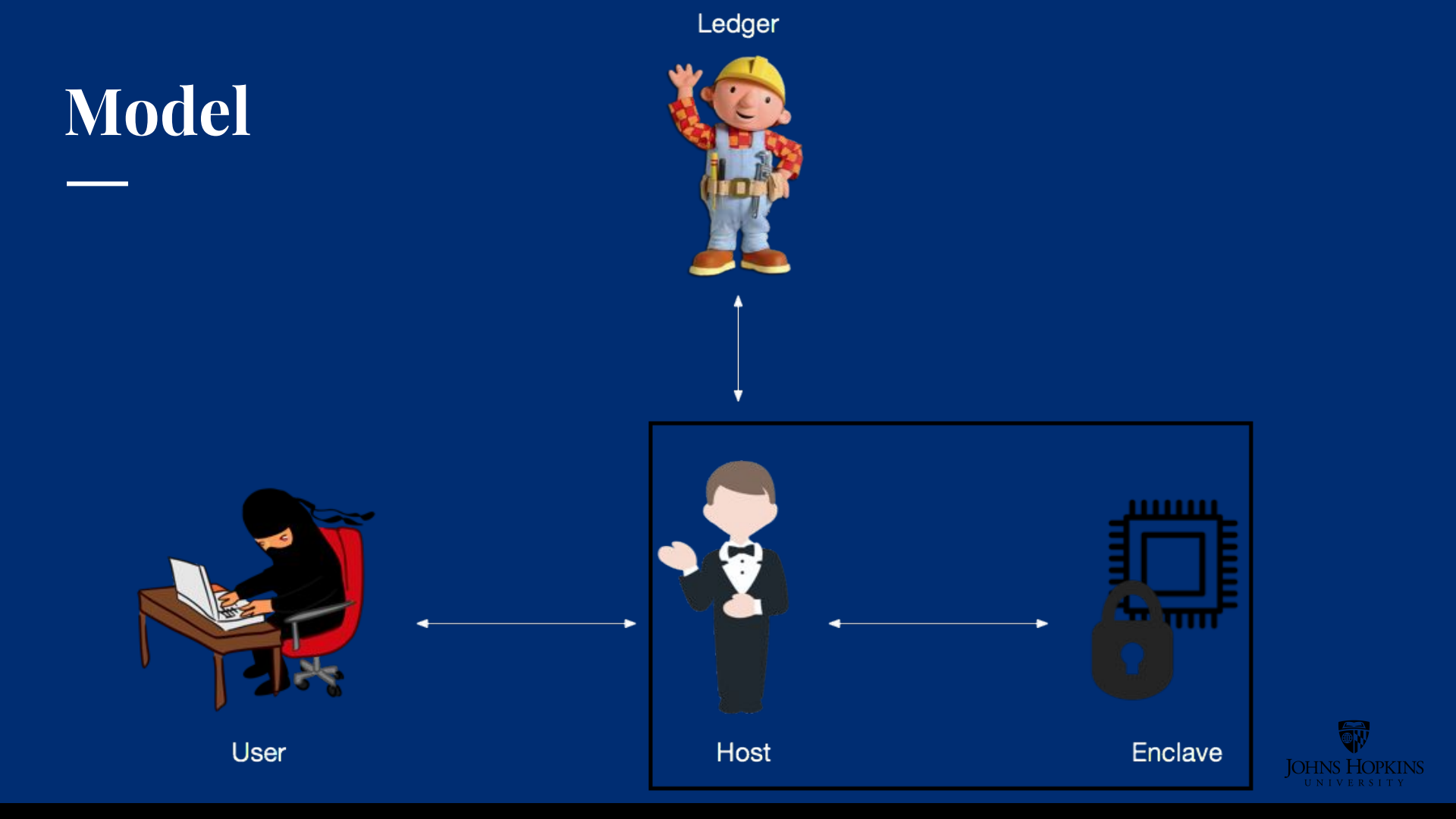
- Re-execution of a path doesn't cause a vulnerability
  - Derive the same key repeatedly
  - Starting again generates new master key
- Forking is dangerous
  - Running new inputs on old state
  - Running old steps with new randomness



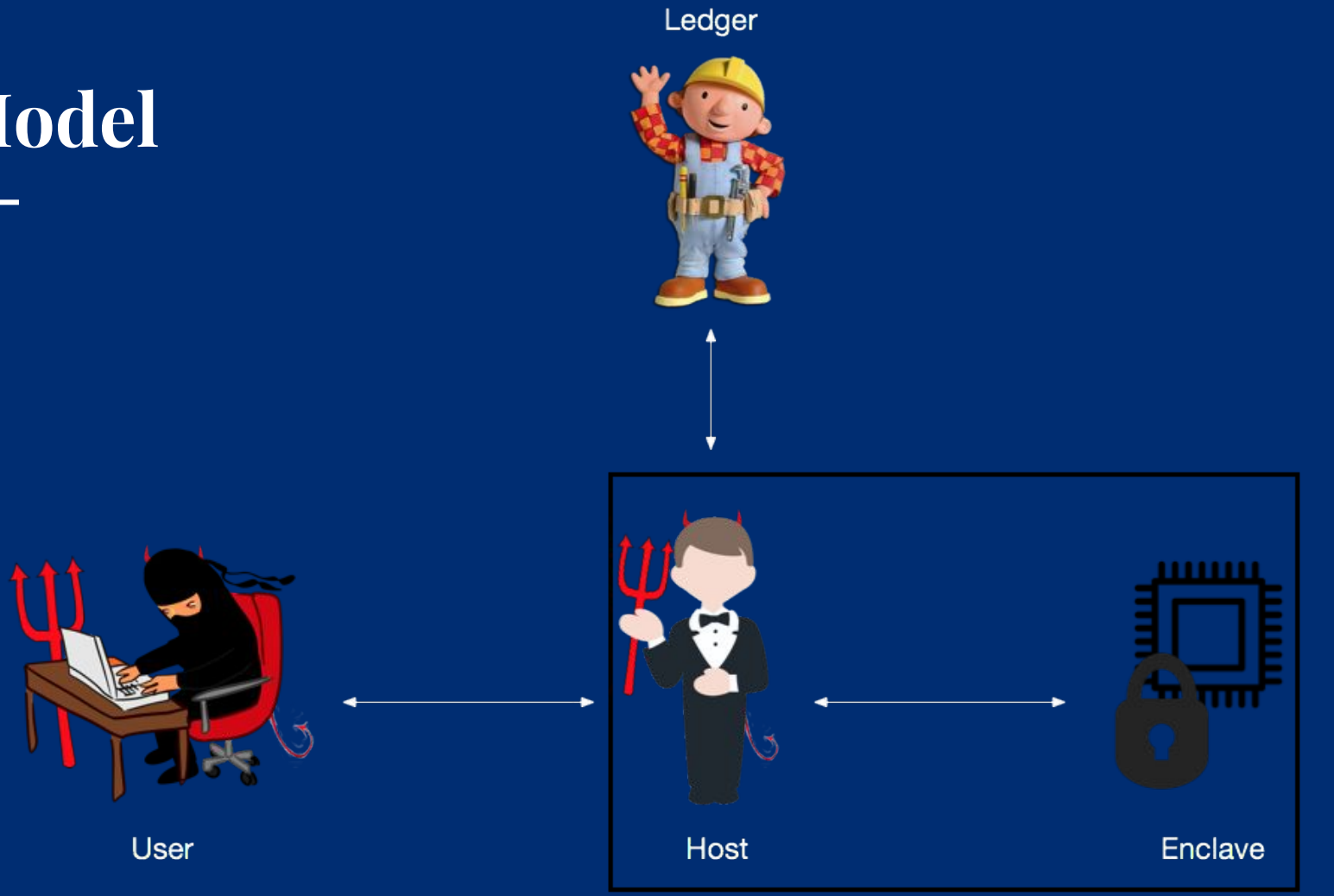
Repeated Execution

- Re-execution of a path doesn't cause a vulnerability
  - Derive the same key repeatedly
  - Starting again generates new master key
- Forking is dangerous
  - Running new inputs on old state
  - Running old steps with new randomness
- Strategy: bind program execution to something linear

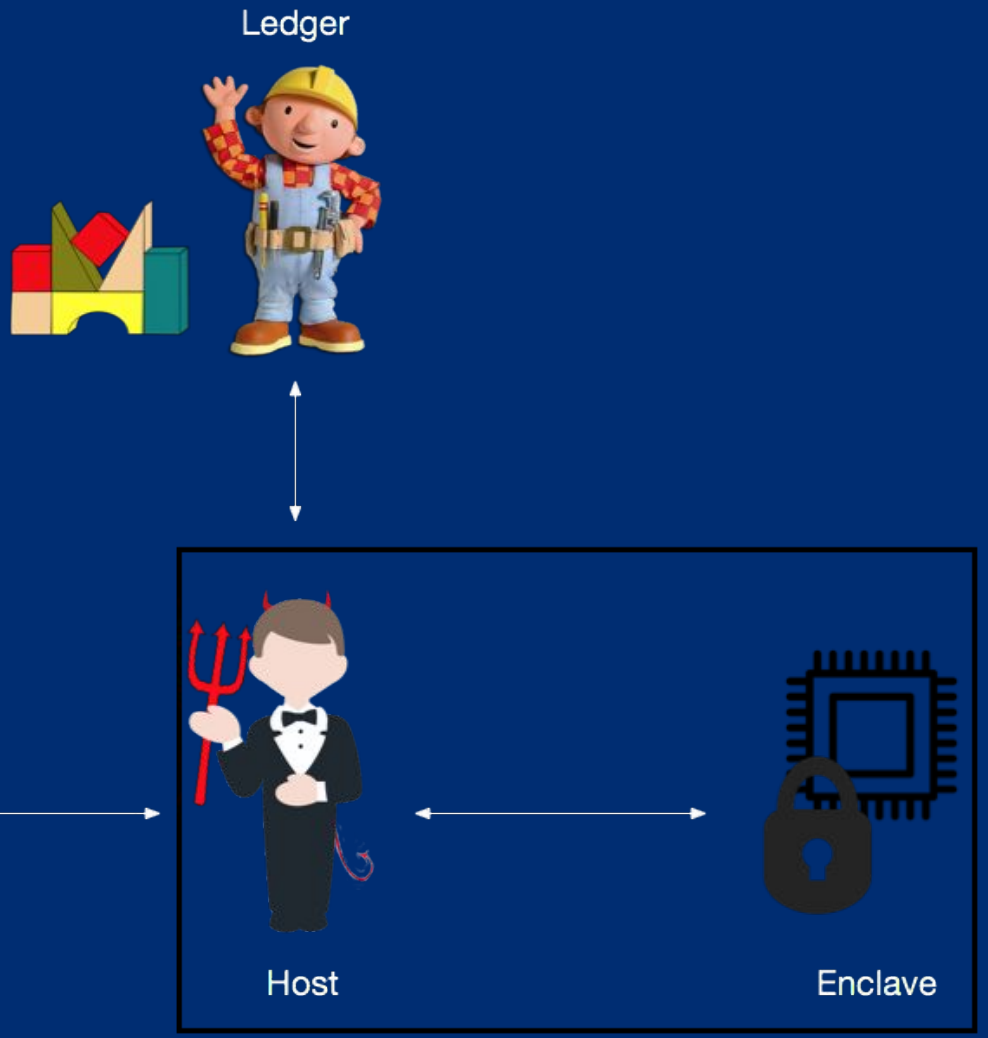
Model



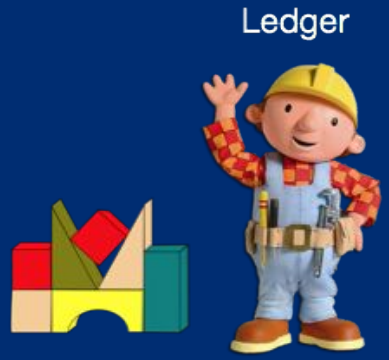
Model

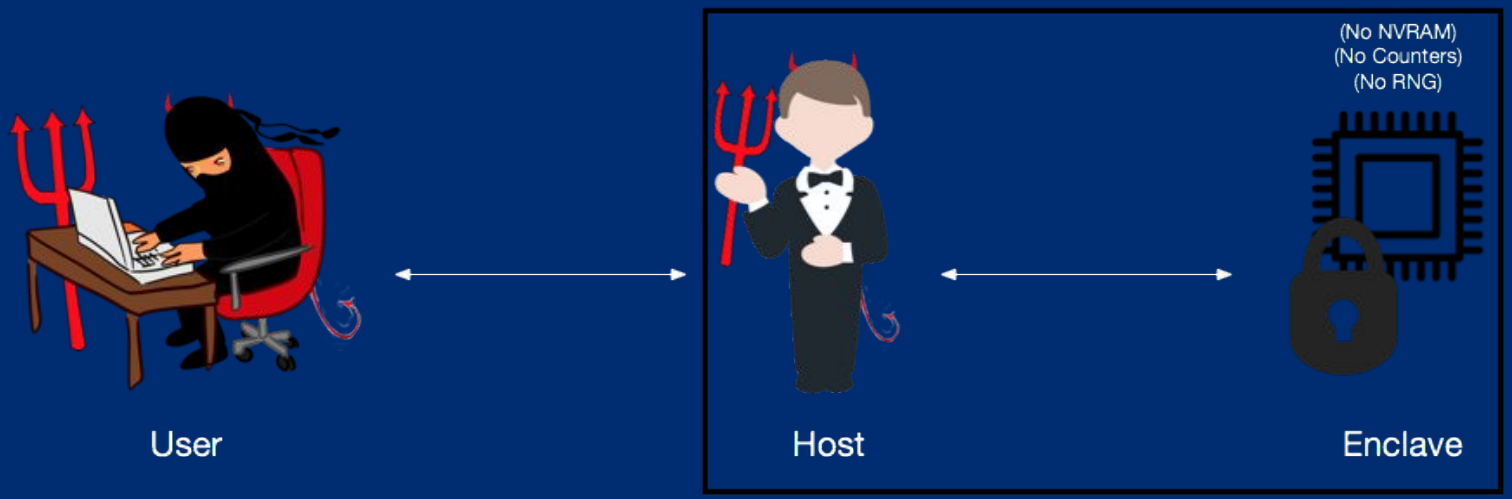


Model

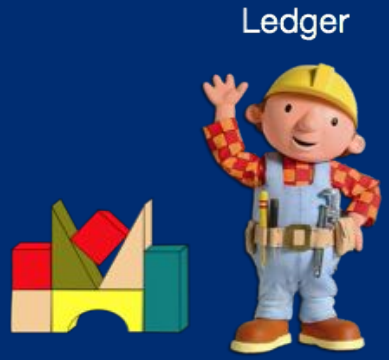


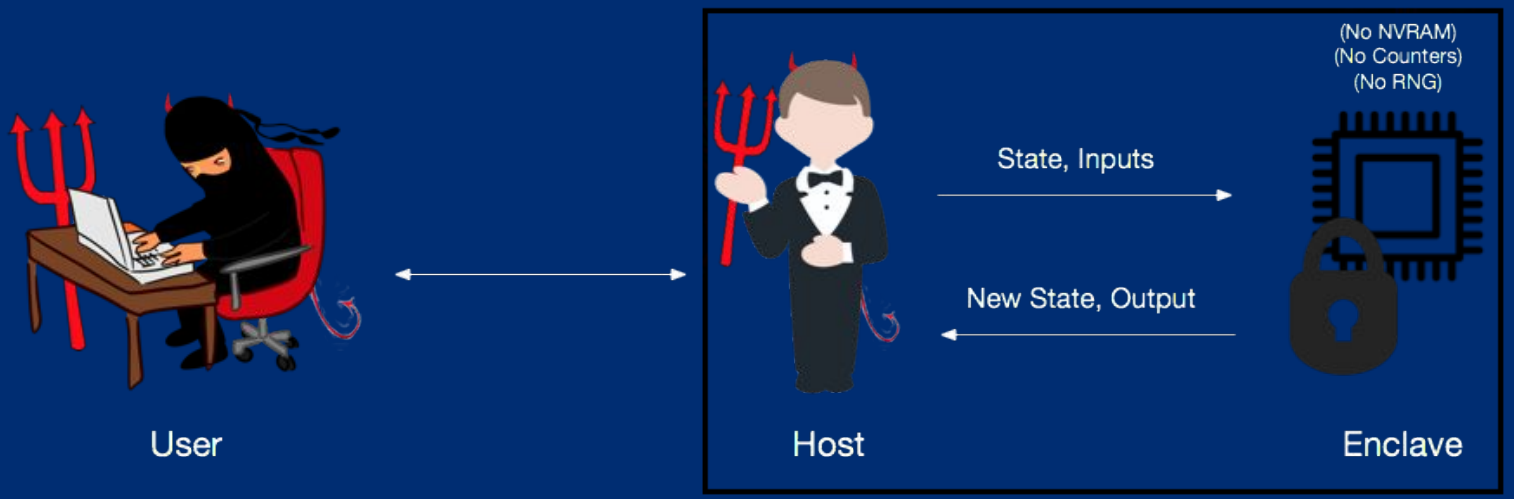
Model



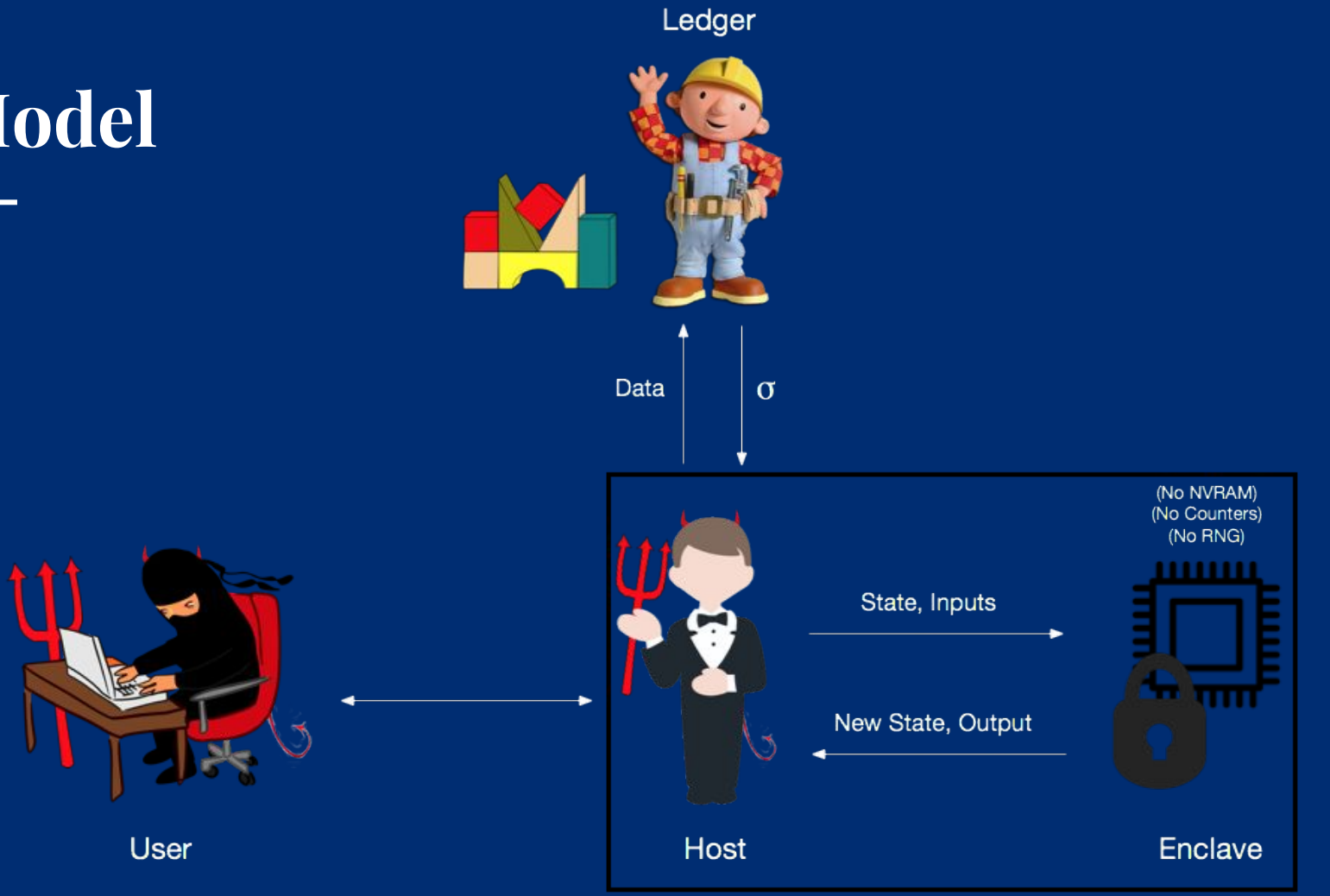


Model

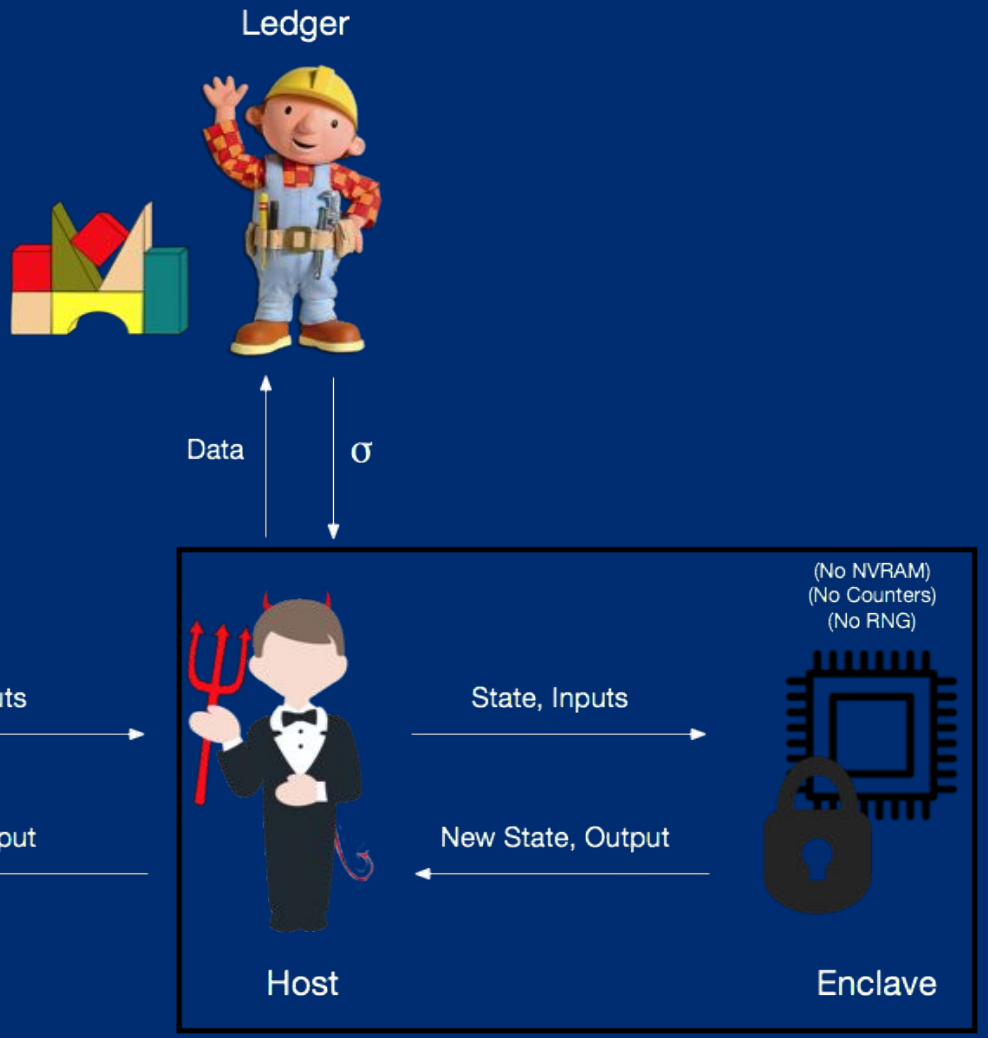

Ledger


(No NVRAM)
(No Counters)
(No RNG)
State, Inputs
New State, Output
User
Host
Enclave

Model

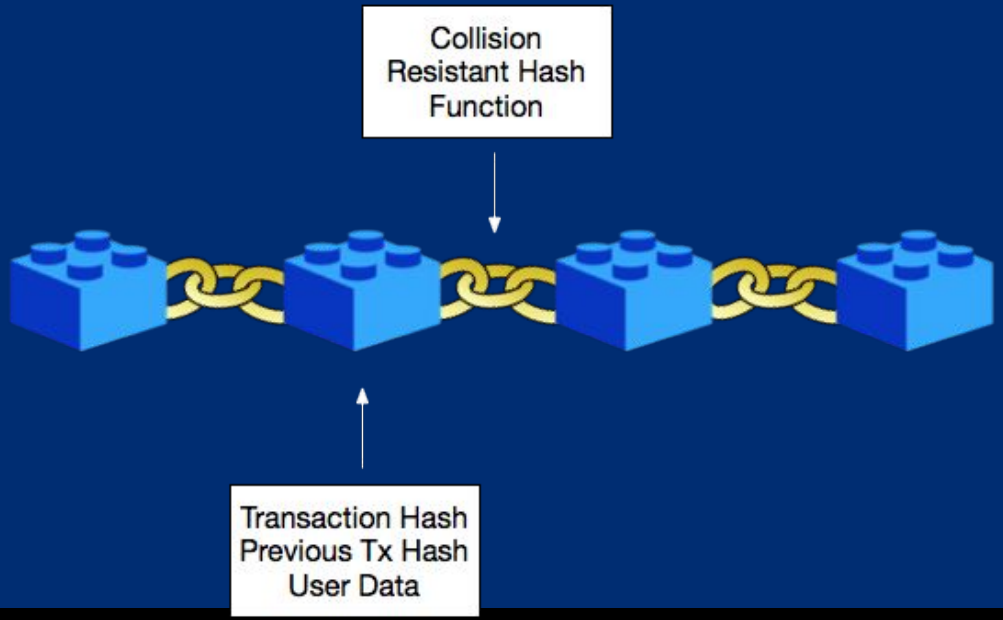

Ledger
Data
σ
(No NVRAM)
(No Counters)
(No RNG)
State, Inputs
New State, Output
User
Host
Enclave

Model


Ledger
Data
σ
(No NVRAM)
(No Counters)
(No RNG)
Inputs
State, Inputs
Output
New State, Output
User
Host
Enclave

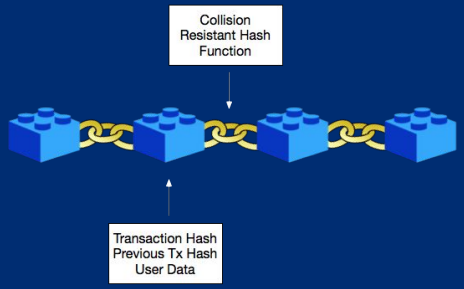
Ledger Requirements

- Creates hash chains of transactions
  - Similar to transaction in bitcoin, ethereum, etc...



Ledger Requirements

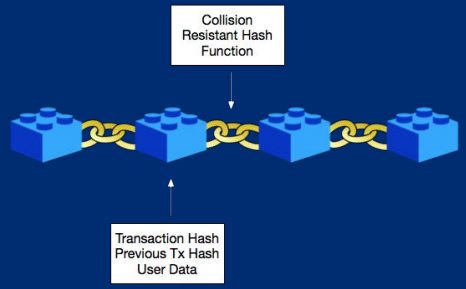
- Creates hash chains of transactions
  - Similar to transaction in bitcoin, ethereum, etc…



- Publicly verifiable proof of publication and public access
  - Digital signatures for computational security
  - Proof of work for economic security

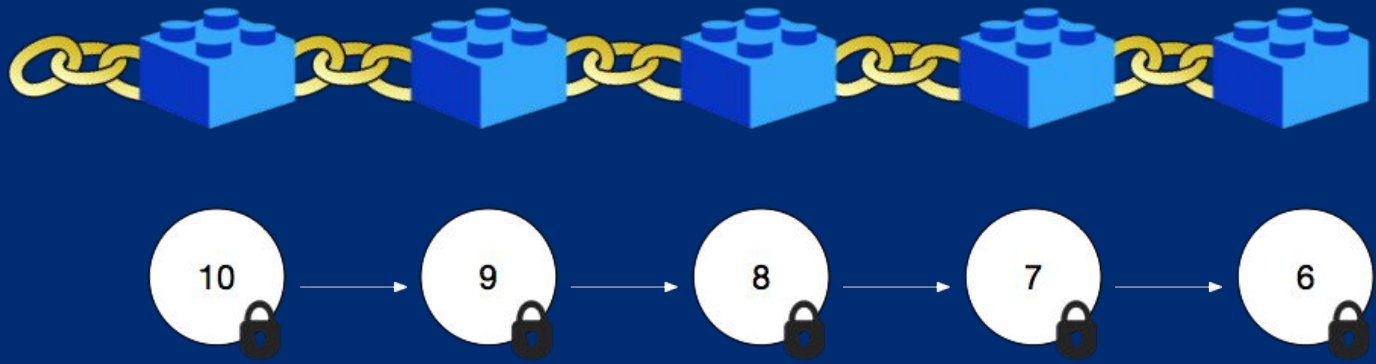
Ledger Requirements

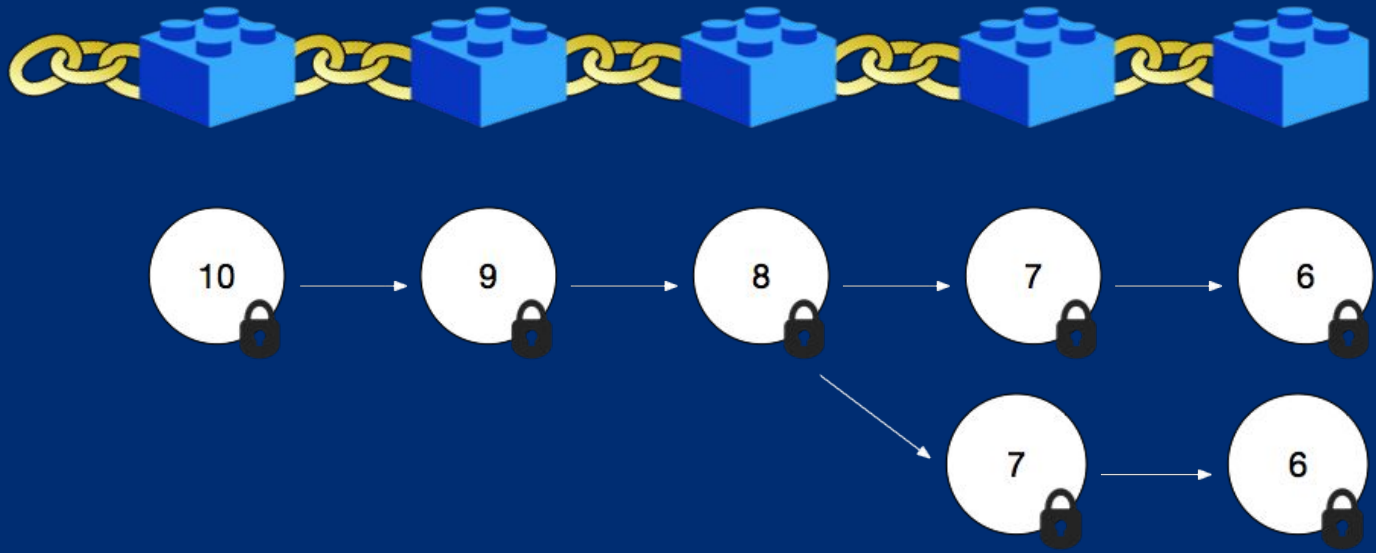
- Creates hash chains of transactions
  - Similar to transaction in bitcoin, ethereum, etc…

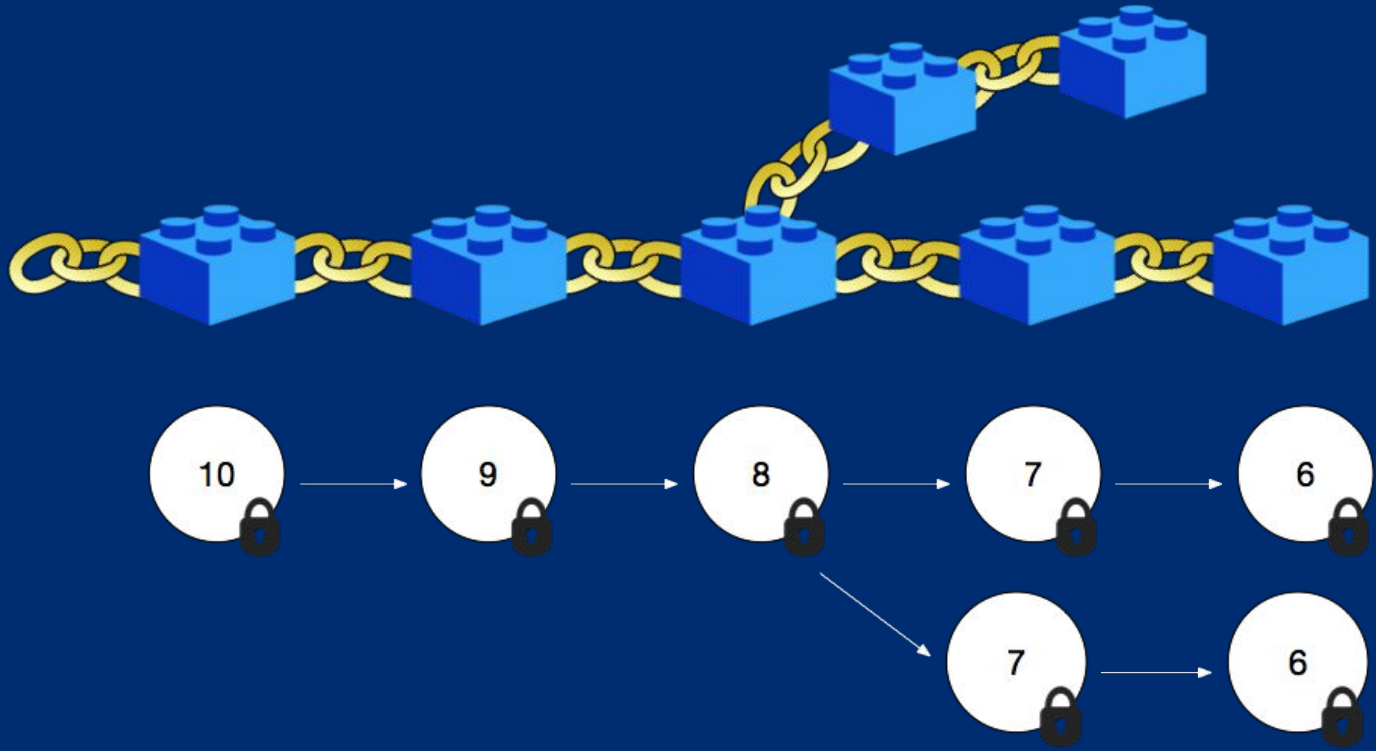


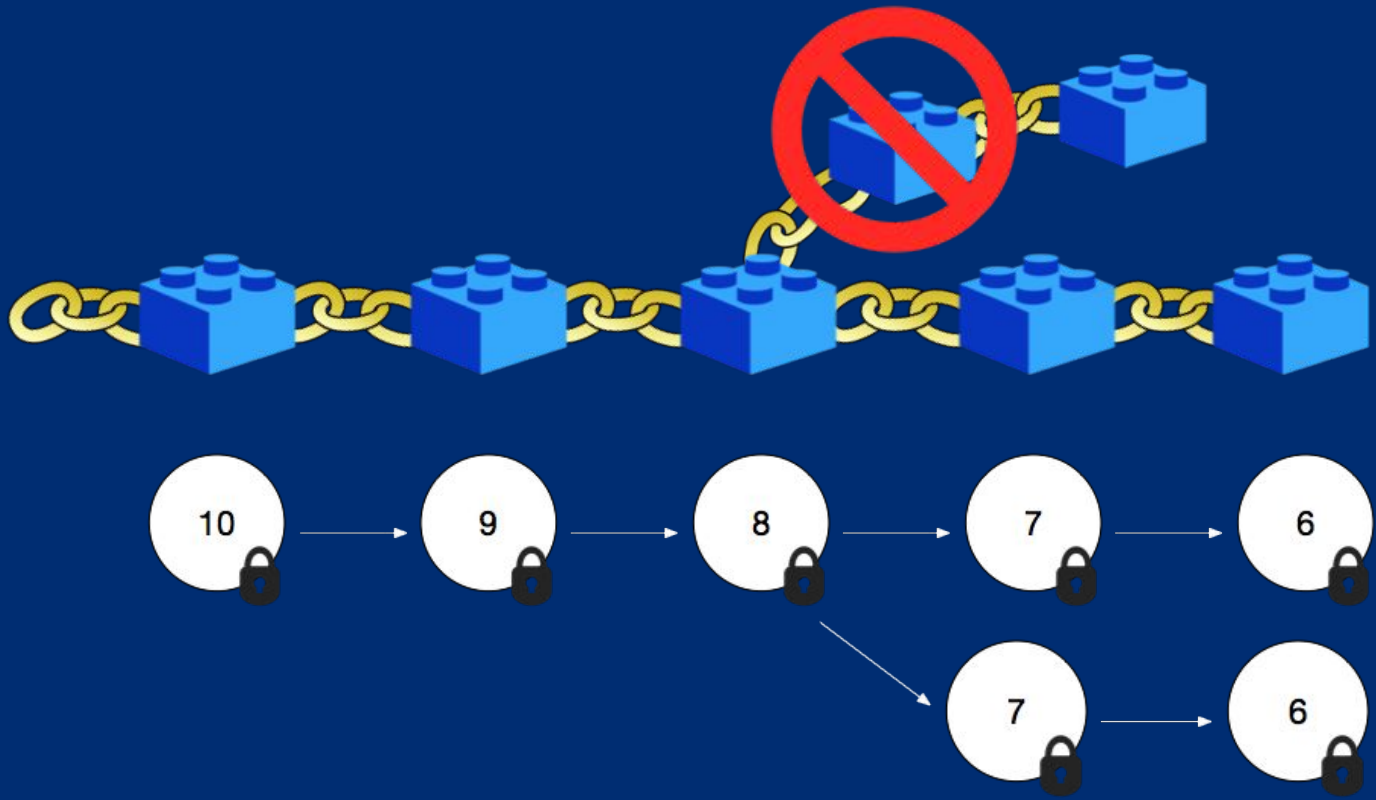
- Publicly verifiable proof of publication and public access
  - Digital signatures for computational security
  - Proof of work for economic security

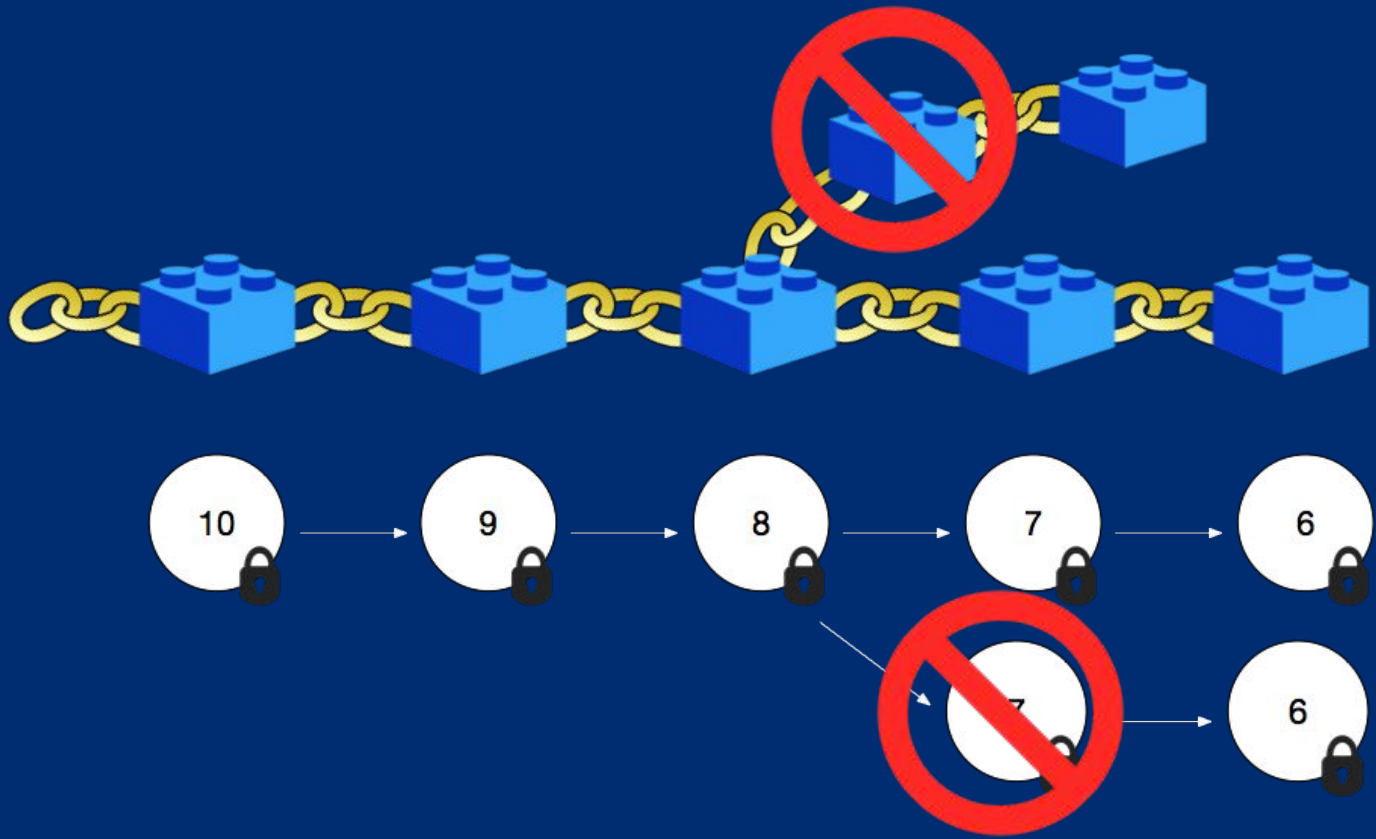
- Simplifying assumption: Single user ledgers











Ledger

User

Host

Enclave

JOHNS HOPKINS
UNIVERSITY

Ledger

User

"1234"

Host

Enclave

JOHNS HOPKINS
UNIVERSITY

Ledger

C = Com(10 , “1234”; r)

“1234”

User

Host

Enclave

JOHNS HOPKINS
UNIVERSITY

Ledger

Transaction Hash
Previous Tx Hash
C

C = Com(10 , “1234”; r)

User

“1234”

Host

Enclave

JOHNS HOPKINS
UNIVERSITY

Ledger

Transaction Hash
Previous Tx Hash
C

C = Com(10 , "1234"; r)

, σ

User

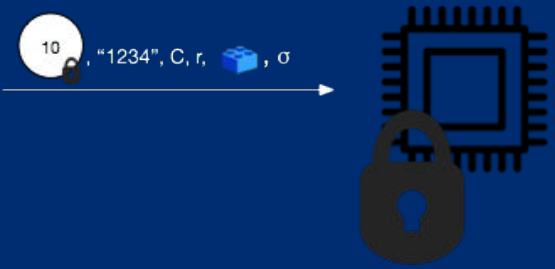
"1234"

Host

Enclave

JOHNS HOPKINS
UNIVERSITY

JOHNS HOPKINS UNIVERSITY



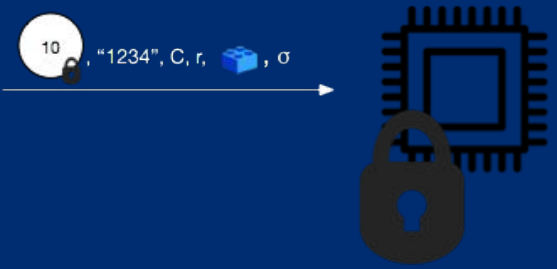
Verify(, σ)

Verify(C = Com(10 , “1234”; r))

Derive encryption key for next state

Transaction Hash
Previous Tx Hash
C

Derive decryption key for previous state



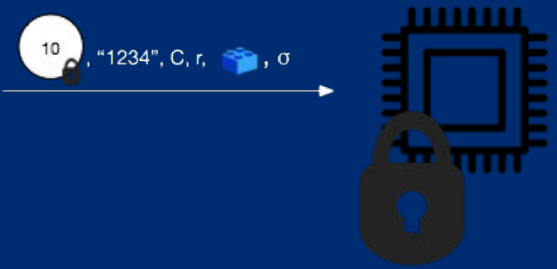
Verify(, σ)

Verify(C = Com(10 , “1234”; r))

Derive encryption key for next state

Transaction Hash
Previous Tx Hash
C

Derive decryption key for previous state



Verify(, σ)

Verify(C = Com(10 , “1234”; r))

10 = Decrypt(10 , PRF_{sk} (Previous Tx Hash)

Derive encryption key for next state

Transaction Hash
Previous Tx Hash
C

Derive decryption key for previous state

10 , “1234”, C, r, , σ

Verify(, σ)

Verify(C = Com(10 , “1234”; r))

10 = Decrypt(10 , PRF_{sk} (Previous Tx Hash)

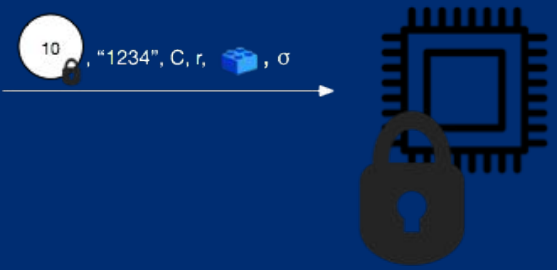
9 = Program(10 , “1234”; PRF_{sk} (“rand” || Previous Tx Hash))

JOHNS HOPKINS
UNIVERSITY

Derive encryption key for next state

Transaction Hash
Previous Tx Hash
C

Derive decryption key for previous state



Verify(, σ)

Verify(C = Com(10 , "1234"; r))

10 = Decrypt(10 , PRF_{sk} (Previous Tx Hash)

9 = Program(10 , "1234"; PRF_{sk} ("rand" || Previous Tx Hash))

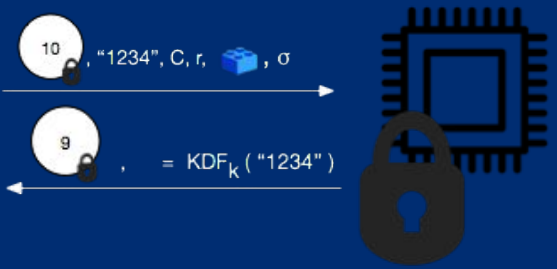
9 = Encrypt(9 , PRF_{sk} (Current Tx Hash)

JOHNS HOPKINS
UNIVERSITY

Derive encryption key for next state

Transaction Hash
Previous Tx Hash
C

Derive decryption key for previous state



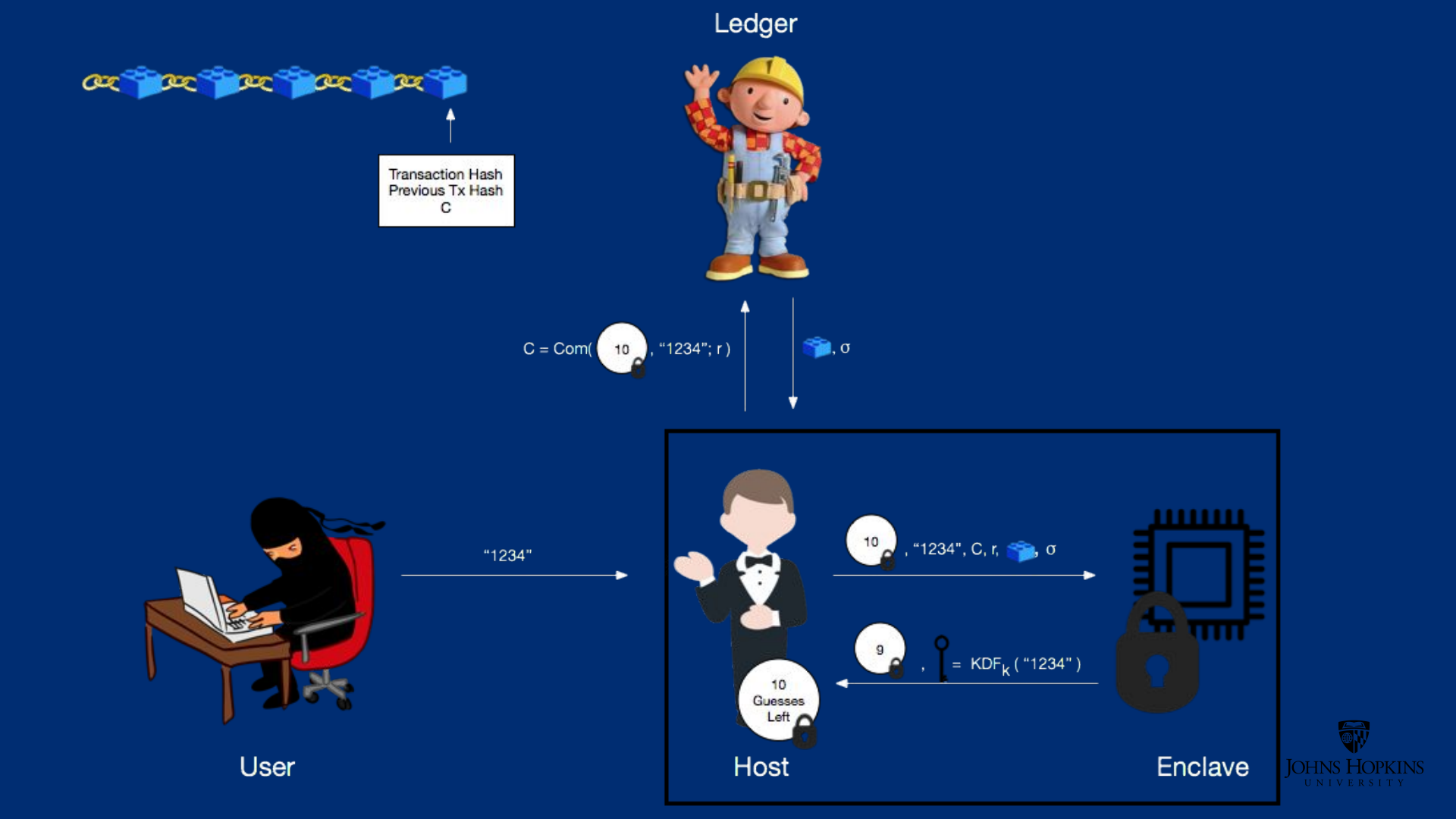
Verify(, σ)

Verify(C = Com(10 , "1234"; r))

10 = Decrypt(10 , PRF$_{sk}$ (Previous Tx Hash)

9 = Program(10 , "1234"; PRF$_{sk}$ ("rand" || Previous Tx Hash))

9 = Encrypt(9 , PRF$_{sk}$ (Current Tx Hash)


Ledger
Transaction Hash
Previous Tx Hash
C
C = Com(10 , "1234"; r)
, σ
"1234"
10 , "1234", C, r, , σ
9 , = KDF_k ("1234")
10 Guesses Left
User
Host
Enclave
JOHNS HOPKINS UNIVERSITY

Protocol Extensions

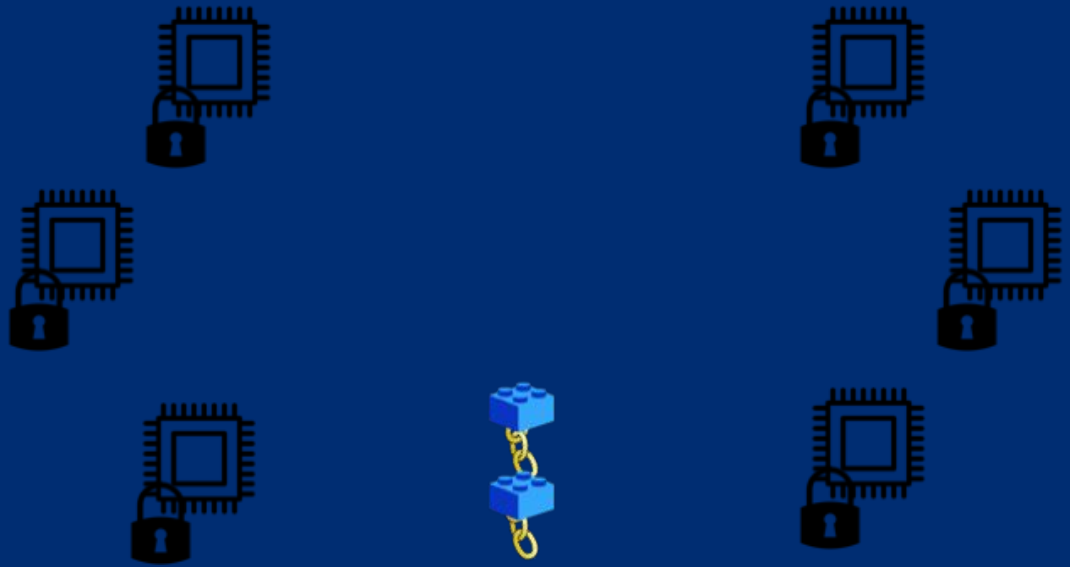
- We have managed to condition execution on ledger postings

- Extension #1: Programs can require public posting
  - *E.g.* Error reporting, guaranteed logging

- Extension #2: One Time Programs
  - Swept under the rug: so far we have secure *multi-execution programs*
  - Derive *unique* valid hash chain from program code

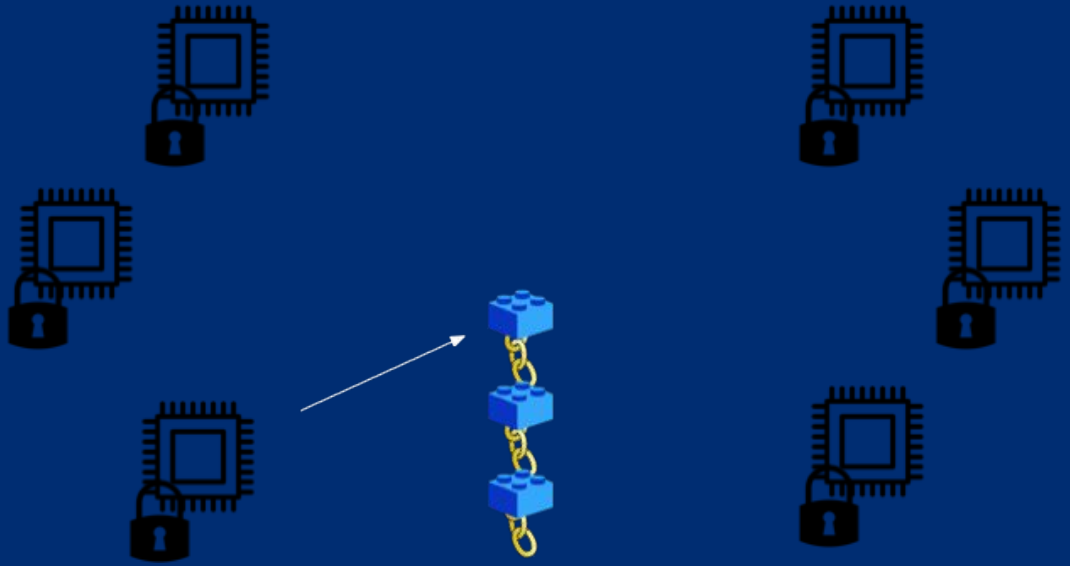
Additional Applications

- Smart contracts computing on private data
  - Concurrent work with Intel's Private Data Objects
  - Later follow-up work in the same area [Eikiden]



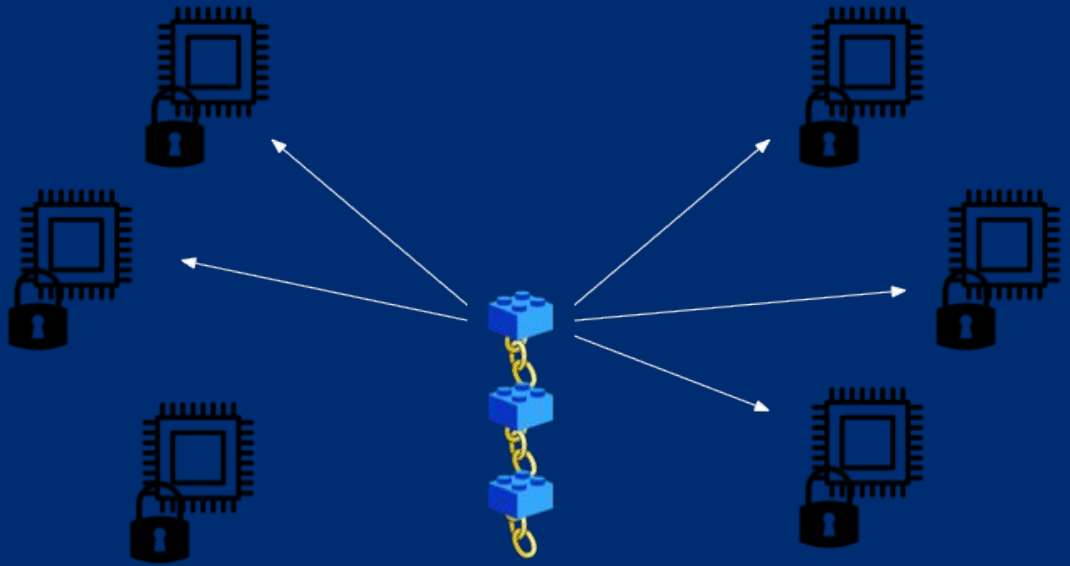
Additional Applications

- Smart contracts computing on private data
  - Concurrent work with Intel's Private Data Objects
  - Later follow-up work in the same area [Eikiden]



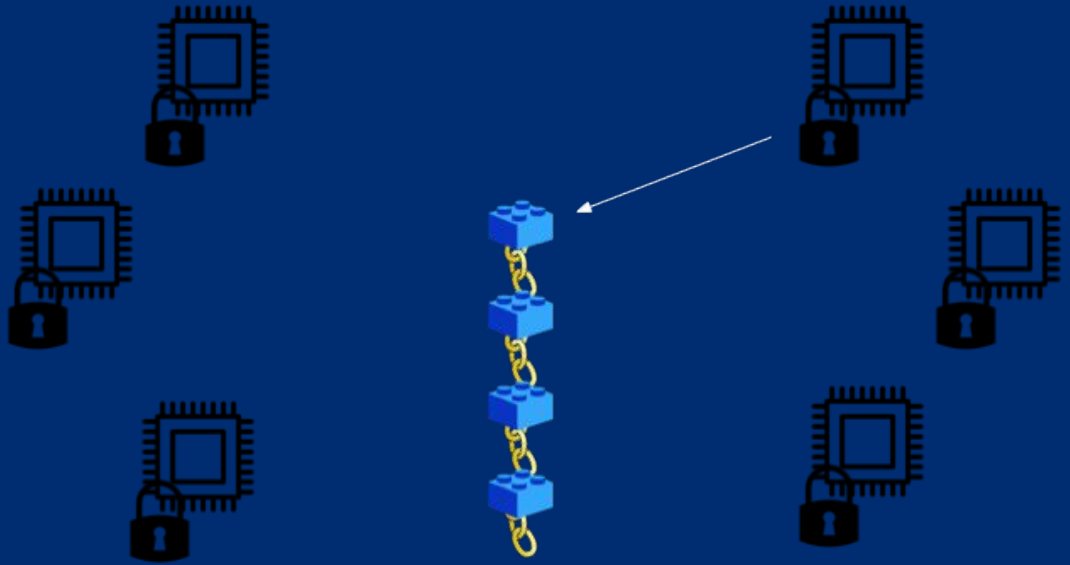
Additional Applications

- Smart contracts computing on private data
  - Concurrent work with Intel's Private Data Objects
  - Later follow-up work in the same area [Eikiden]



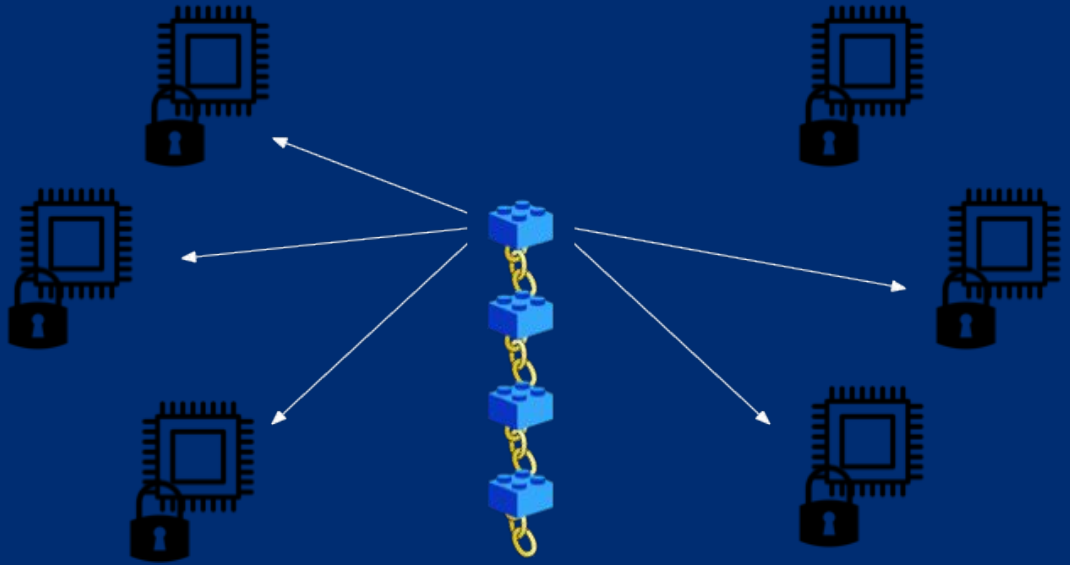
Additional Applications

- Smart contracts computing on private data
  - Concurrent work with Intel's Private Data Objects
  - Later follow-up work in the same area [Eikiden]



Additional Applications

- Smart contracts computing on private data
  - Concurrent work with Intel's Private Data Objects
  - Later follow-up work in the same area [Eikiden]



Additional Applications

- Autonomous Ransomware
  - Inevitable outcome of malicious trusted execution environments
  - Eliminates the need for command and control systems

Conclusions

- We create a novel protocol that provides trustworthy state for TEE's by binding state to an append-only ledger

- Ledgers are here to stay — lets do more than just currency-related research

- Keeping state is a difficult problem with wide ranging applications

Thank You!

Gabriel Kaptchuk
kaptchuk.com
gabe@kaptchuk.com

Johns Hopkins University

Bonus Slides