# Trojan-tolerant Hardware
# + Supply Chain Security in Practice

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# Who we are

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*CEO, Enigma Bridge*

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*CTO, Enigma Bridge*

# Highlights

- The private life of keys
- Weak links of the supply chain
- Lessons learned from airplanes
- Demo of our crypto hardware
- Protocols, Maths & Magic
- Politics, Distrust & Hardware Security

# The Private Life of Keys

1. Someone designs an integrated circuit (IC)
2. IC is fabricated
3. IC is delivered to hardware vendor
4. Vendor loads firmware & assembles device
5. Device is sent to customer
6. Customer generates and stores key on the device

# The Private Life of Keys

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***Any attack in these steps can compromise the key!***

# Hardware Security Modules

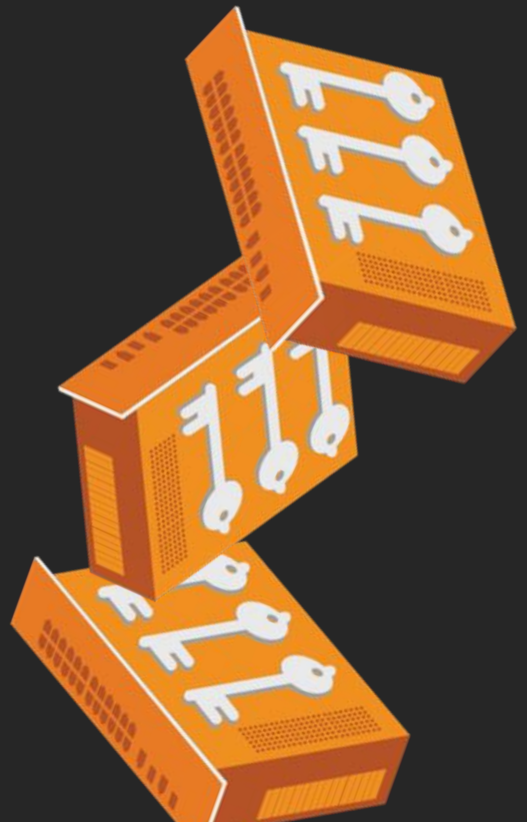
*Physical computing device that safeguards and manages digital keys for strong authentication and provides cryptoprocessing.*

**Features:**

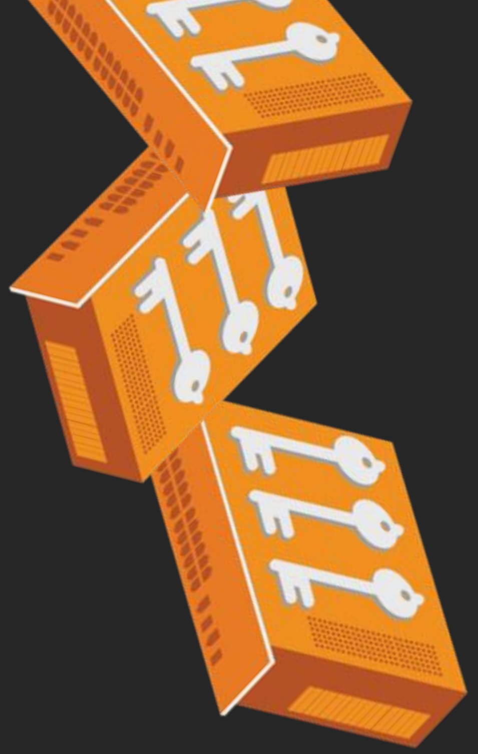
- Cryptographic key generation, storage, management
- Tamper-evidence, Tamper-resistance, Tamper-response
- Security Validation & Certification

**Crypto Operations are carried out in the device**

**No need to output the private keys!**



# Hardware Security Modules



**Common Applications**

- Public Key Infrastructures
- Payment Processing Systems
- SSL Connections
- DNSSEC
- Transparent Data Encryption

**Cost**

- Hardware (>$10k)
- Integration Cost
- Operational/Support

# HSM Guarantees

1. Someone designs an integrated circuit (IC)
2. IC is fabricated
3. IC is delivered to hardware vendor
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# What could go wrong?

- Bugs

*CVE-2015-5464*
The HSM allows remote authenticated users to bypass intended key-export restrictions …

- Backdoors/HT?

THIS 'DEMONICALLY CLEVER' BACKDOOR HIDES IN A TINY SLICE OF A COMPUTER CHIP

NSA's Own Hardware Backdoors May Still Be a "Problem from Hell"

Expert Says NSA Have Backdoors Built Into Intel And AMD Processors

Snowden: The NSA planted backdoors in Cisco products

# Proposed Solutions

- Trusted Foundries
  - Very expensive
  - Prone to errors/bugs
- Split-Manufacturing
  - Still Expensive
  - Again prone to errors/bug
- Post-fabrication Inspection
  - Expensive (+ re-tooling)
  - A huge pain, doesn’t scale

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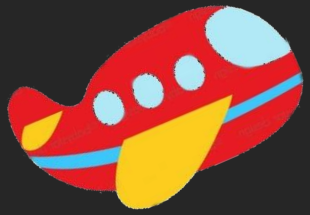
**Arms Race**

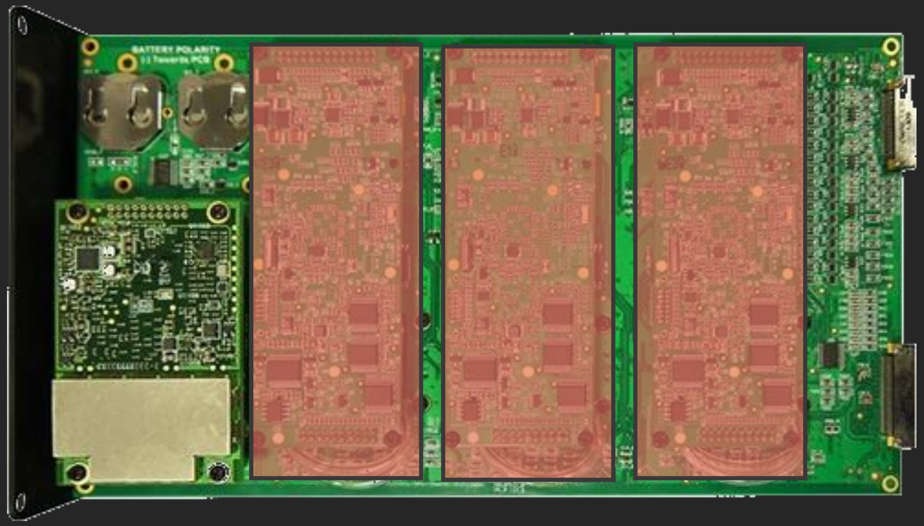
- Adversaries always one step forward
- Can never be 100% certain



# A solution from the sky (not the cloud)

***Lockstep systems** are fault-tolerant computer systems that run the same set of operations at the same time in parallel.*

- Dual redundancy
  allows error detection and error correction
- Triple redundancy
  automatic error correction, via majority vote
  → Triple Redundant 777 Primary Flight Computer



# Not for Security

Fault-tolerant systems are built for safety

and the computations are simply replicated.

**Not enough for security!**

# Not for Security

**Fault-tolerant systems are bad for security:**

- The private key is generated/stored in each IC
- Device is as secure as its weakest link
- Increase the attack surface

# Our Solution

1. Someone designs an integrated circuit (IC)
2. IC is fabricated
3. IC is delivered to hardware vendor
4. Vendor loads firmware & assembles device
5. Device is sent to customer
6. Customer generates and stores key on the device

# Ingredients of the Solution

1. Hardware Components (IC)
   - Independent Fabrication
   - Non-overlapping Supply Chains
   - Programmable
   - Affordable
   - Bonus if COTS

2. Cryptographic Protocols
   - No single trusted party
   - Full Distribution of Secrets
   - Distributed Processing
   - Provably Secure (i.e., Math)

# Smart Cards

**Many Independent Manufacturers**

- Private Fabrication Facilities
- Disjoint Supply Chains (location, factories, design)

**Programmable Secure Execution Environment**

- NIST FIPS140-2 standard, Level 4
- Common Criteria EAL4+/5+

**Off-the-shelf Cost** $1-$20

# Multiparty Computation Protocols

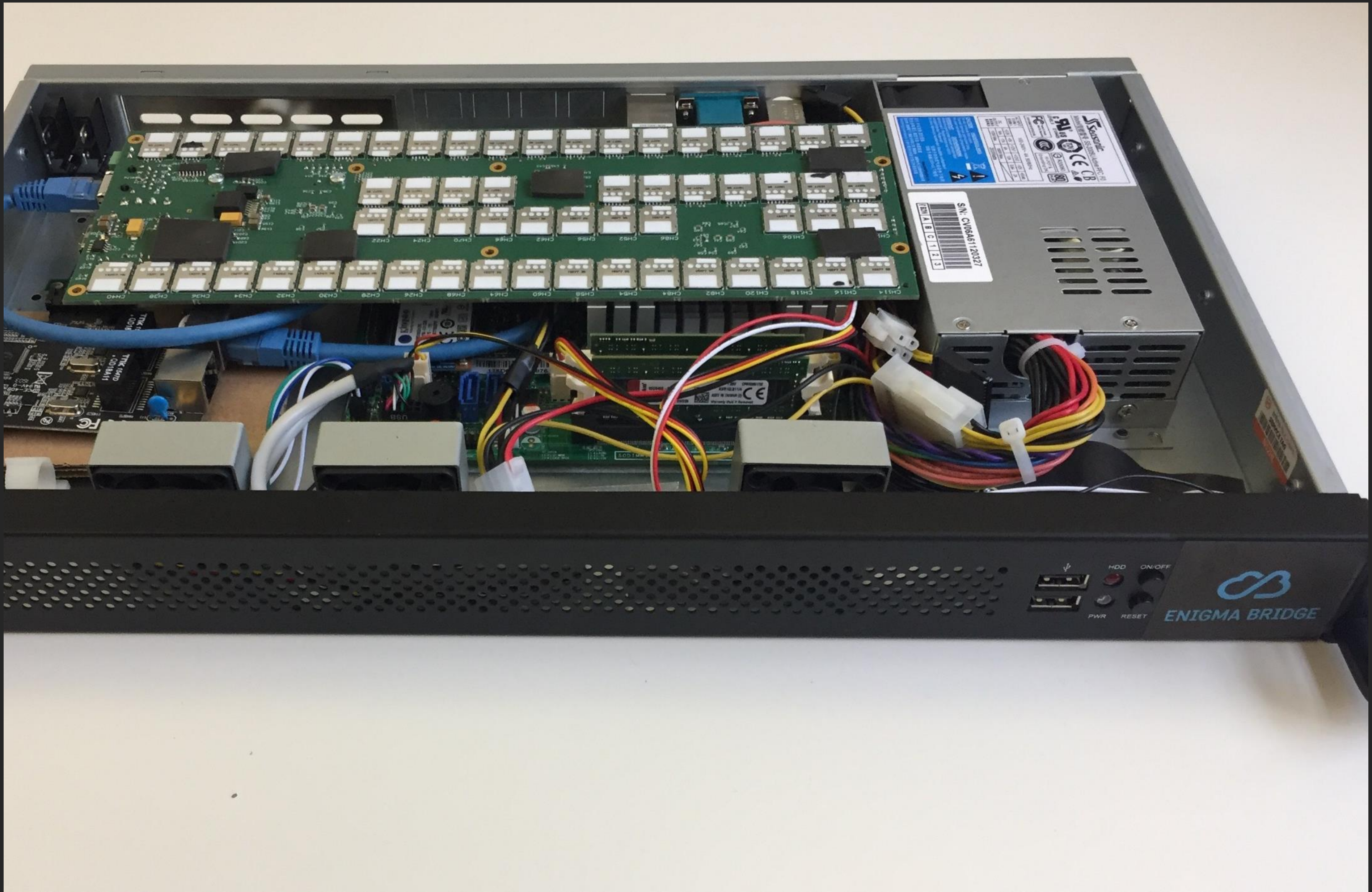
**Distributed Operations**

- ❑ Random number Generation
- ❑ Key Pair Generation
- ❑ Decryption
- ❑ Signing

**Provably Protect against**

- ❑ All-1 Malicious & Colluding parties
- ❑ All Malicious & non-colluding parties

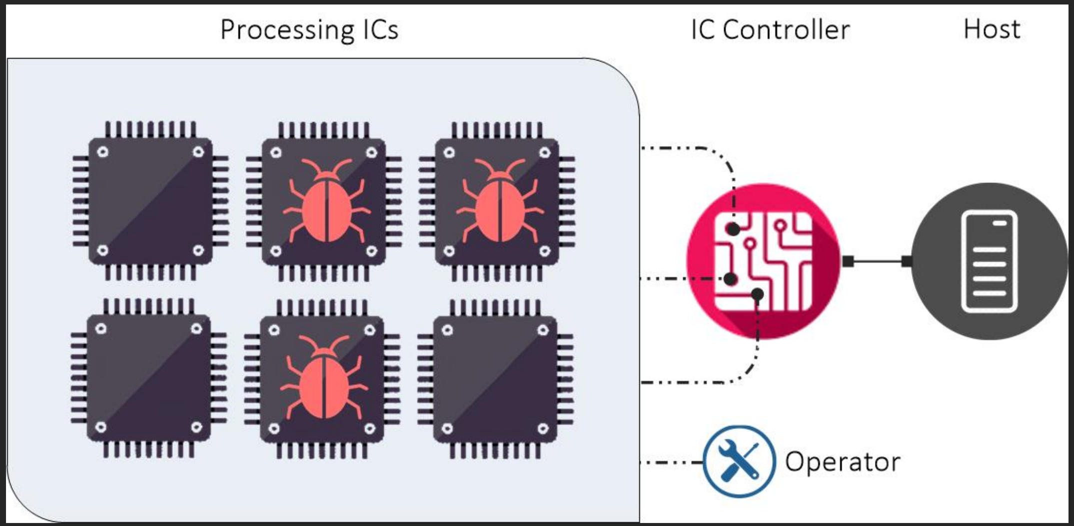
# THE PROTOTYPE

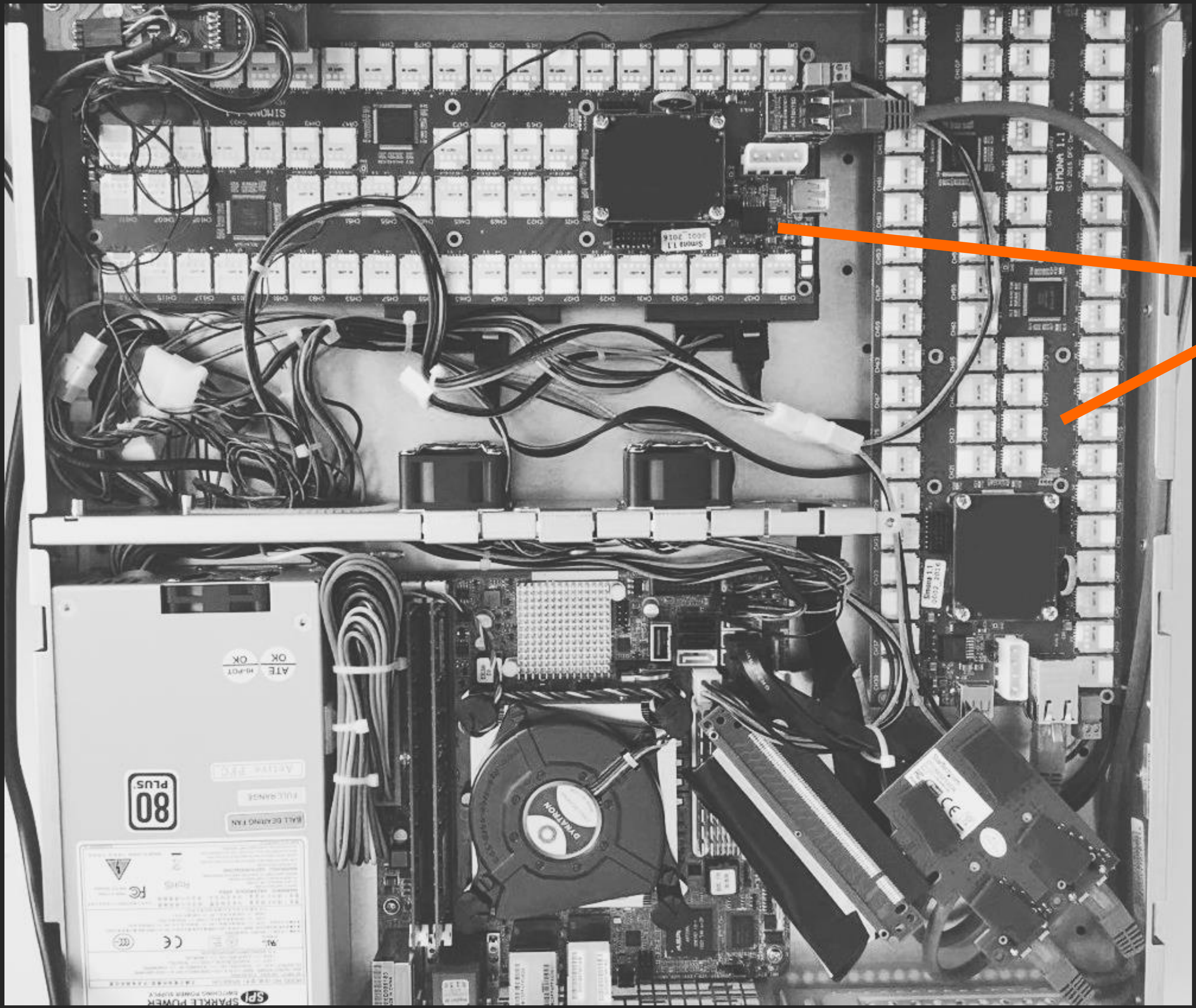

HDD
ON/OFF
PWR
RESET
ENIGMA BRIDGE

# Many Smart Cards

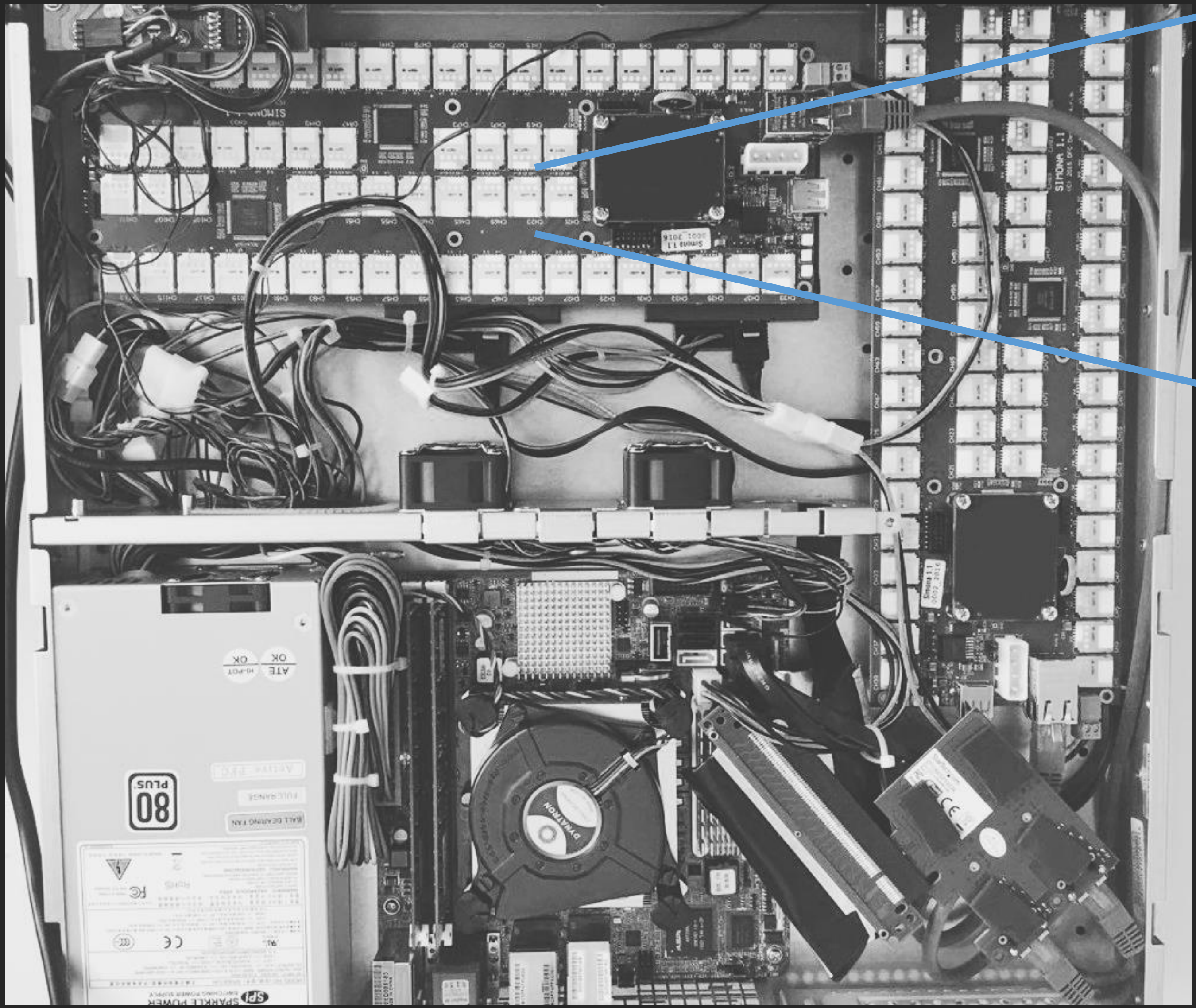
**Components**

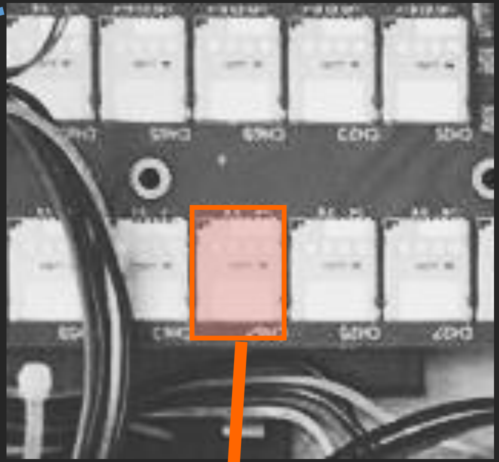
- 120 SmartCards
  - 40 Groups of 3 Cards
  - 1.2Mbps dedicated inter-IC buses
- FPGA manages the communication bus
  - 1Gbit/s bandwidth for requests





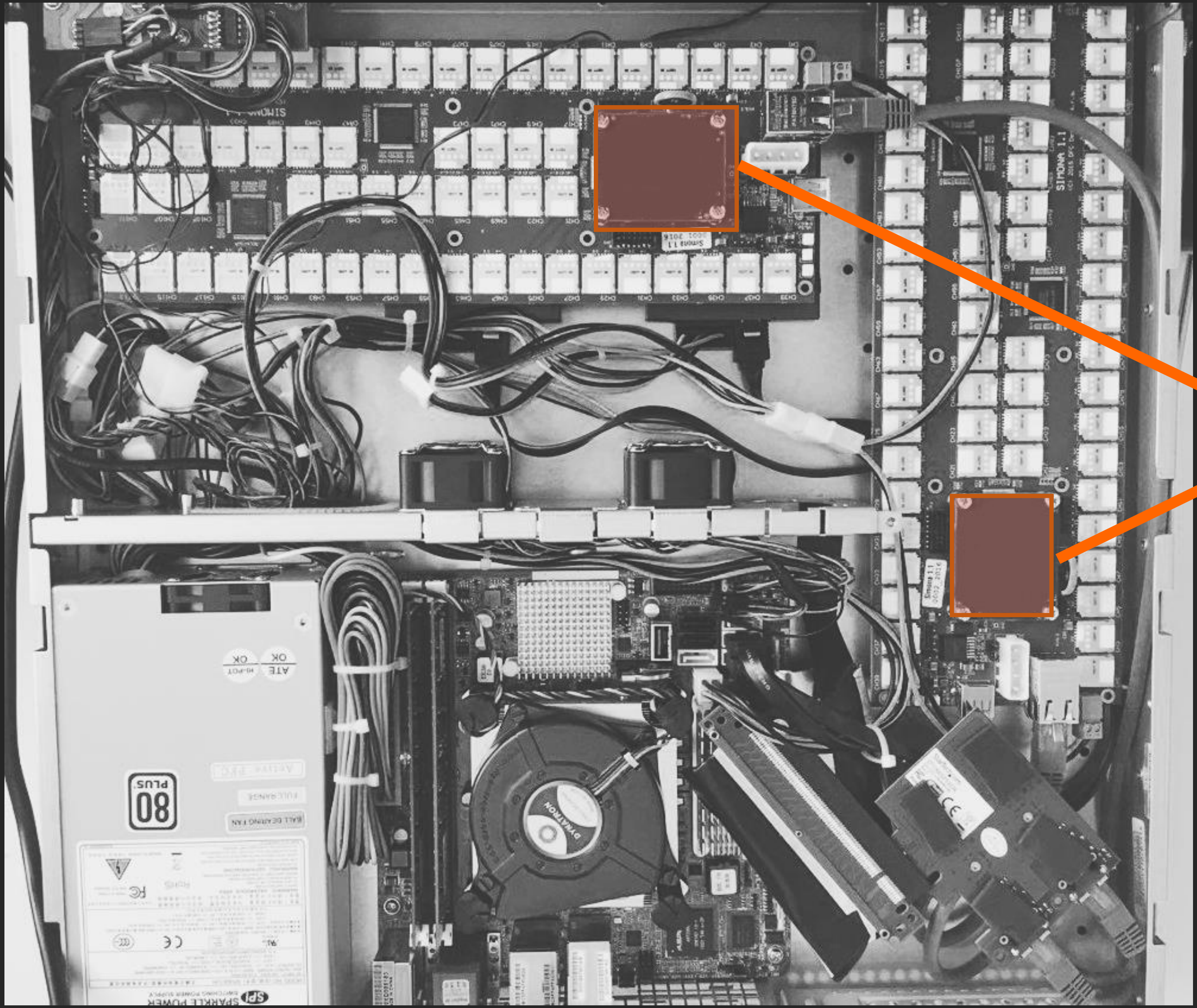
Custom boards with 120 JCs





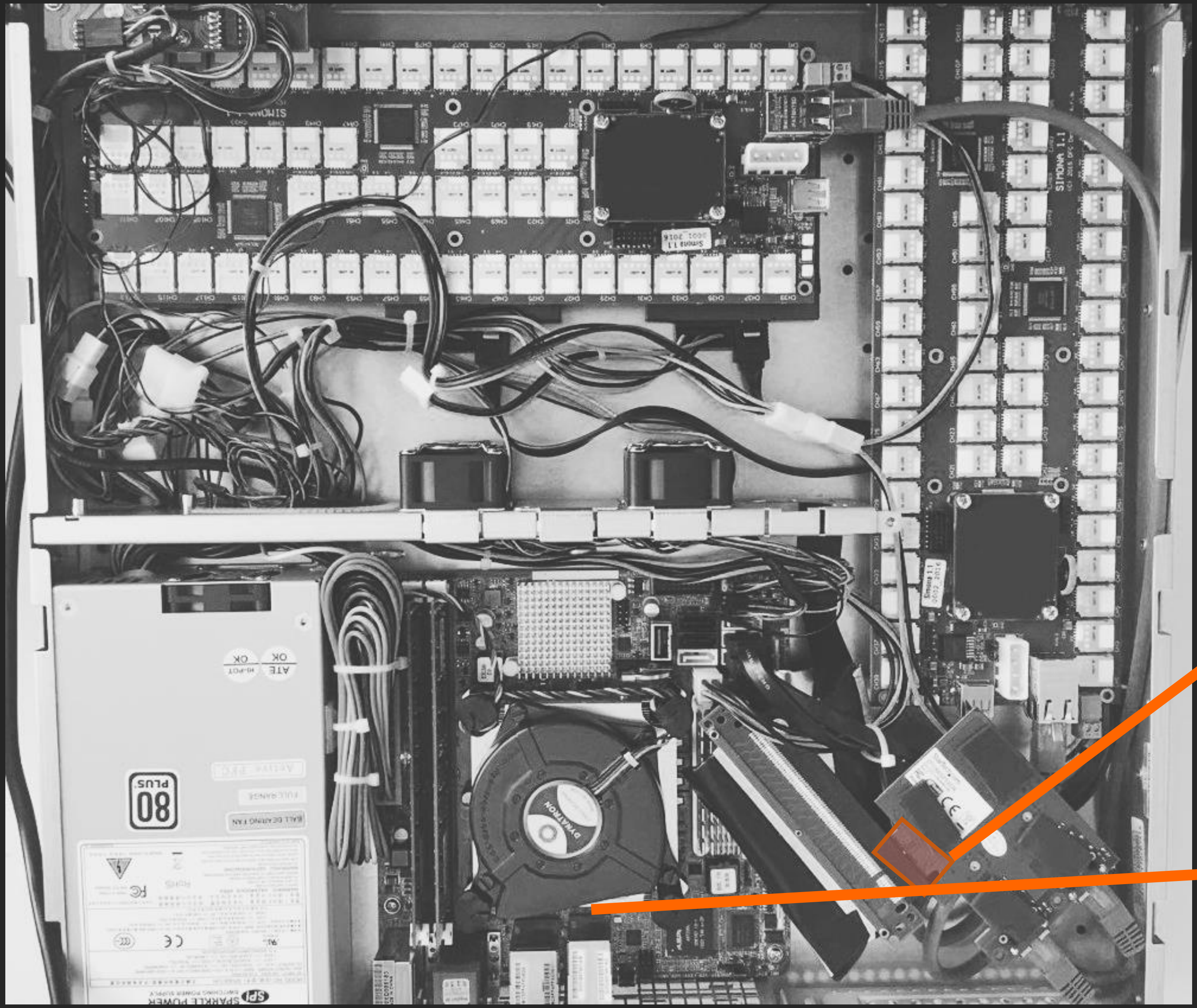
JavaCards

- FIPS140-2 Level 3
- CC EAL5+



**FPGA**

JavaCard→TCP



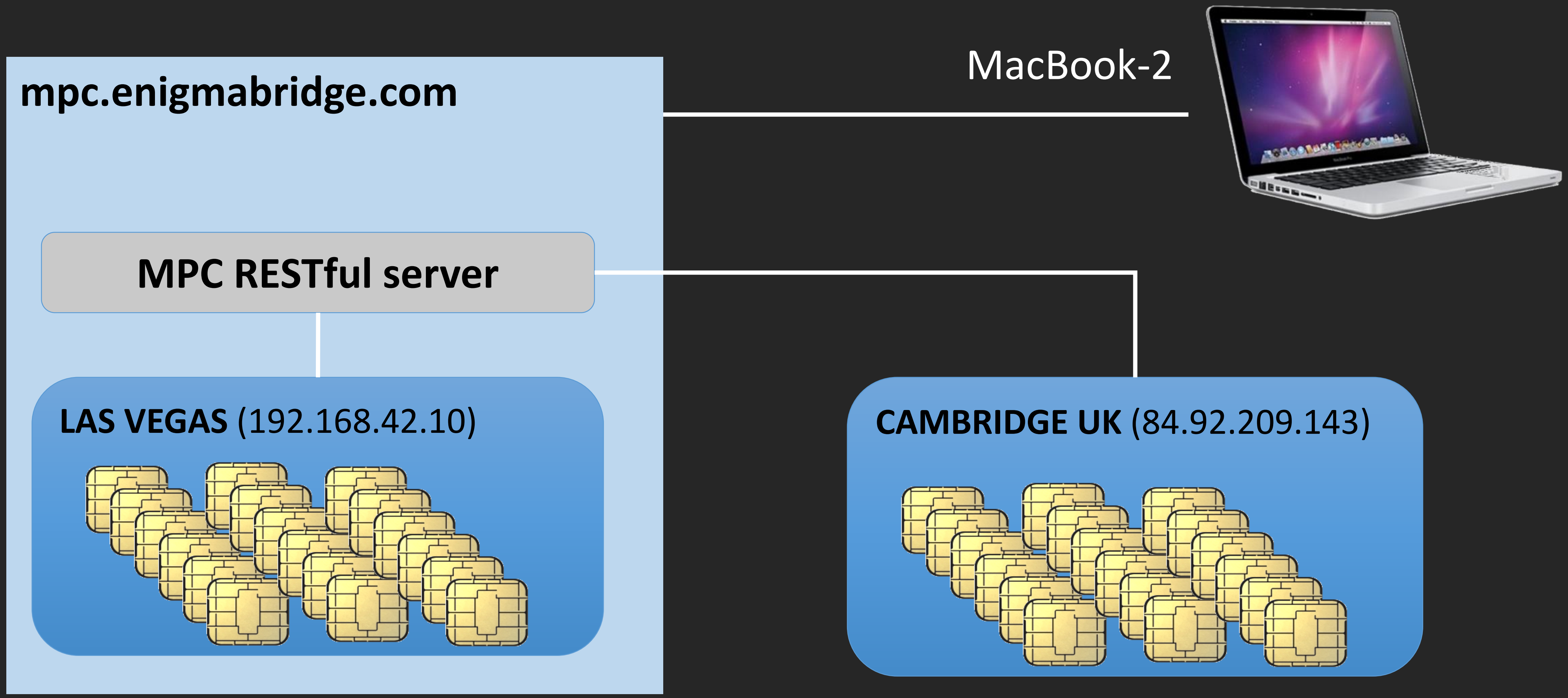
Gigabit link to untrusted

Linux server

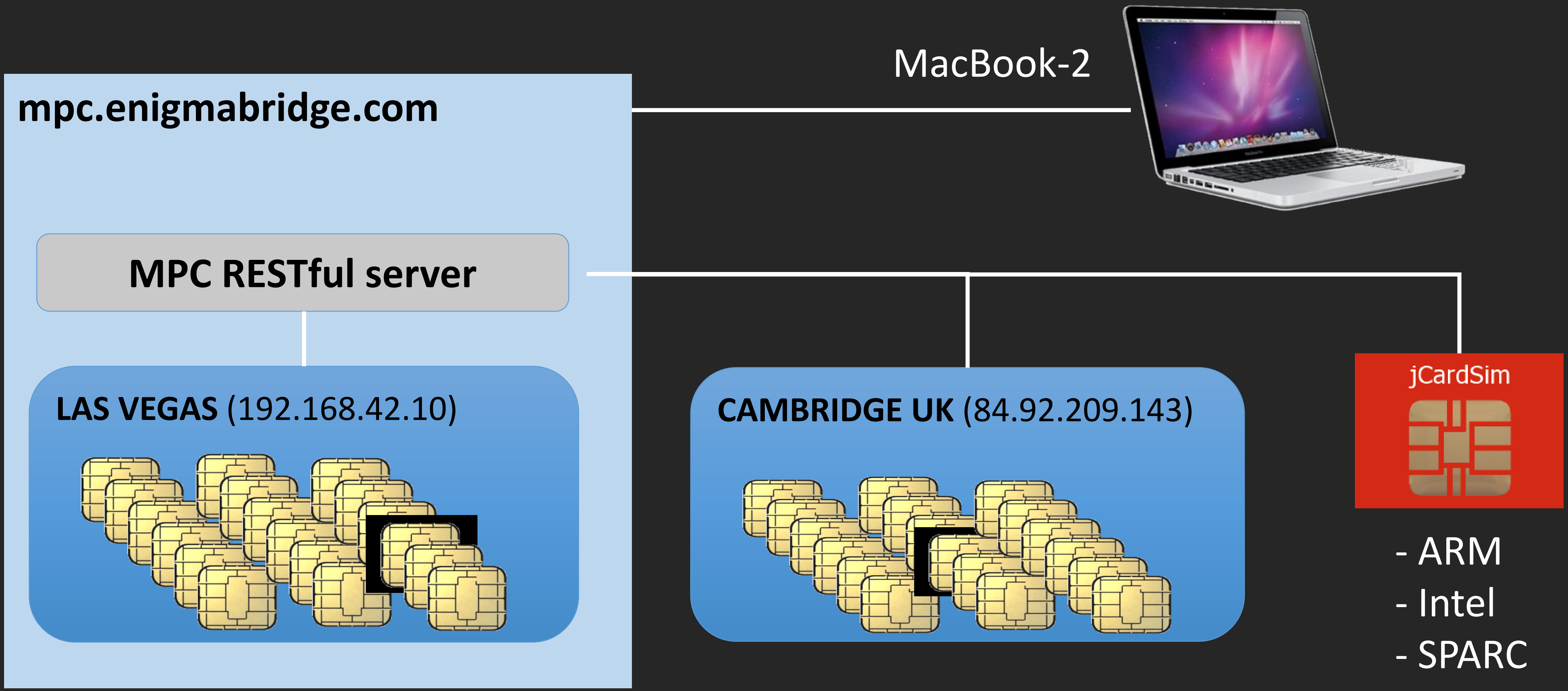
# DEMO 1

Geographically Distributed IC Control

# Giving smart-cards an infrastructure



# Giving smart-cards an infrastructure

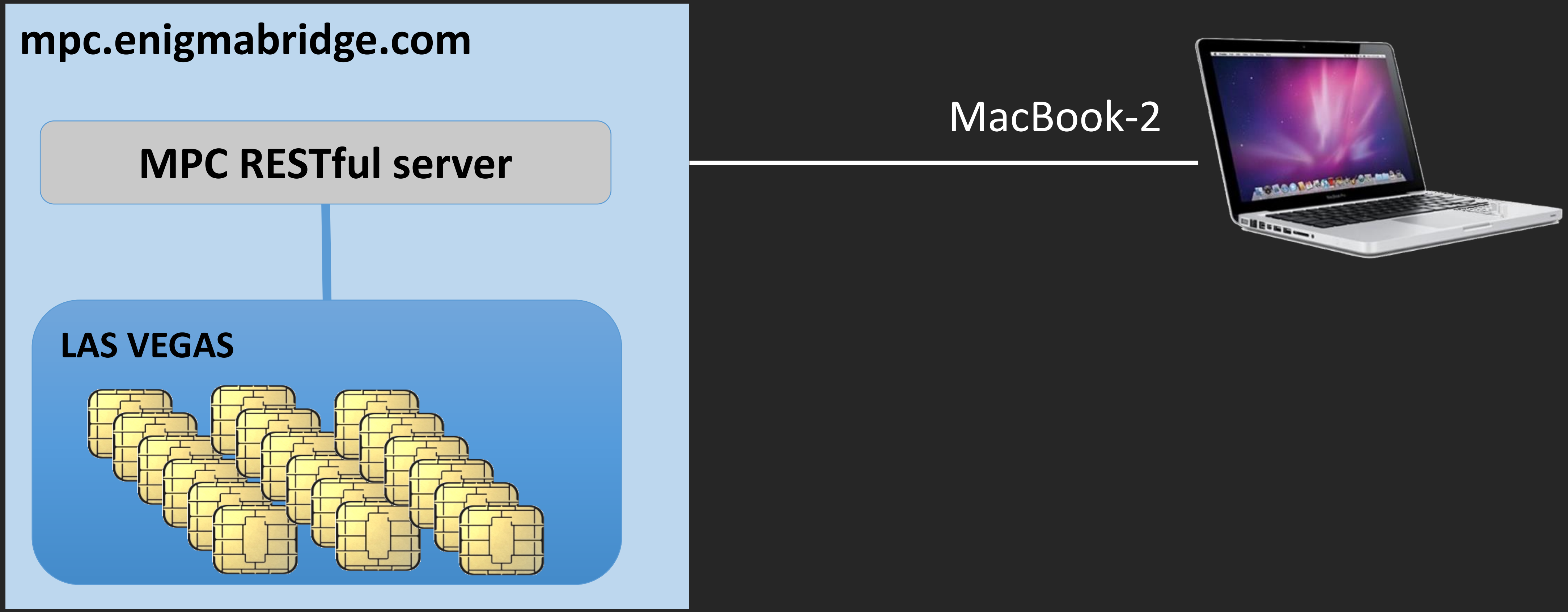


# DEMO 2

Key Generation

Normal Operation

# Giving smart-cards an infrastructure

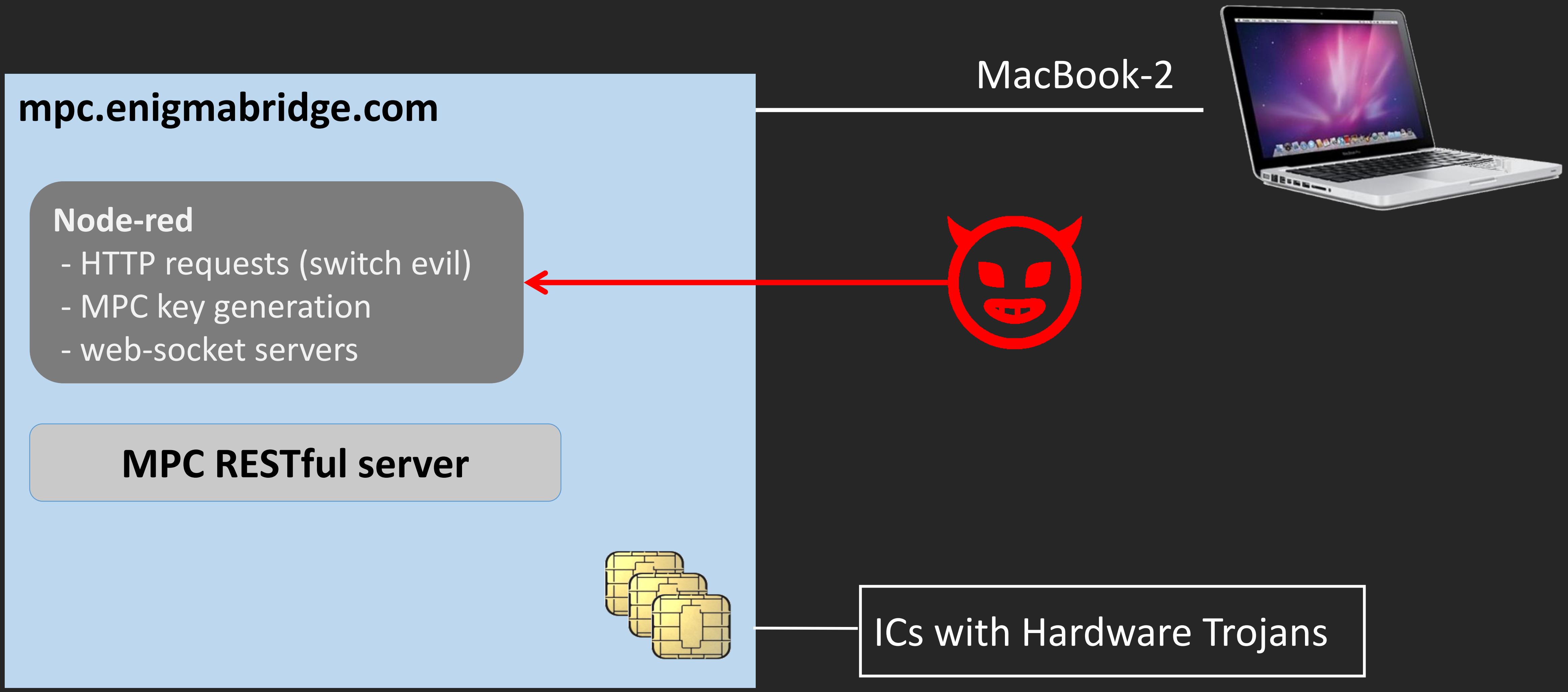


# DEMO 3

Key Generation

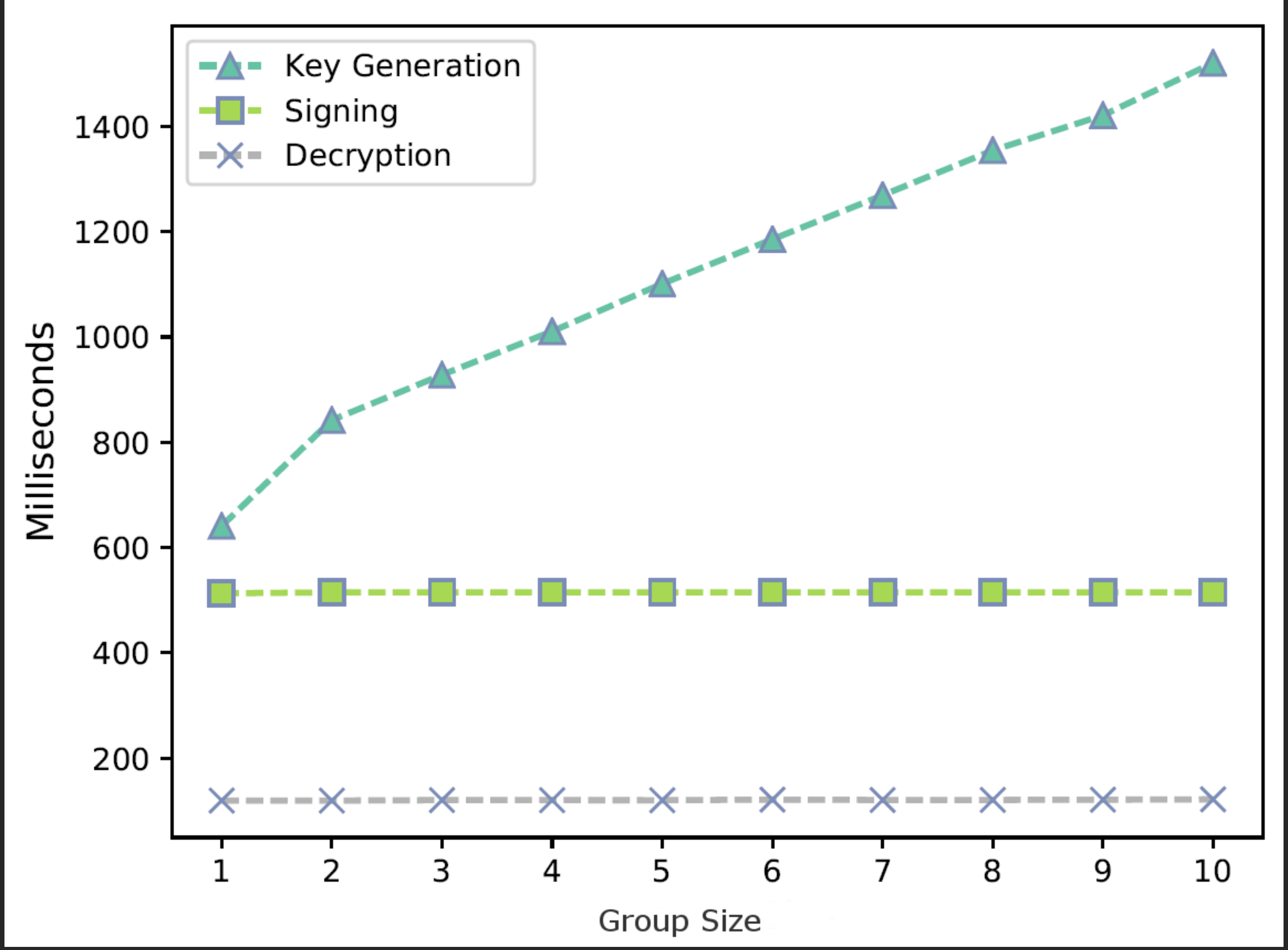
Attack Mode

# Visualizing Cryptography

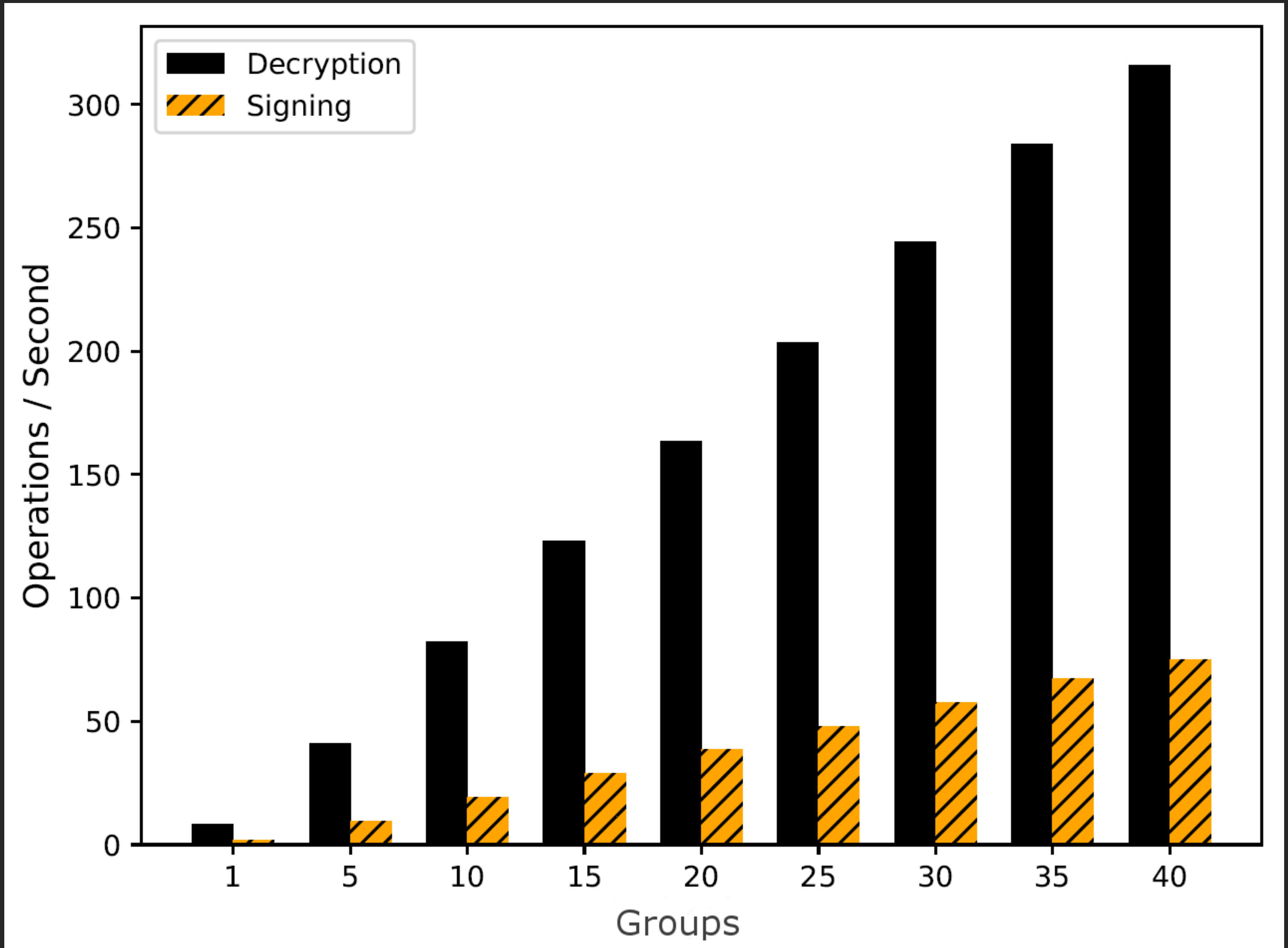


# PERFORMANCE

# Tolerance vs Runtime



# Scalability



# PROTOCOLS

# Key Points

- No single IC is trusted with a secret (e.g., private key)
- Misbehaving ICs can be detected by honest ones
- If one IC is excluded from any protocol, user can tell

Bonus: Minimize interaction between ICs for performance

# Sharing a Secret

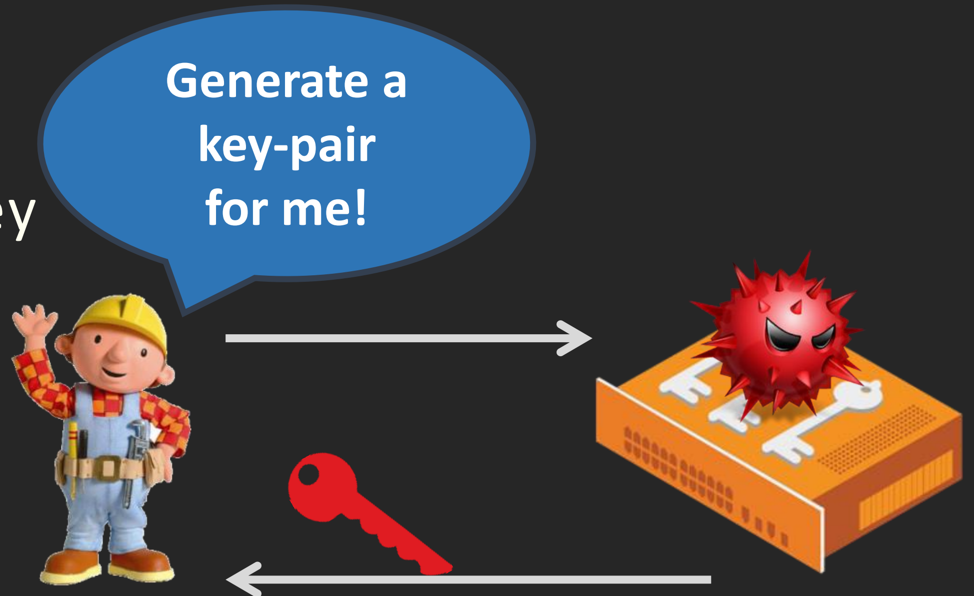
- Split a secret in *shares*
- The secret can be reconstructed later
- Without *sufficient* shares not a single bit is leaked
- Splitting Parameters:
  - How many shares the secret is split into (n)
  - How many shares you need to reconstruct the secret (t)

*In our case: Each 3 ICs hold shares for a secret*

# Classic Key Generation

**Single IC System**

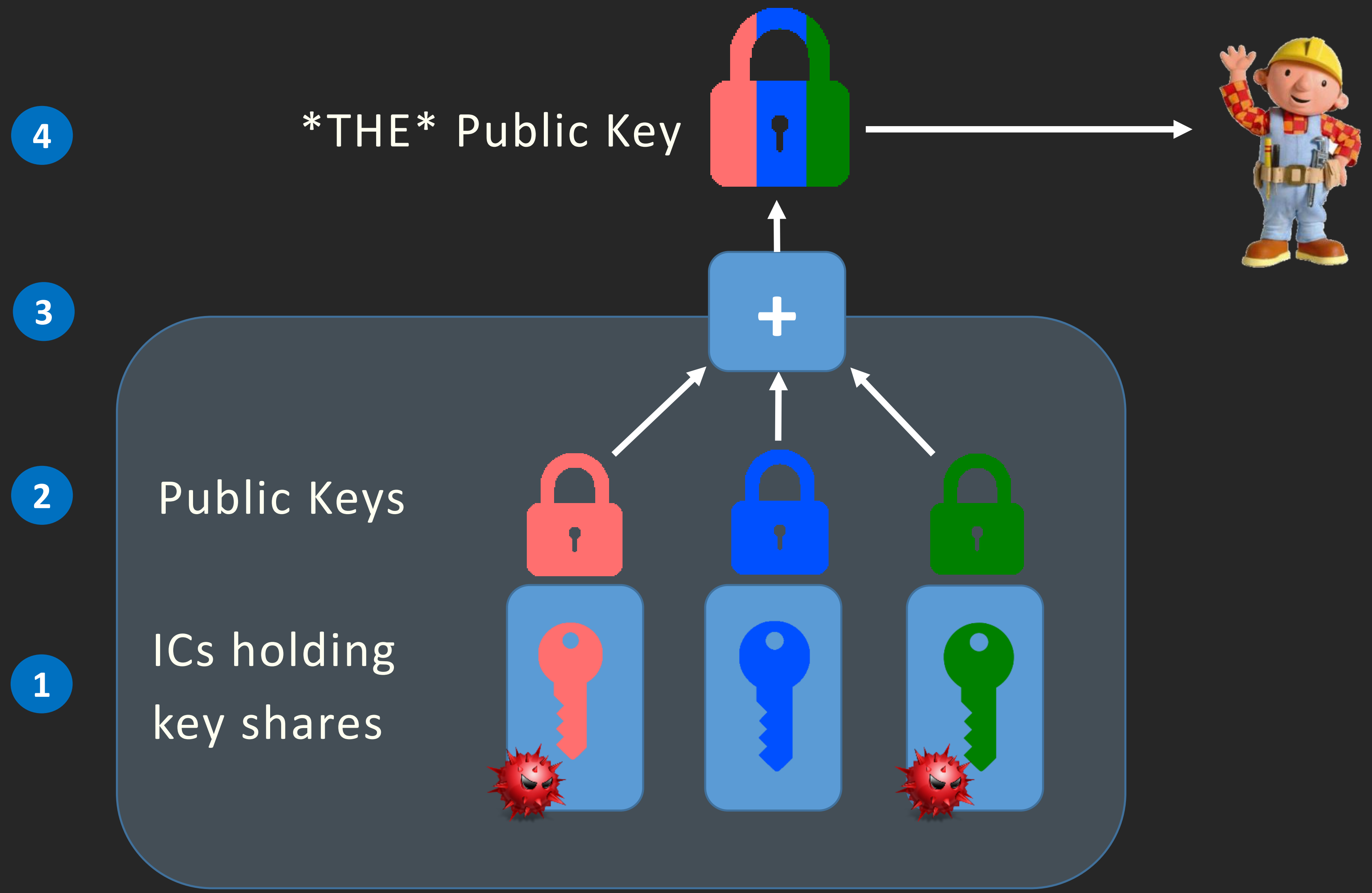
1. Bob asks for new key pair
2. Backdoored IC generates compromised key
3. Private Key is “securely” stored
4. Weak Public key is returned




**Problems**

- Malicious IC has full access to the private key
- Bob can’t tell if he got a “bad” key

# Distributed Key Generation



# Distributed Key Generation

**Key Points**

- No single IC is trusted with a secret (e.g., private key) ✓
- Misbehaving ICs can be detected by honest ones ✓
- If one IC is excluded from any protocol, user can tell ✓

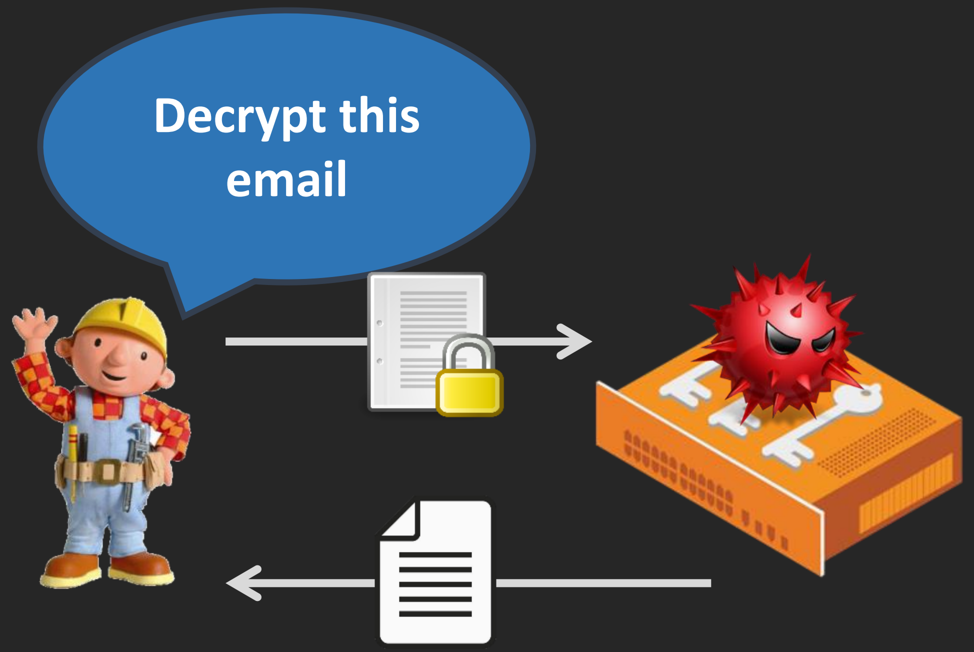
Bonus: Minimize interaction between ICs for performance ✗

# Classic Decryption

**Single IC System**

1. Bob asks for ciphertext decryption
2. Backdoored IC decrypts ciphertext
3. Bob retrieves plaintext

*The IC needs full access to the private key to be able to decrypt ciphertexts.*



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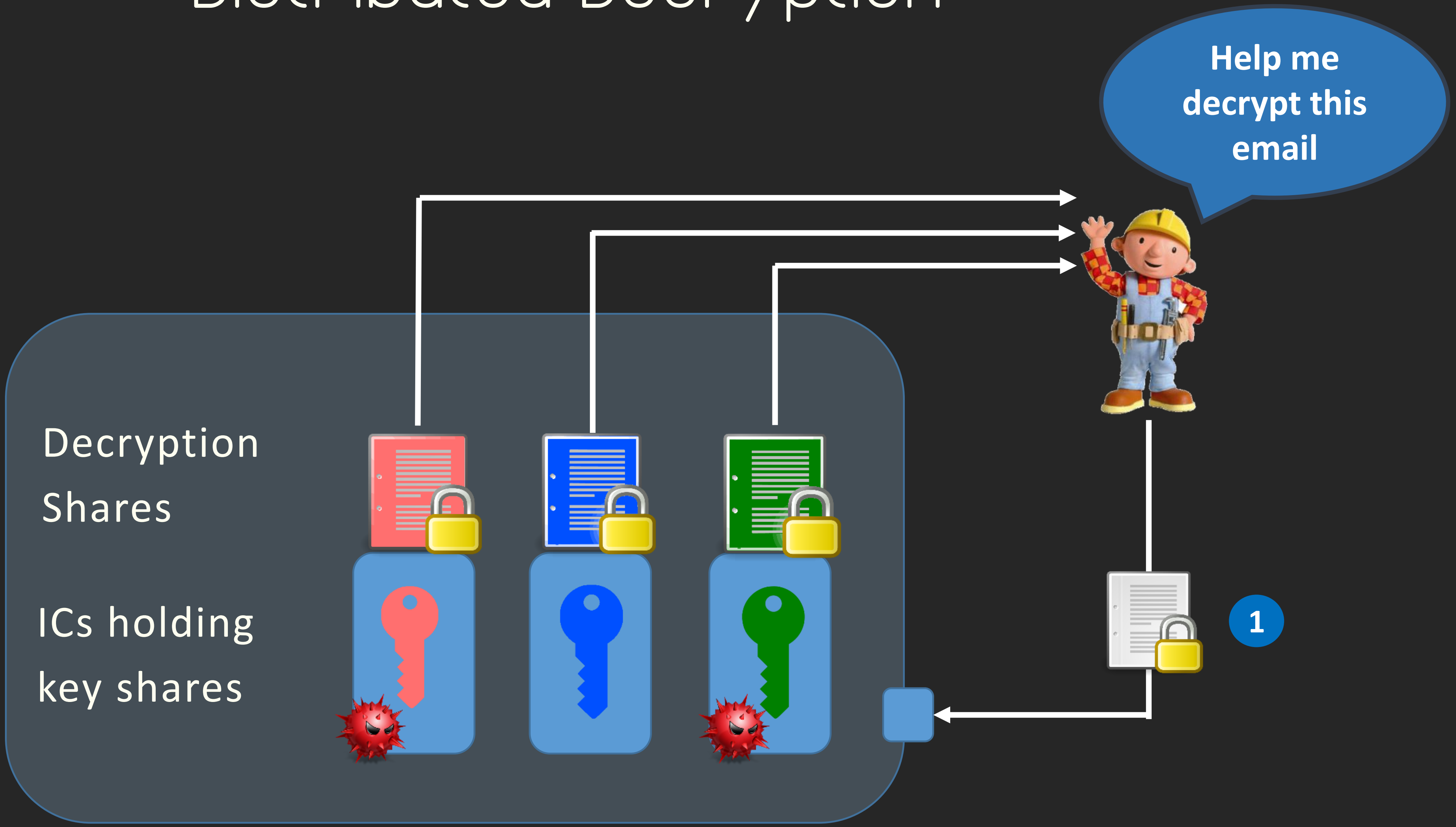

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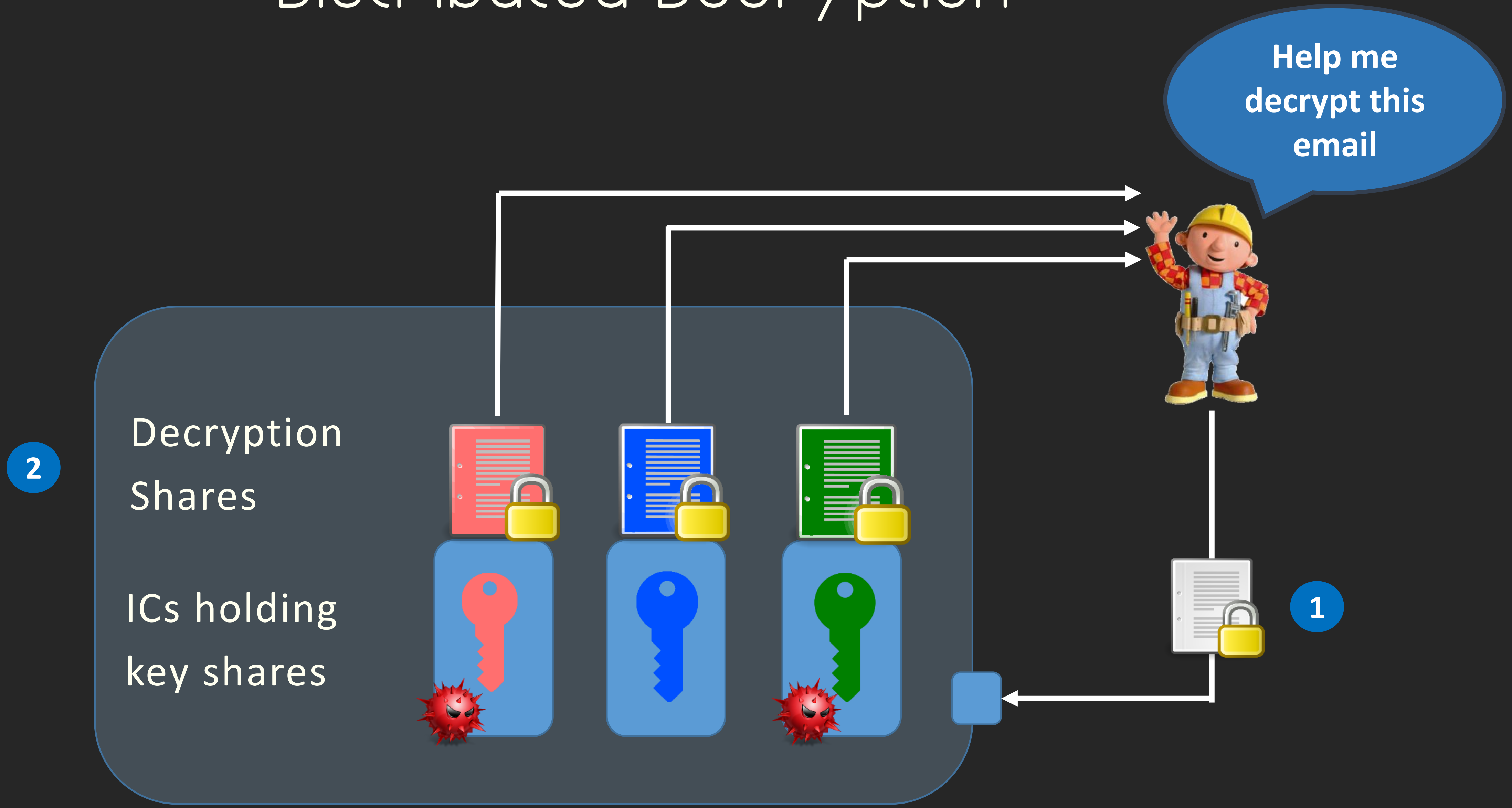

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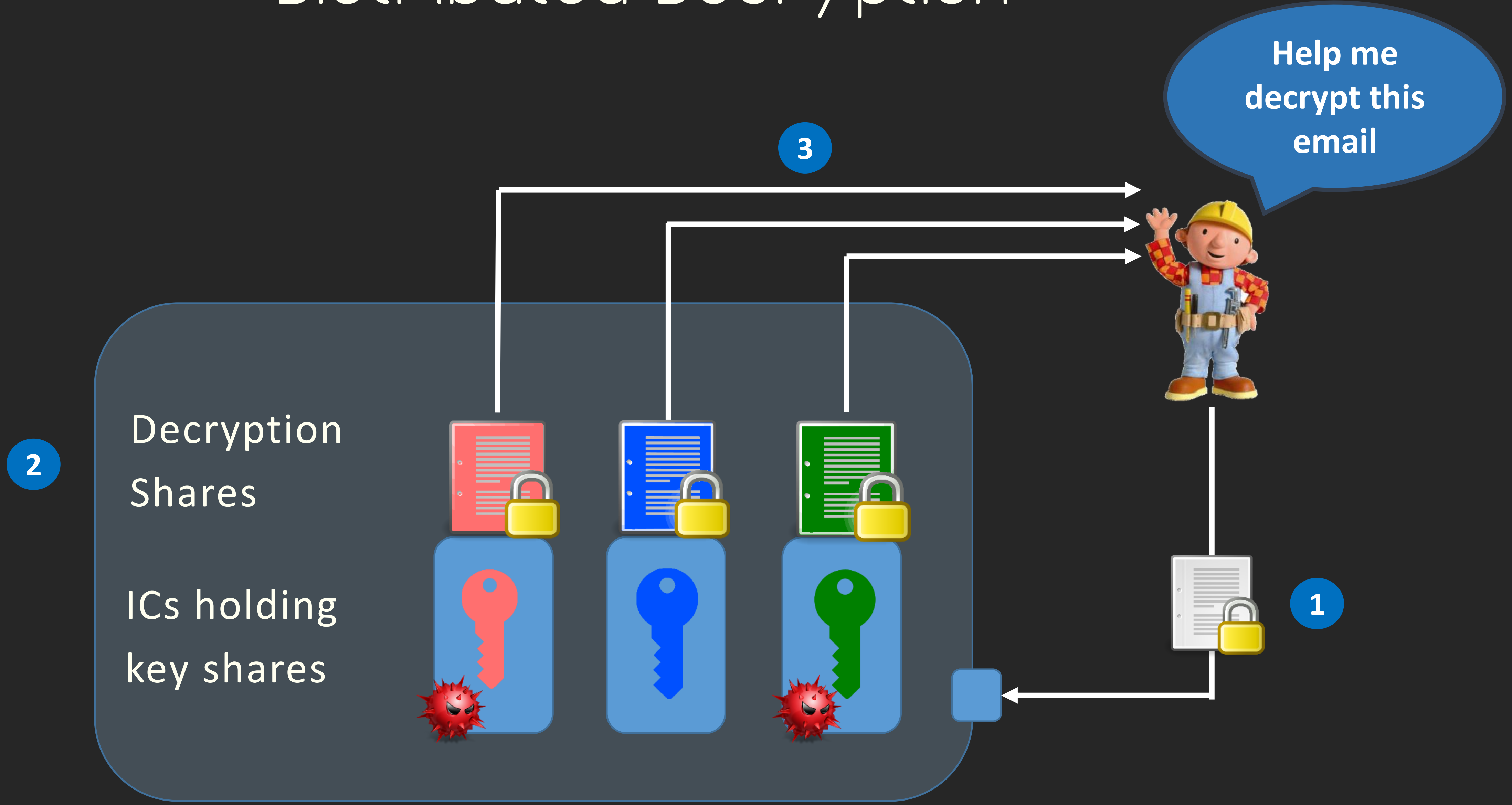

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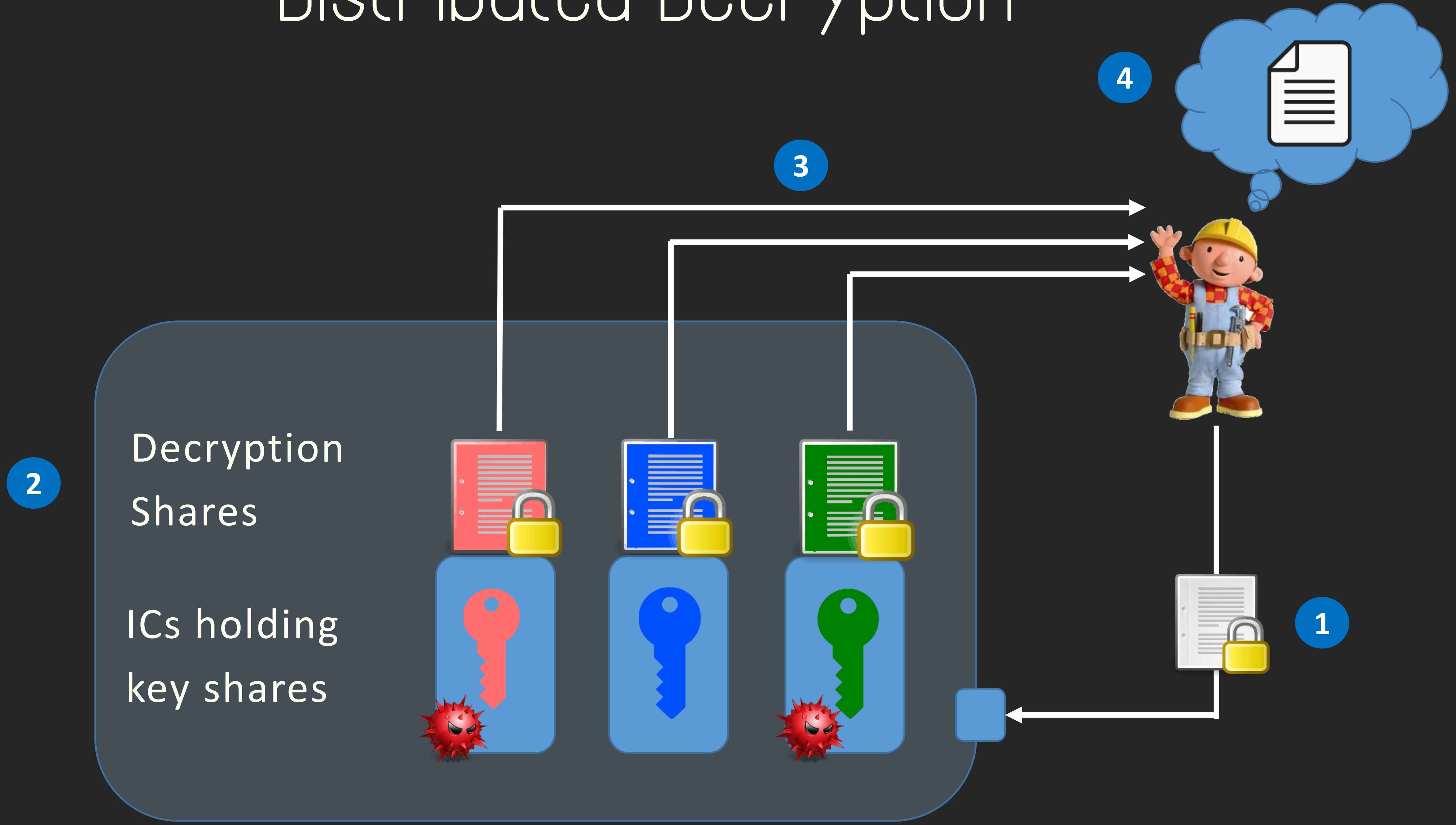


# Distributed Decryption

**Key Points**

- No single IC is trusted with a secret (e.g., private key) ✓
- Misbehaving ICs can be detected by honest ones -
- If one IC is excluded from any protocol, user can tell ✓

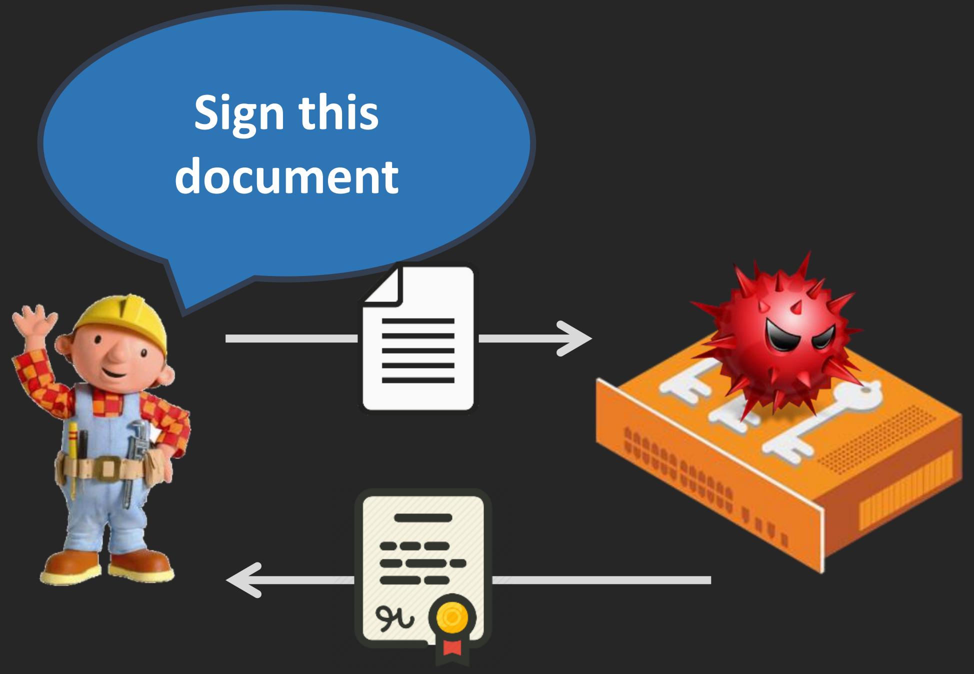
Bonus: Minimize interaction between ICs for performance ✓

# Classic Signing

**Single IC System**

1. Bob asks for document signing
2. Backdoored IC signs the plaintext
3. Bob retrieves signature

*The IC needs full access to the private key to be able to sign plaintexts.*



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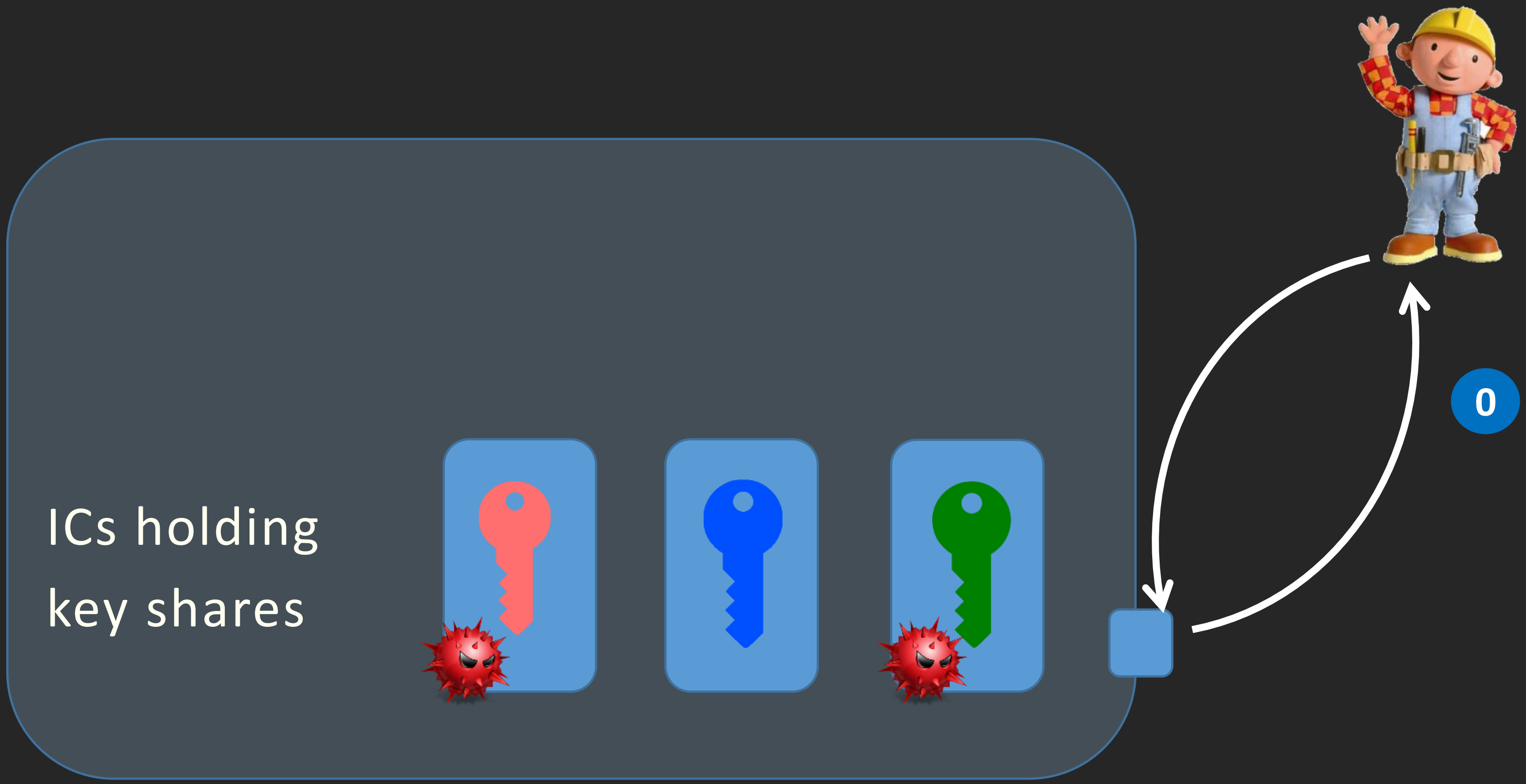

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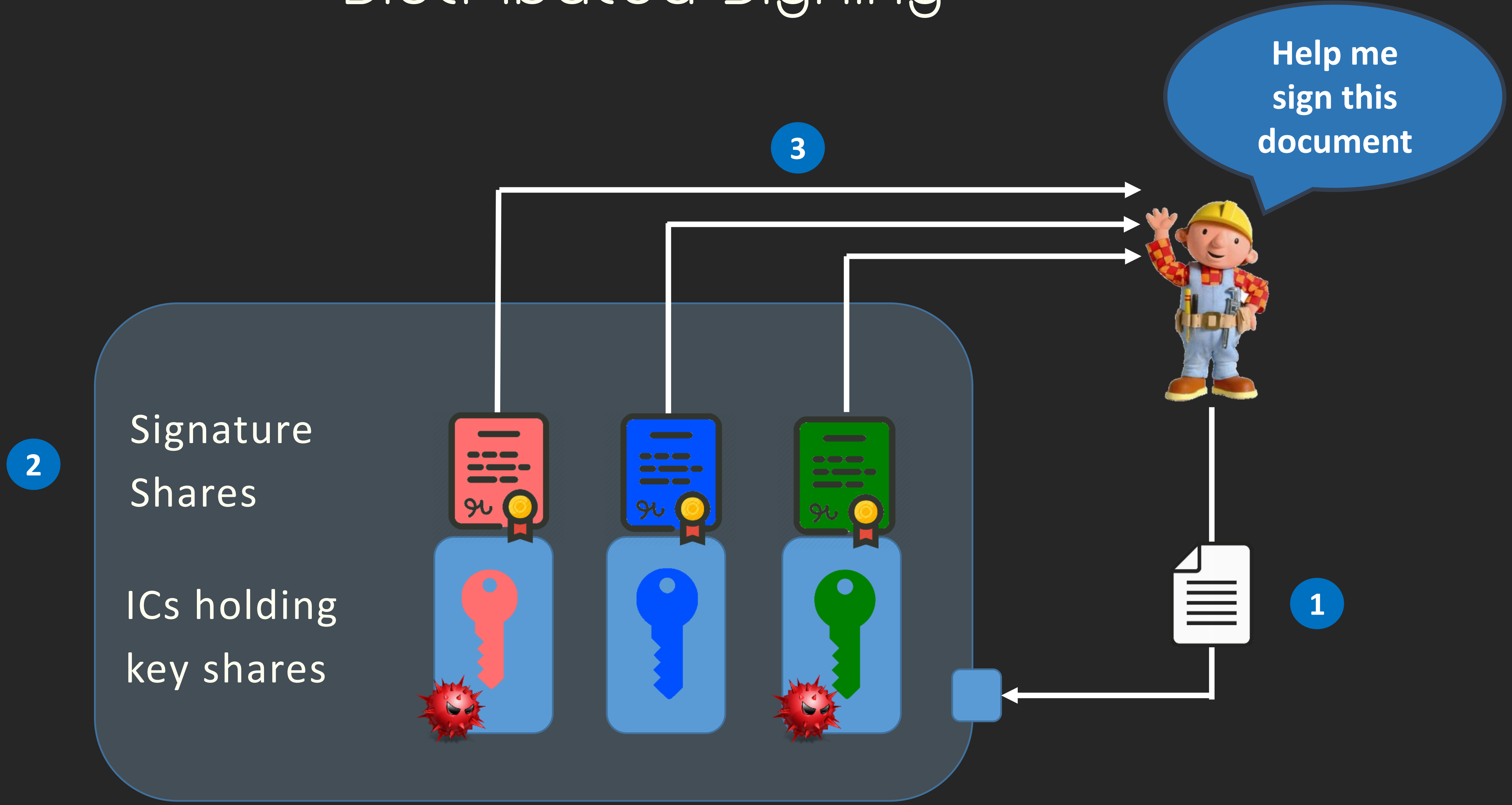

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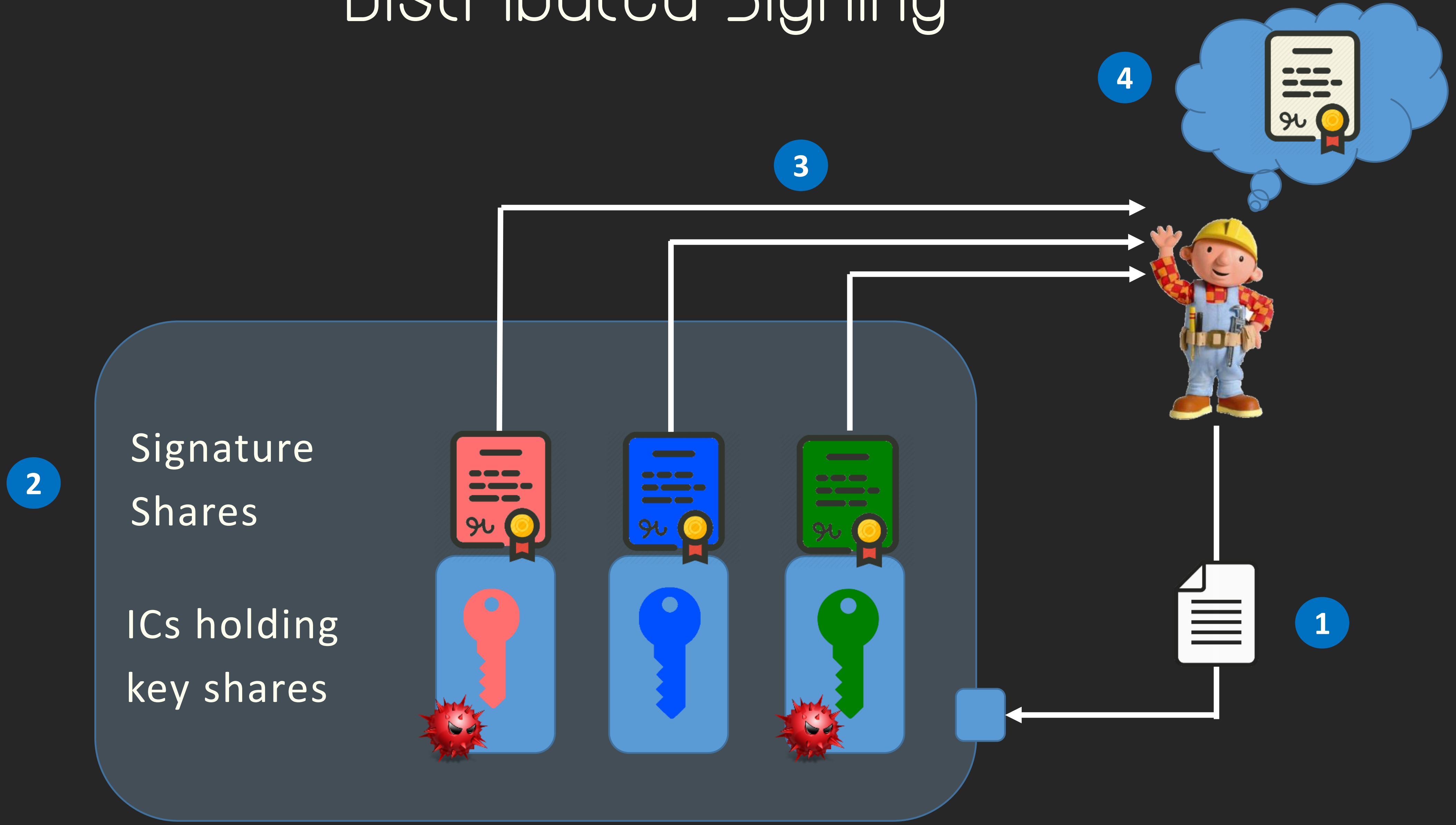

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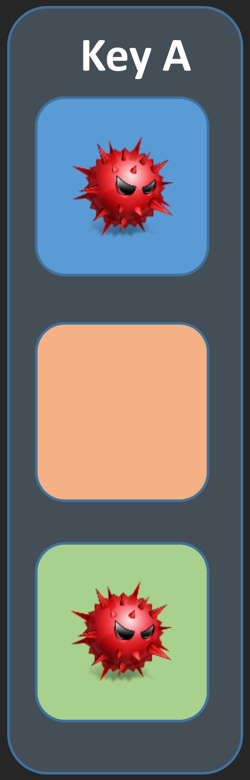
# How we made it scale



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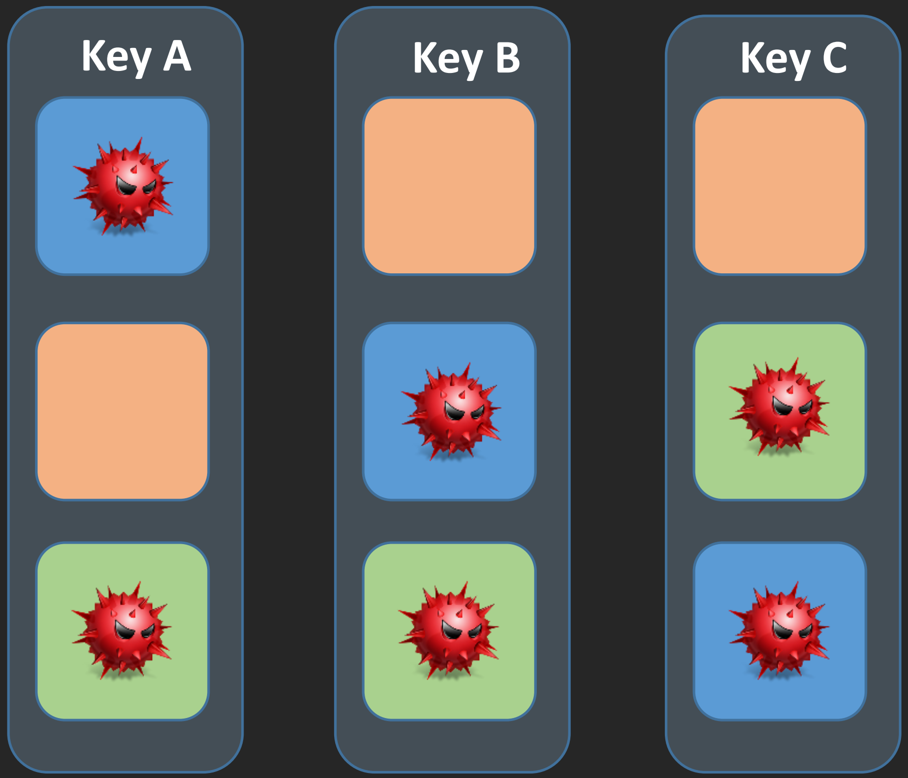

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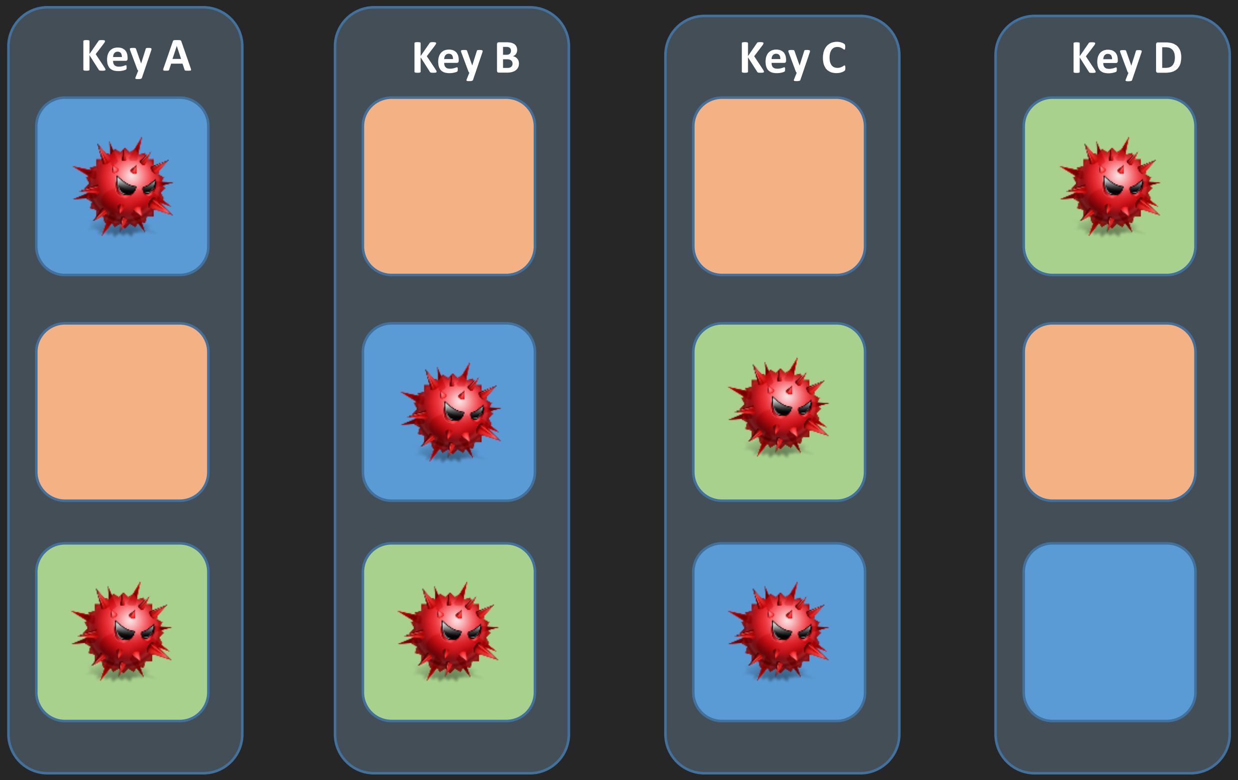

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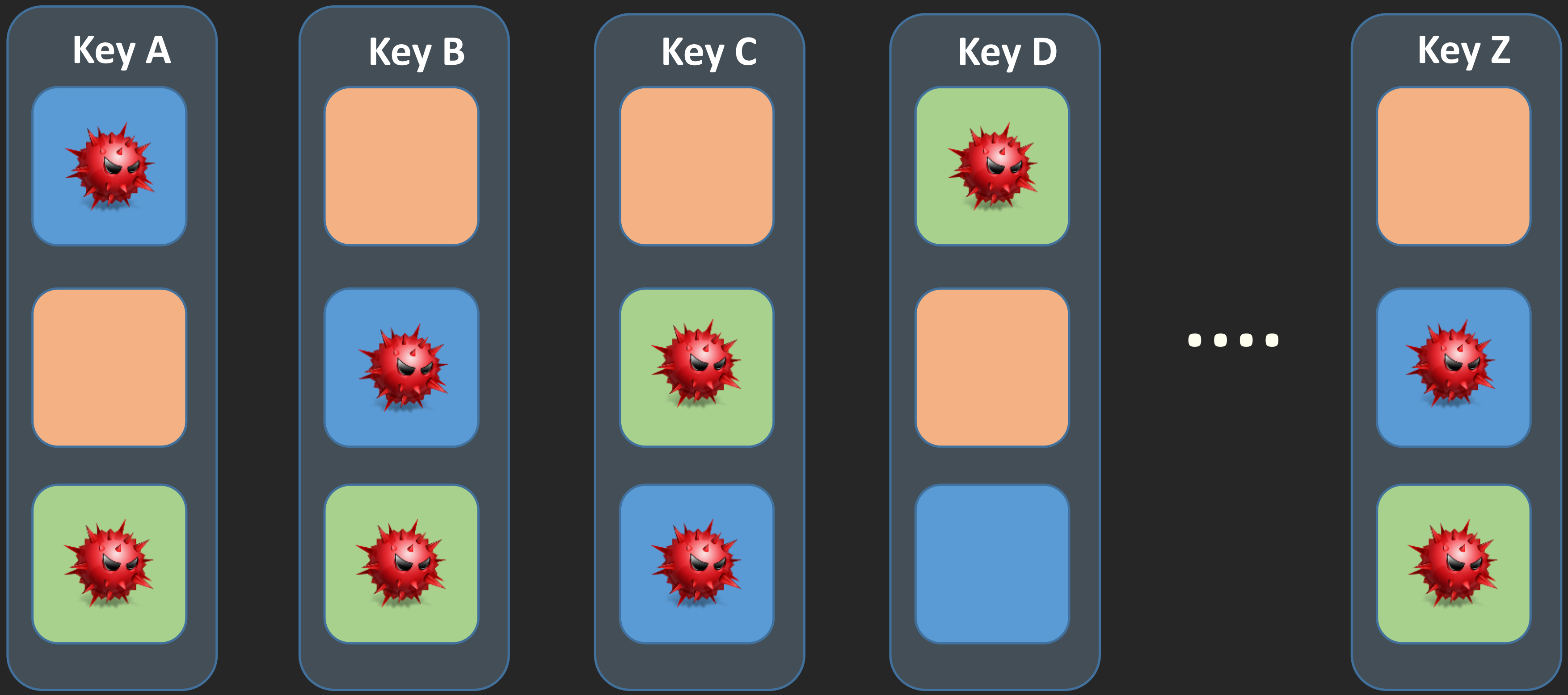
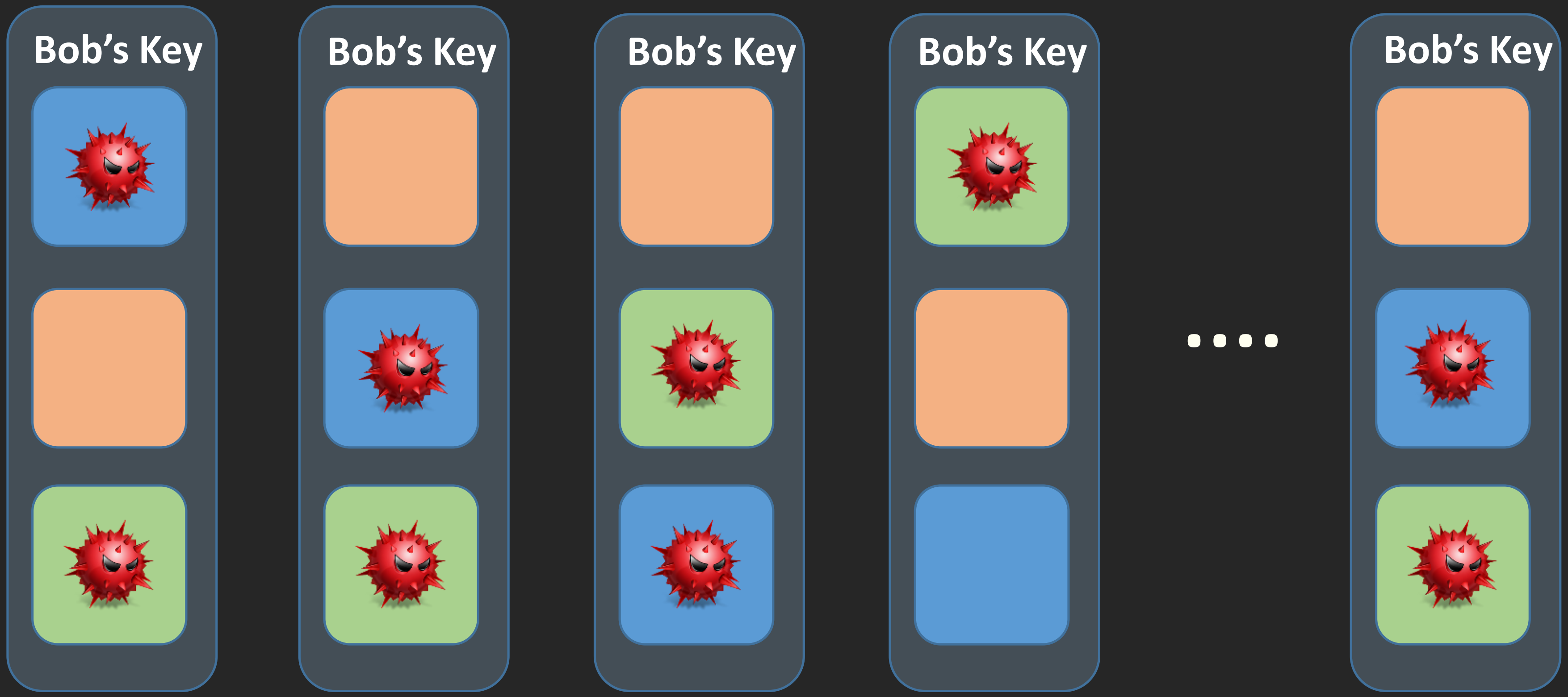
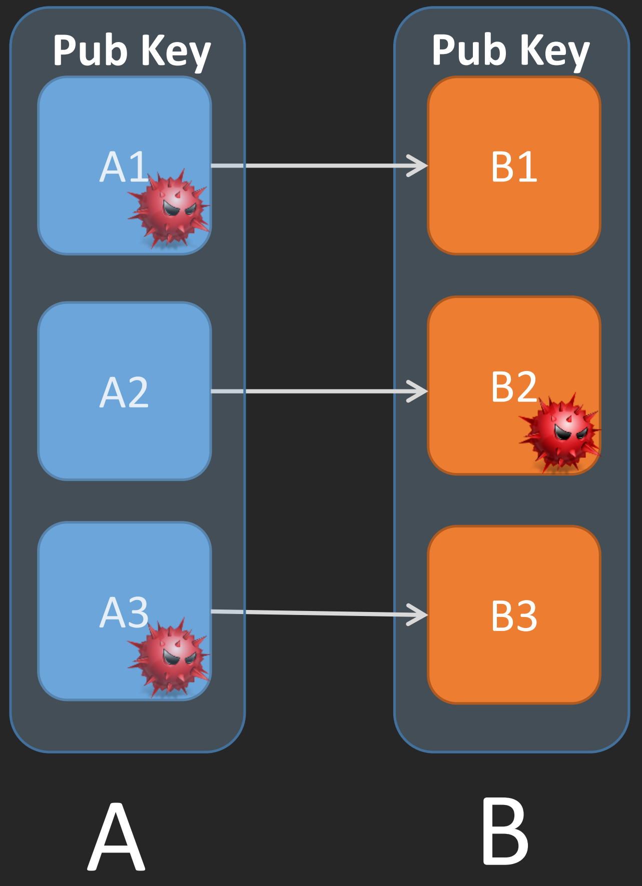


# How we made it scale

**But how can all these groups have shares for the same key?**

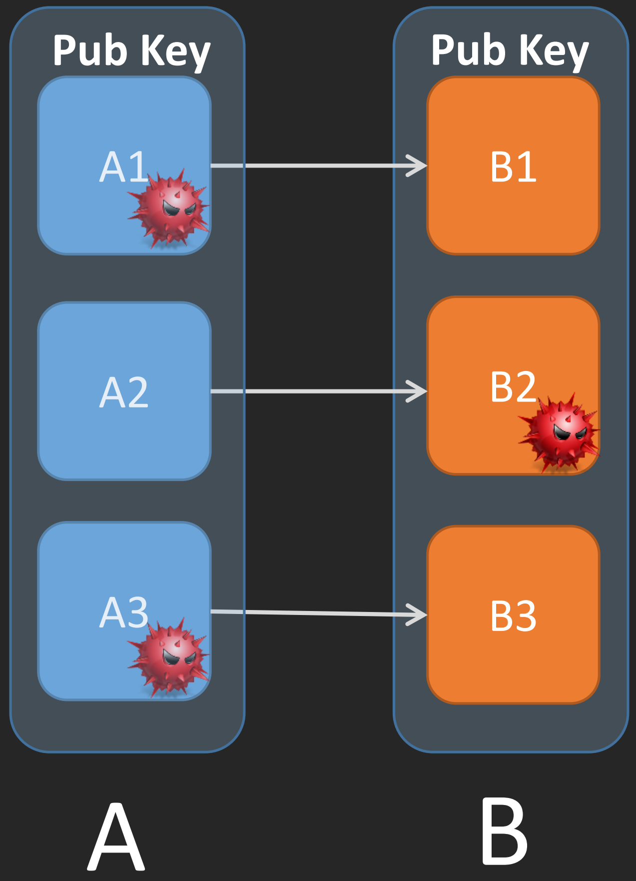


# Key Replication




1. Group A generates a public key
2. A1, A2, A3 send their shares to B1, B2, B3
3. Each IC in B receives shares from A1, A2, A3
4. Each IC in B combines the 3 shares and retrieves its private key

# ~~Key Replication~~

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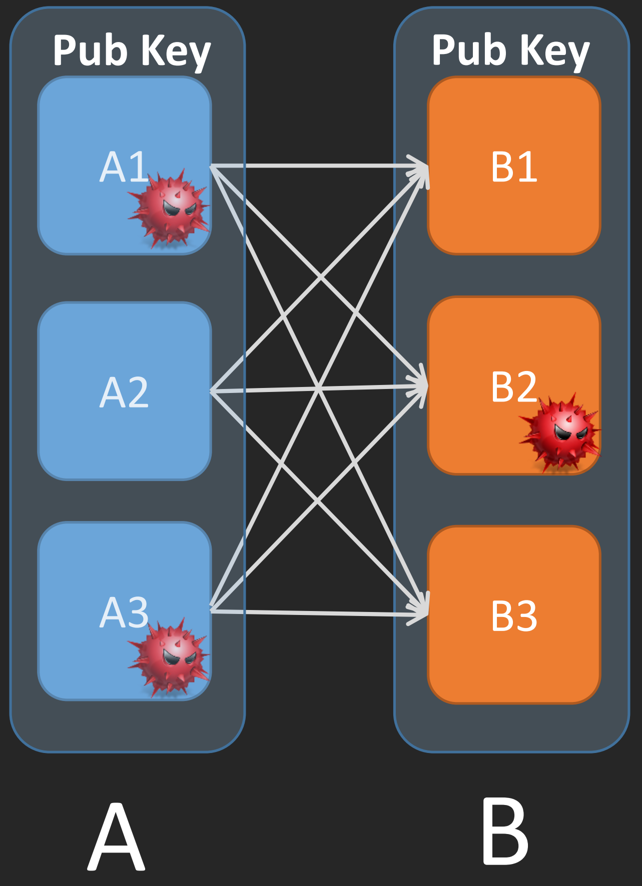
3. Each IC in B receives shares from A1, A2, A3
4. Each IC in B combines the 3 shares and retrieves its private key
5. **A1, A3 and B2 collude**

**The adversary retrieves the secret!**

# Key Replication




1. Group A generates a public key
2. Then each IC in A splits its private key in three shares and sends them to B1, B2, B3
3. Each IC in B receives shares from A1, A2, A3
4. Each IC in B combines the 3 shares and retrieves its private key share

**The full public keys of A and B are the same!**

# GEOPOLITICS

“We can guarantee *security* if t*here is at least one honest IC that is not backdoored or faulty.”*

“We can guarantee *security* if *there is at least one honest IC that is not backdoored or faulty.*”

What if all ICs are malicious?

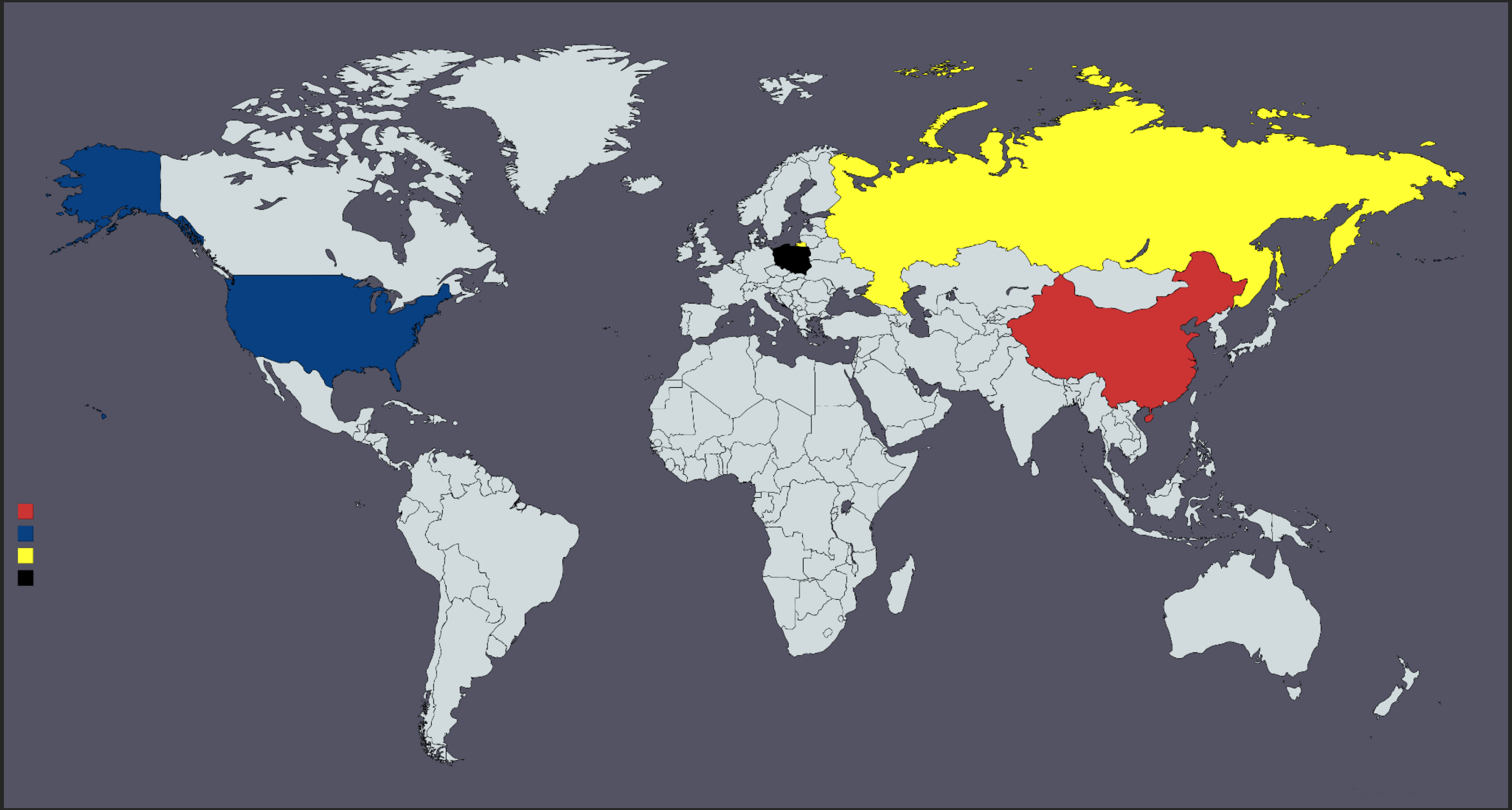
**Government-level adversaries**

- Deep access to fabrication facilities
- Very sophisticated techniques
- Very hard to detect their Backdoors/Trojans
- Very secretive; highly classified
- Won’t share their backdoor details

**Government-level adversaries**

- Deep access to fabrication facilities
- Very sophisticated techniques
- Very hard to detect their Backdoors/Trojans
- Very secretive; highly classified
- Won’t share their backdoor details
- Unlikely to collude with anyone

“We can guarantee security even when all *ICs are malicious, if at least one does not collude.”*



# Conclusions & Future

**New crypto hardware architecture**

- For the first time, tolerates faulty & malicious hw
- Decent Performance
- Scales nicely; just keep adding ICs
- Suitable for commercial-off-the-shelf components
- Existing malicious insertion countermeasures are very welcome!

# DIY

**Poor man's HSM**

1. Buy a USB hub
2. 3-4 card readers (or more)
3. Buy cards from various manufacturers
4. Download our MPC applet
5. Review the code
6. Install the applet into your cards
7. Enjoy your homemade HSM!

# Q & A

# Trojan-tolerant Hardware

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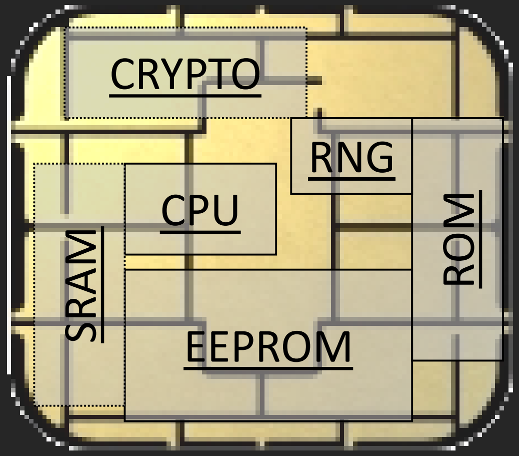
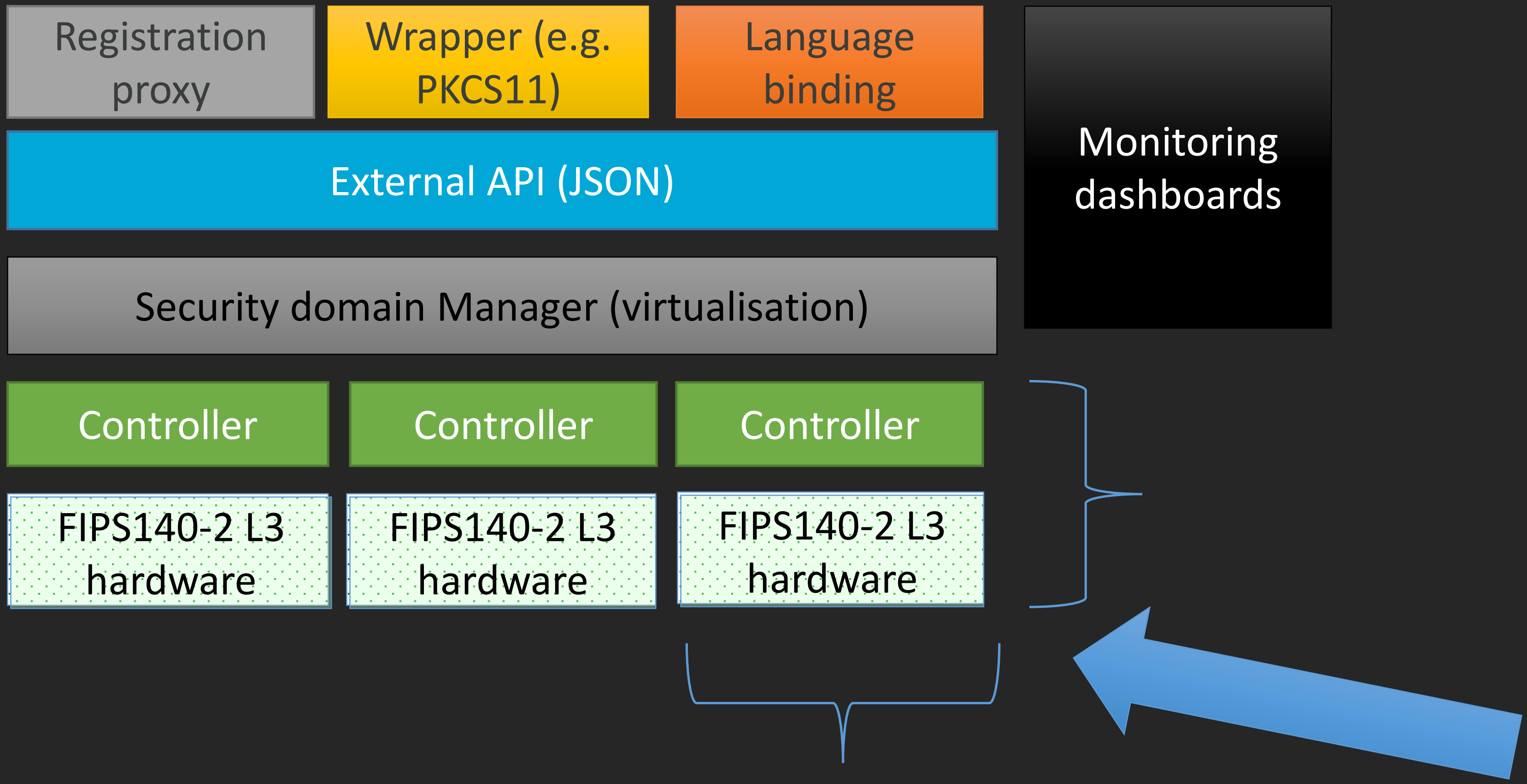
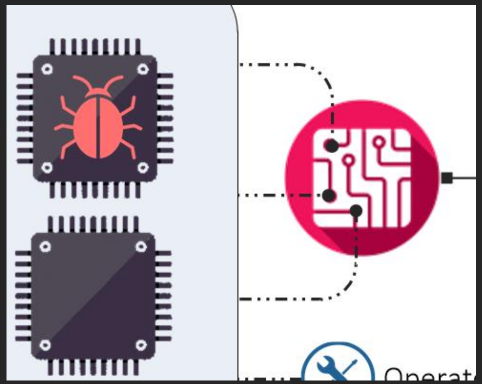
# Smart Cards




- 8-32 bit processor @ 30MHz+
- Persistent memory 32-500kB (EEPROM)
- Volatile fast RAM, usually <10kB
- True Random Number Generator (FIPS140-2)
- Cryptographic Coprocessor (3DES,ECC,AES,RSA-2048,...)
- Limited attack surface
  - Clear API
  - small trusted computing base

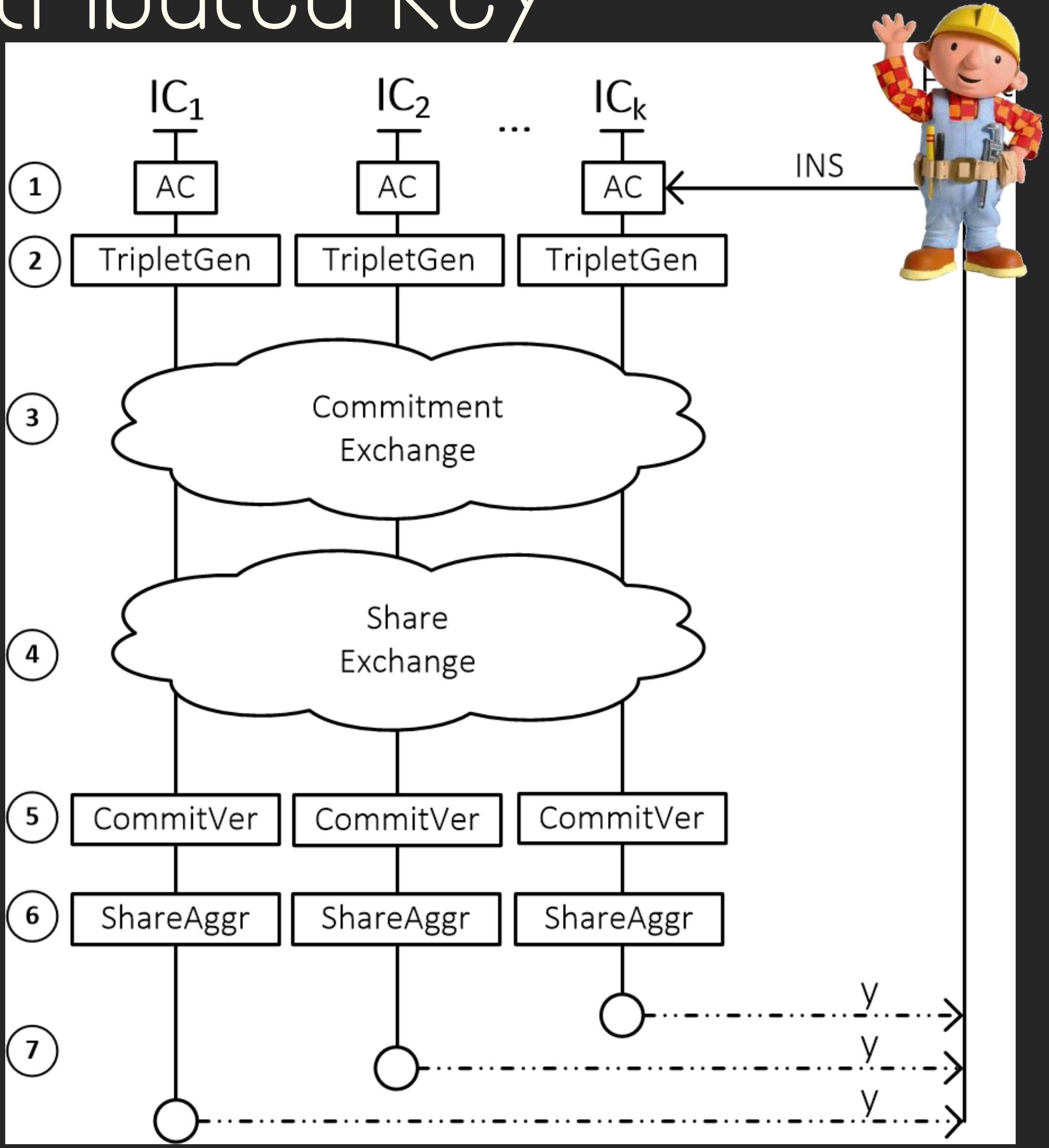
# Plugging it into a cloud service



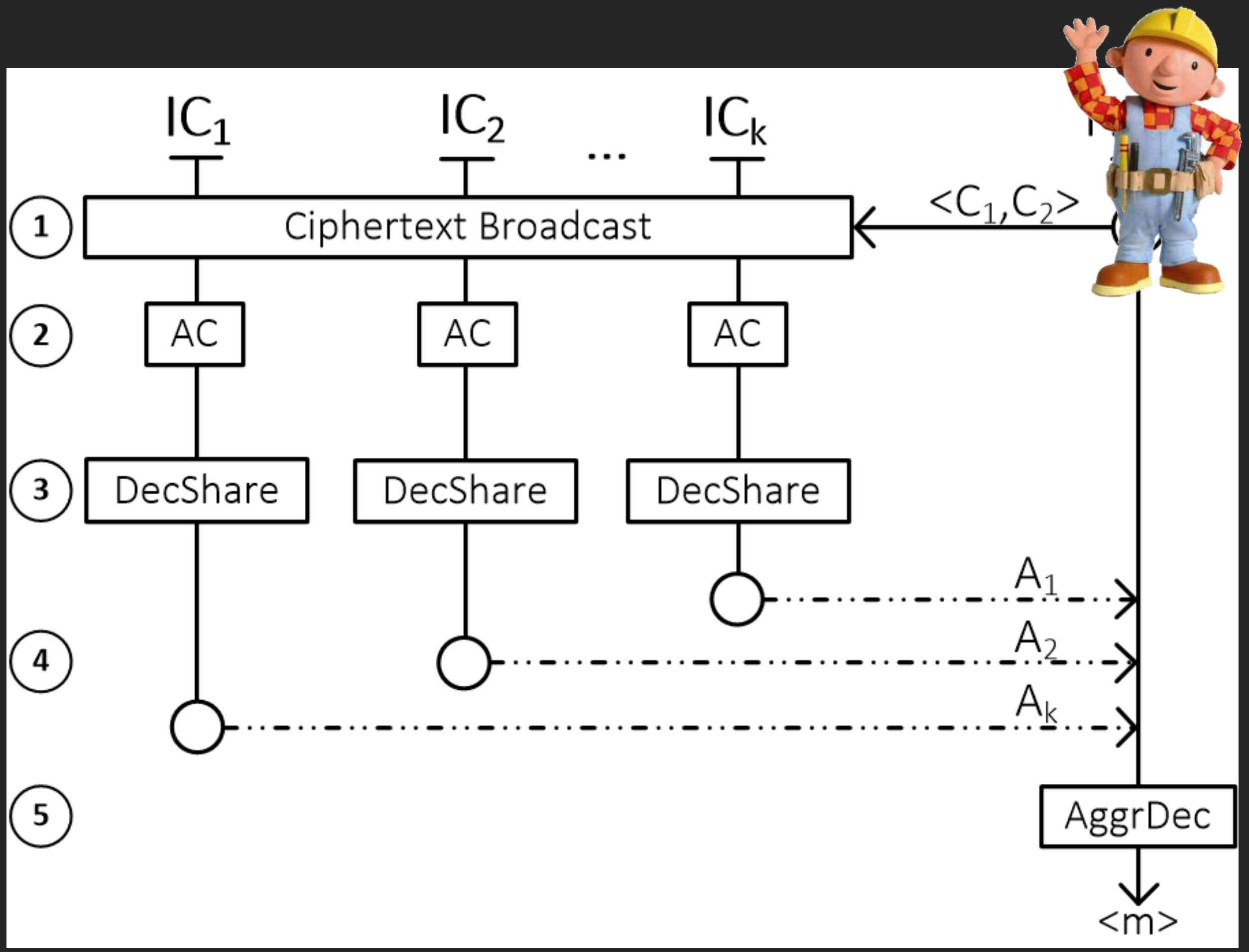
# The Birth of a Distributed Key

1. User asks for new key pair
2. ICs generate their key pairs
3. ICs exchange hashes of their shares
4. ICs reveal their shares
5. ICs verify each others' shares
6. ICs compute the common public key
7. ICs return the common public keys
8. Bob verifies that all the keys are same



# Distributed Decryption

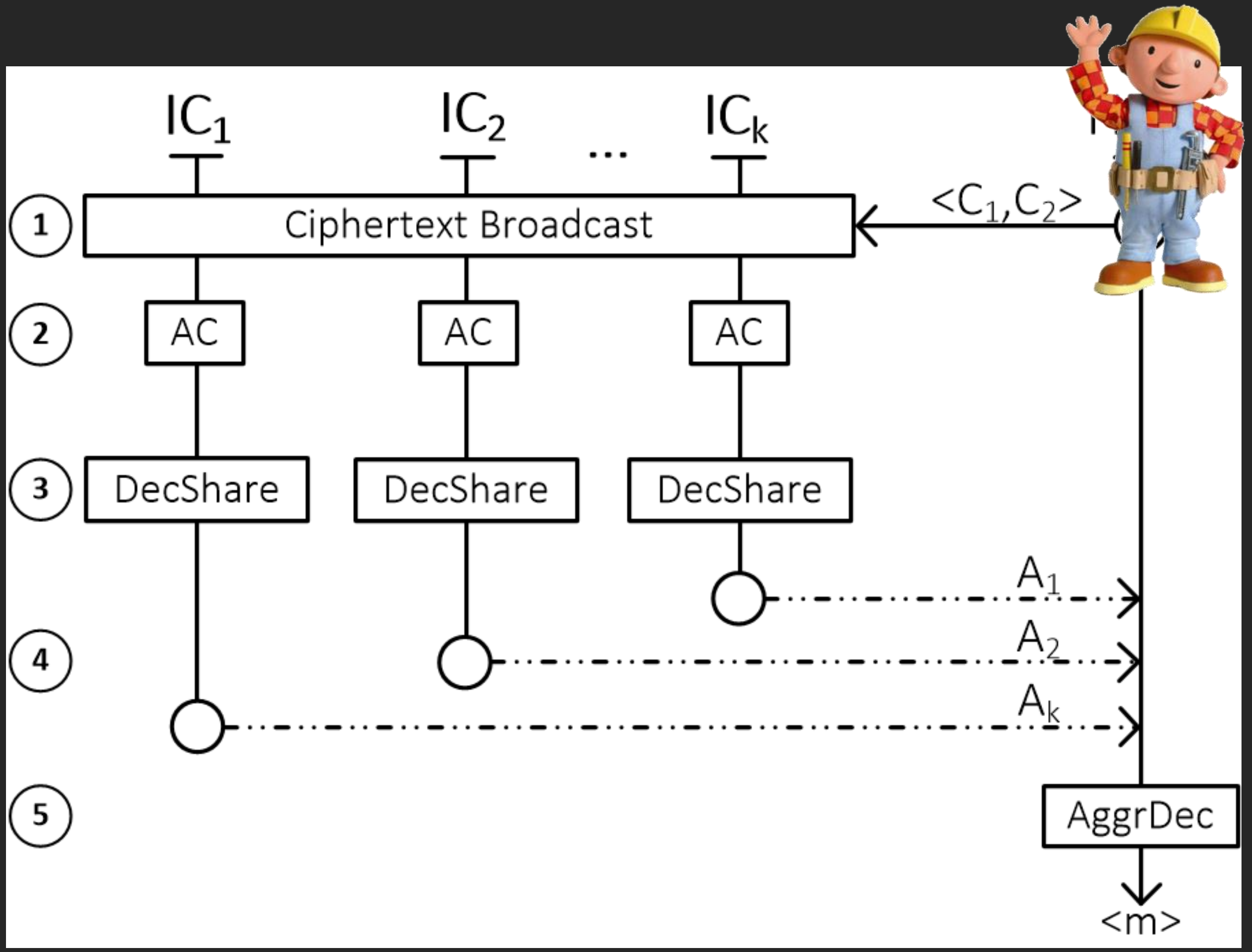
1. Bob asks for ciphertext decryption
2. His authorization is verified
3. ICs compute their decryption shares
4. Bob receives the decryption shares
5. Bob combines them to decrypt



# Distributed Decryption

**Properties**

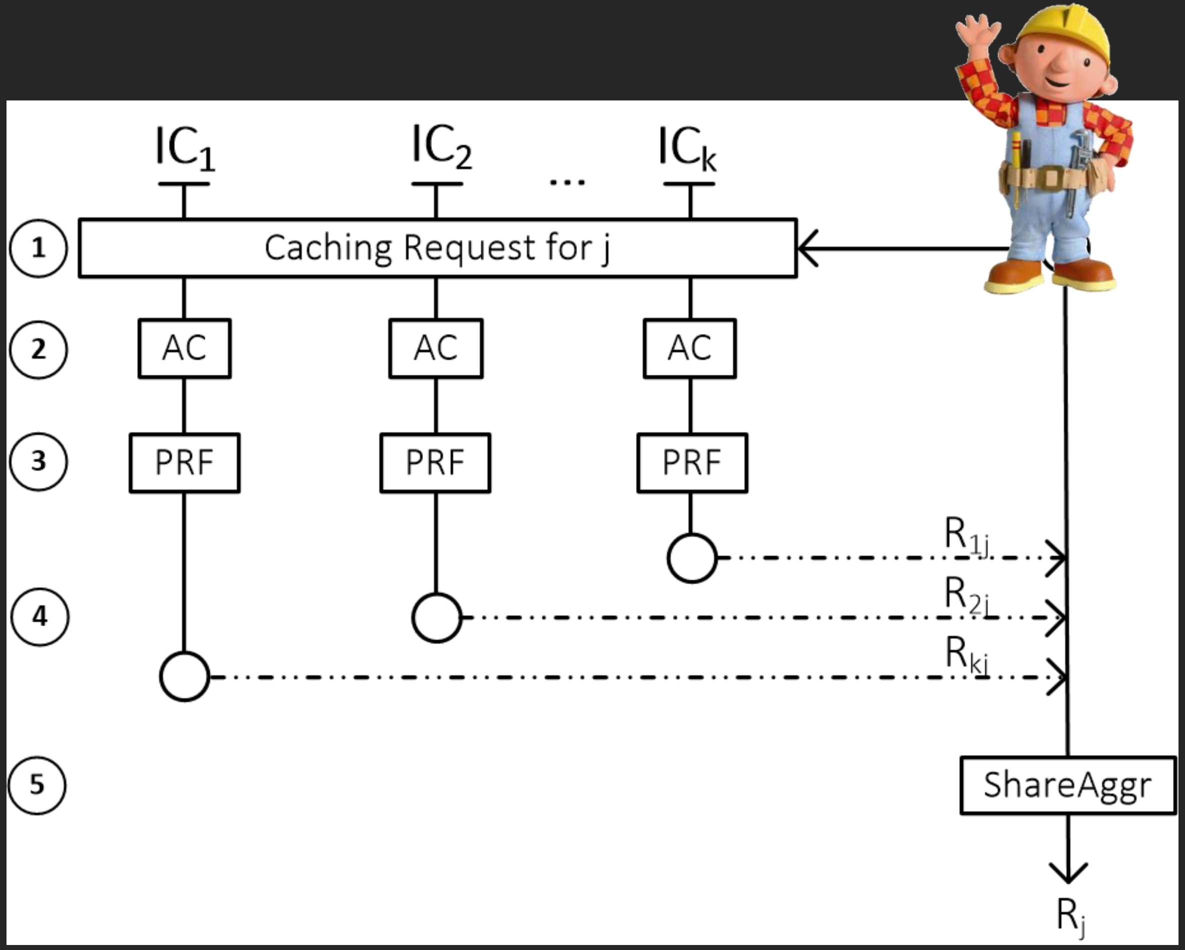
- No single authority gains access to the full private key
- ICs check on each other
- If one IC abstains, decryption fails



# Distributed Signing I

**Caching**

1. Bob sends a caching request
2. The ICs verify Bob’s authorization
3. Generate a random group element based on j
4. Bob sums the random elements




**Properties**

- Caching for thousands of rounds (j)
- Bob stores $R_j$

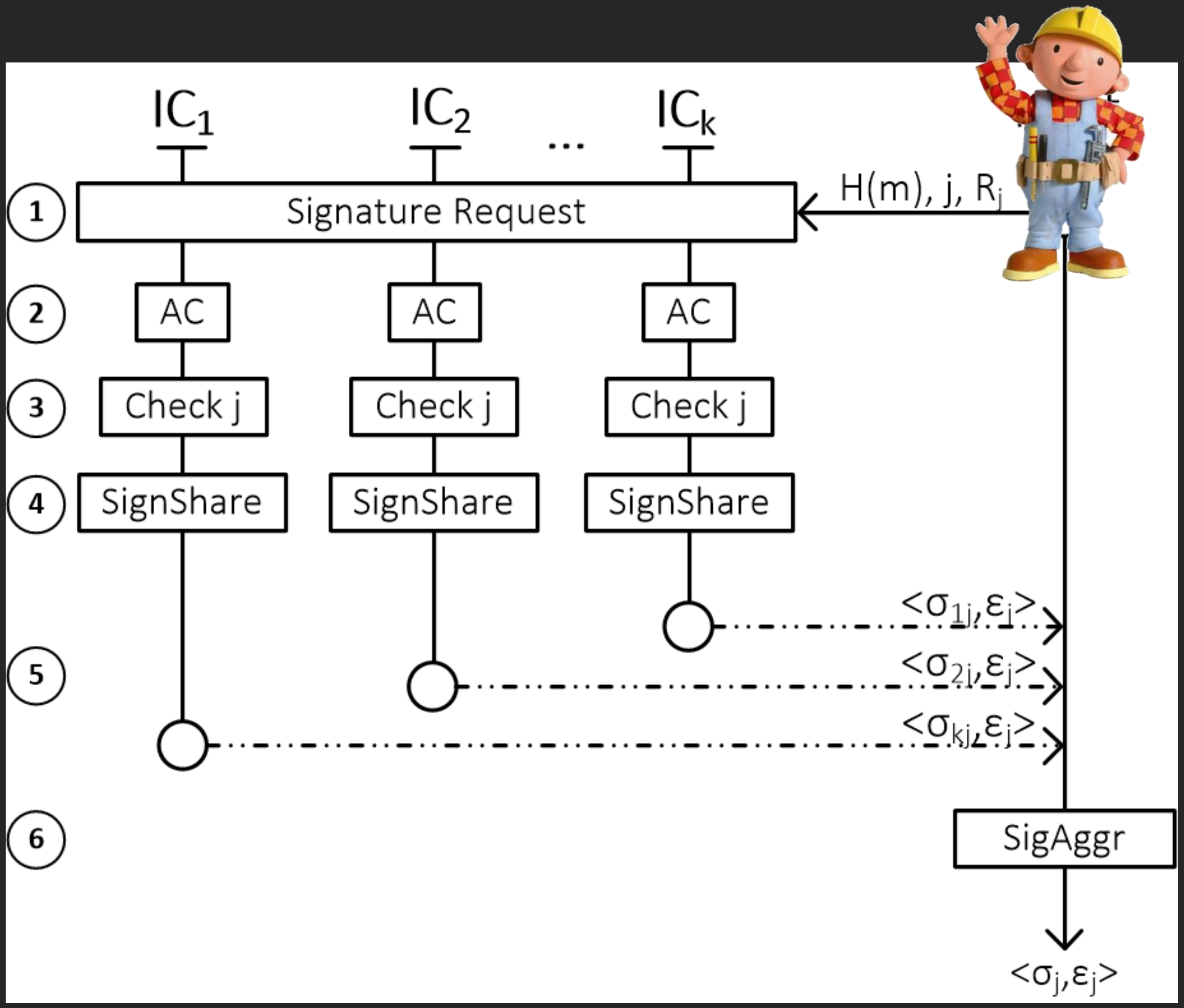
# Distributed Signing II

**Signing**

1. Bob asks for document signing & sends $R_j$, j, and the hash of m
2. ICs verify his authorization
3. ICs check if j has been used again
4. ICs compute their signature share
5. Bob sums all signature shares

**Properties**

- All ICs must participate
- Significant speed up with caching



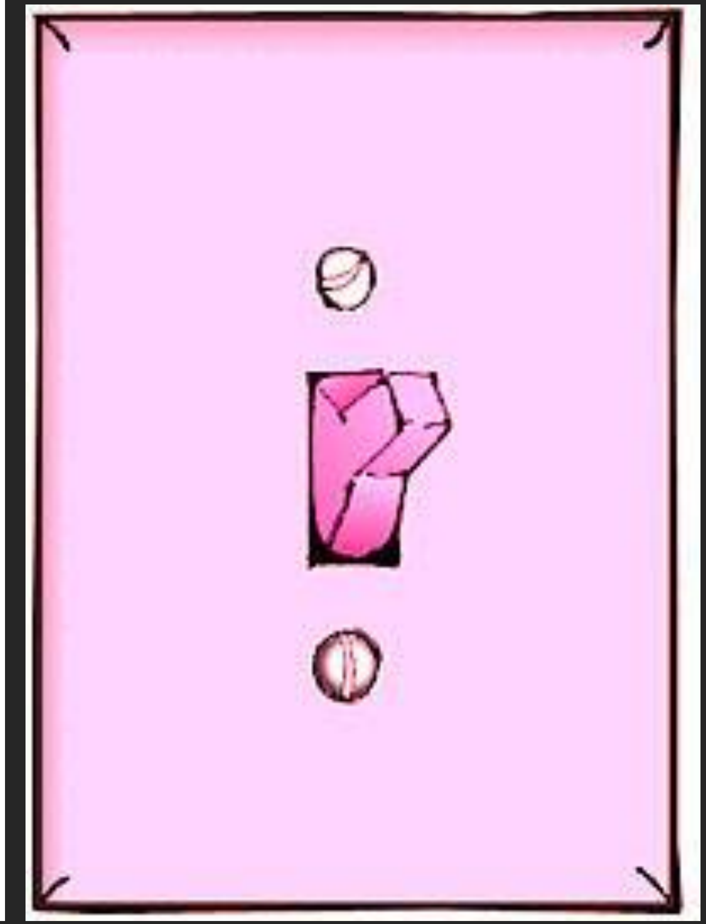
# Kill Switches

That same basic scenario is cropping up more frequently lately, and not just in the Middle East, where conspiracy theories abound. According to a U.S. defense contractor who spoke on condition of anonymity, a "European chip maker" recently built into its microprocessors a kill switch that could be accessed remotely. French defense contractors have used the chips in military equipment, the contractor told *IEEE Spectrum*. If in the future the equipment fell into hostile hands, "the French wanted a way to disable that circuit," he said. *Spectrum* could not confirm this account independently, but spirited discussion about it among researchers and another defense contractor last summer at a military research conference reveals a lot about the fever dreams plaguing the U.S. Department of Defense (DOD).

IEEE Spectrum

# Kill Switches

The Pentagon is worried that "backdoors" in computer processors might leave the American military vulnerable to an instant electronic shut-down. Those fears only grew, after an Israeli strike on an alleged nuclear facility in Syria. Many speculated that Syrian air defenses had been sabotaged by chips with a built-in 'kill switch" – commercial off-the-shelf microprocessors in the Syrian radar might have been purposely fabricated with a hidden "backdoor" inside. By sending a preprogrammed code to those chips, an unknown antagonist had disrupted the chips' function and temporarily blocked the radar."



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# Redundancy & Availability