Technische Universität Braunschweig

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Institute of Operating Systems and Computer Networks

Hybrid Fault-Tolerant Consensus in Asynchronous and Wireless Embedded Systems

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Wenbo Xu, Signe Rüsch, Bijun Li, Rüdiger Kapitza
TU Braunschweig

Controlling Concurrent Change

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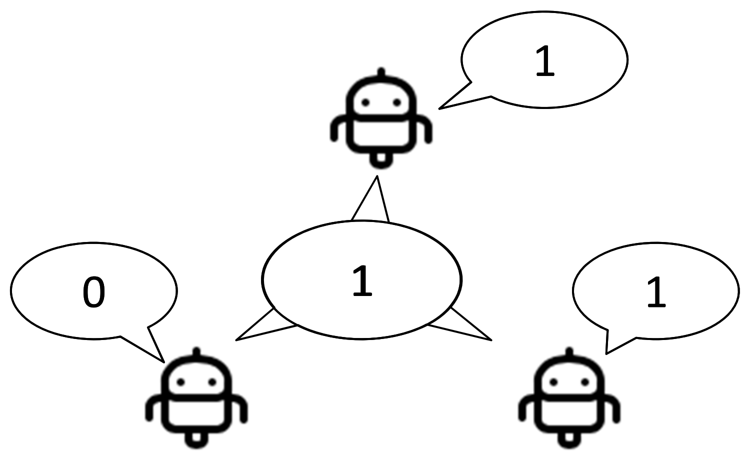
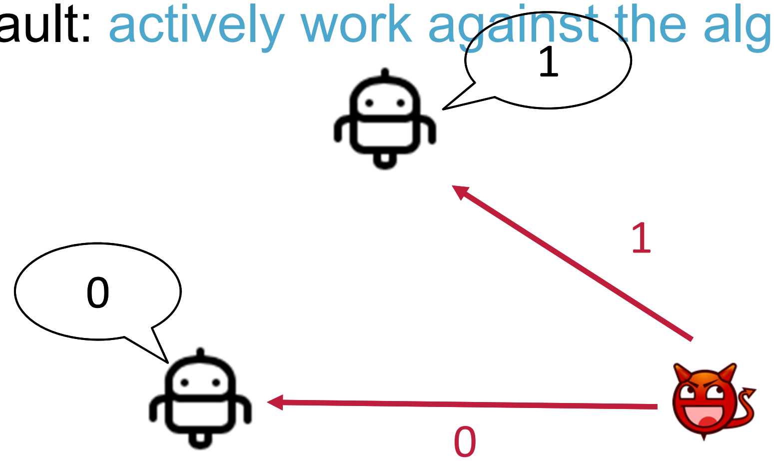
Background: (Binary) Byzantine-Fault Tolerant Consensus

- Fundamental problem in distributed systems
- Totally *n* node in the group, each proposes a value , 0 or 1
- In the end all nodes should decide the same value → consensus



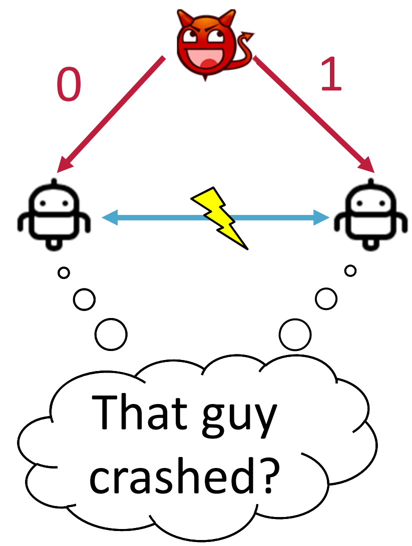
Background: (Binary) Byzantine-Fault Tolerant Consensus

- Fundamental problem in distributed systems
- Totally *n* node in the group, each proposes a value , 0 or 1
- In the end all nodes should decide the same value → consensus
- At most *f* faulty nodes
  - Crash
  - Byzantine fault: actively work against the algorithm



Background: Asynchronous System

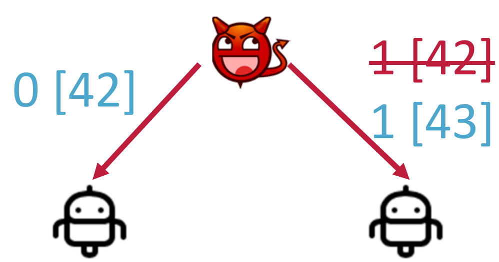
- Nodes communicate via messages
- Asynchronous network
  - No message omissions
  - But messages can take arbitrarily long time
  - → Too slow? Or he didn't send? Cannot wait forever!



- Strong adversary: the worst case
  - The adversary can inspect the status of every message and node
  - … then reorder arrivals of messages, and adjust faulty nodes' behavior
  - Cannot break cryptography and a trusted subsystem

Background: Hybrid Fault Model

- Trusted subsystem, tamperproof
- A strict monotonic counter to prevent “two-faced cheating”
- Faulty nodes cannot send contradictory messages in one broadcast



Related Work and Motivation

- Randomization to bypass FLP impossibility of asynchrony
  - Crash fault tolerance with $n \geq 2f+1$: Ben-Or's algorithm [1]
  - Byzantine fault tolerance requires $n \geq 3f+1$
- Limit the Byzantine behavior with a trusted subsystem
  - Only requires $n \geq 2f+1$
  - Built upon complex algorithm stacks, e.g. reliable broadcast primitive
  - Not resilient against strong adversary → not terminate in worst

2f+1 consensus , but less complex and suitable in wireless embedded systems

Correctness proof under all cases, even strong adversary

[1] Michael Ben-Or. Another advantage of free choice (extended abstract): Completely asynchronous agreement protocols. In *Proceedings of the second annual ACM symposium on Principles of distributed computing*, 1983.

Outline

- Trusted-Ben-Or Algorithm
- A Common Issue in the Proof of Termination
- Experiment

Original Ben-Or's Algorithm

Round based, 2 phases per round

PR: Propose Phase

Propose a value 0 or 1

Round		Node 1	Node 2	Node 3
1	PR	0	1	0
	VO			
2	PR			
	VO			

Ben-Or's Algorithm

Round based, 2 phases per round

PR: Propose Phase

VO: Vote Phase

Wait for *(n-f)* proposals

If >n/2 propose the same *v*

→ Vote for *v*

Else

→ Vote for ⊥ (default)

Round		Node 1	Node 2	Node 3
1	PR	0	1	0
	VO	0	⊥	⊥
2	PR			
	VO			

Ben-Or’s Algorithm

Round based, 2 phases per round

PR: Propose Phase

VO: Vote Phase

PR: Propose Phase

Wait for *(n-f)* votes

If all vote for ⊥

→ Propose (*$*, *R*),

$ is a random value

If someone votes for *v*

→ Propose (*v*, *D*)

Round		Node 1	Node 2	Node 3
1	PR	0	1	0
	VO	0	⊥	⊥
2	PR	0, D	0, D	0, R
	VO			

R = Randomly get the value

D = Deterministically get the value

Ben-Or's Algorithm

Round based, 2 phases per round

PR: Propose Phase

VO: Vote Phase

PR: Propose Phase

VO: Vote Phase

...

If >n/2 vote for the same *v*

→ Decide *v*

Round		Node 1	Node 2	Node 3
1	PR	0	1	0
	VO	0	⊥	⊥
2	PR	0, D	0, D	0, R
	VO	0	0	0
		decide 0	decide 0	decide 0

Ben-Or’s Algorithm

Round based, 2 phases per round

PR: Propose Phase

VO: Vote Phase

PR: Propose Phase

VO: Vote Phase

…

Round		Node 1	Node 2	Node 3
1	PR	0	1	0
	VO	0	⊥	⊥
2	PR	0, D	0, D	0, R
	VO	0	0	0
		decide 0	decide 0	decide 0

Only tolerate crash fault, no Byzantine fault!

Trusted-Ben-Or: Tackle Byzantine faults

- Message uniqueness per phase

→ Trusted monotonic counter for message authentication

- Unbiased random number

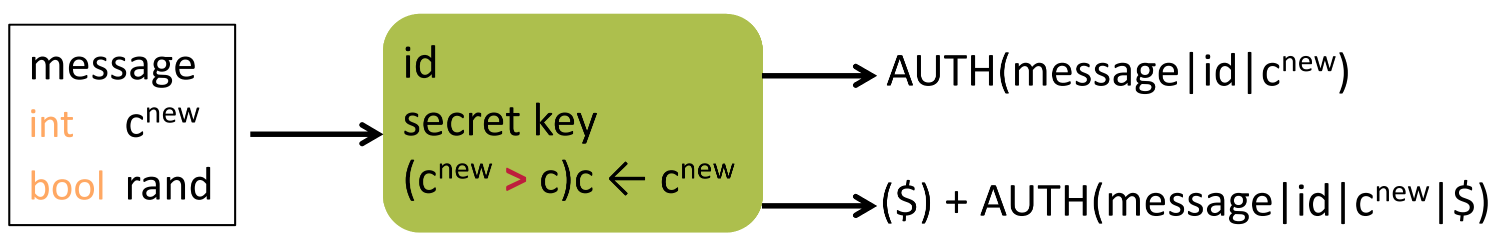
→ Trusted random number generator (combined with the counter)

- Semantic correctness

→ Message certificate

Message Uniqueness | Unbiased Random | Semantic Correctness

- In round *k,* each node only sends 2 messages
- Trusted monotonic counter authentication:
  - <PR, k, *, *> with counter value [k|0]
  - <VO, k, *> with counter value [k|1]
- Trusted random number generator
- Protected by hardware, can only crash but not Byzantine



Message Uniqueness | Unbiased Random | **Semantic Correctness**

- Piggyback received, authenticated messages to proof the correctness
- No recursive certificates
  - Limited message size (≤ $n+2$ messages in one certificate)
  - Faulty node can include invalid into a certificate

Adaption to Embedded Wireless Systems

- Local broadcast instead of peer-to-peer communication
- Tackle (limited) omission faults:
  - Stubborn re-transmission of last message
  - Round jumping when received a valid message of future round

  → No specific network protocols / primitives required for reliable communication
- HMAC in trusted subsystem instead of digital signature

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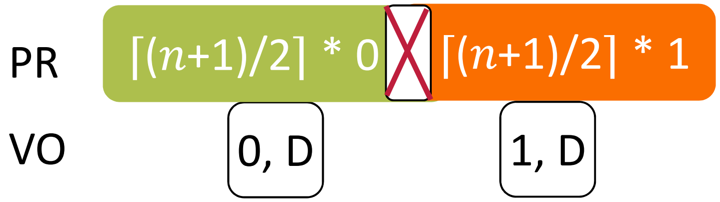
Proof of Termination

- No valid proposals of (0, D) and (1, D) at the same time



- In a lucky round:
  - All trusted coins of each node toss the same random value *v*
  - … which is the same as the valid deterministic value

→ Terminate in this round

Proof of Termination

A corner case of flaw

- Firstly let a node R-get v

Round	Node 1	Node 2	Node 3
PR	0,D	1,D	
VO	⊥	⊥	
PR	0,R		
VO			
PR			

Proof of Termination

A corner case of possible flaw

- Firstly let a node R-get v
- Then let another node D-get (1-

→ Turn the lucky value into unluck

Round	Node 1	Node 2	Node 3
PR	0,D	1,D	1,D
VO	⊥	⊥	1
PR	0,R		1,D
VO			
PR			

Proof of Termination

A corner case of possible flaw

- Firstly let a node R-get v
- Then let another node D-get (1-

→ Turn the lucky value into unluck

Round	Node 1	Node 2	Node 3
PR	0,D	1,D	1,D
VO	⊥	⊥	1
PR	0,R		1,D
VO	⊥		⊥
PR	1,R		

Is 0 still the lucky value here?

"Luckiness" should not depend on future events!

Marcos K Aguilera and Sam Toueg. The correctness proof of ben-or's randomized consensus algorithm. *Distributed Computing*, 25(5), 2012.

Proof of Termination

- In our work, termination is ensured by:
  - Counter authentication
  - Trusted random number generator
  - Semantic certificate
  - “Luckiness”
- Luckiness depends only on the current system state and past events!
- For more details please refer to our paper

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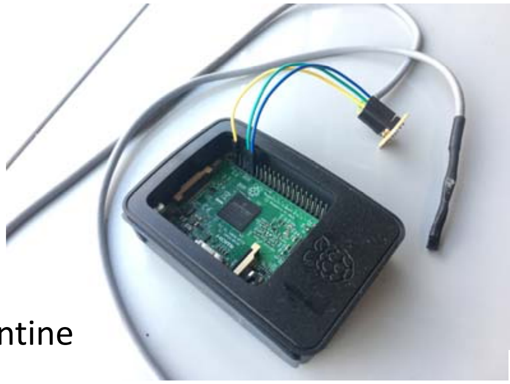
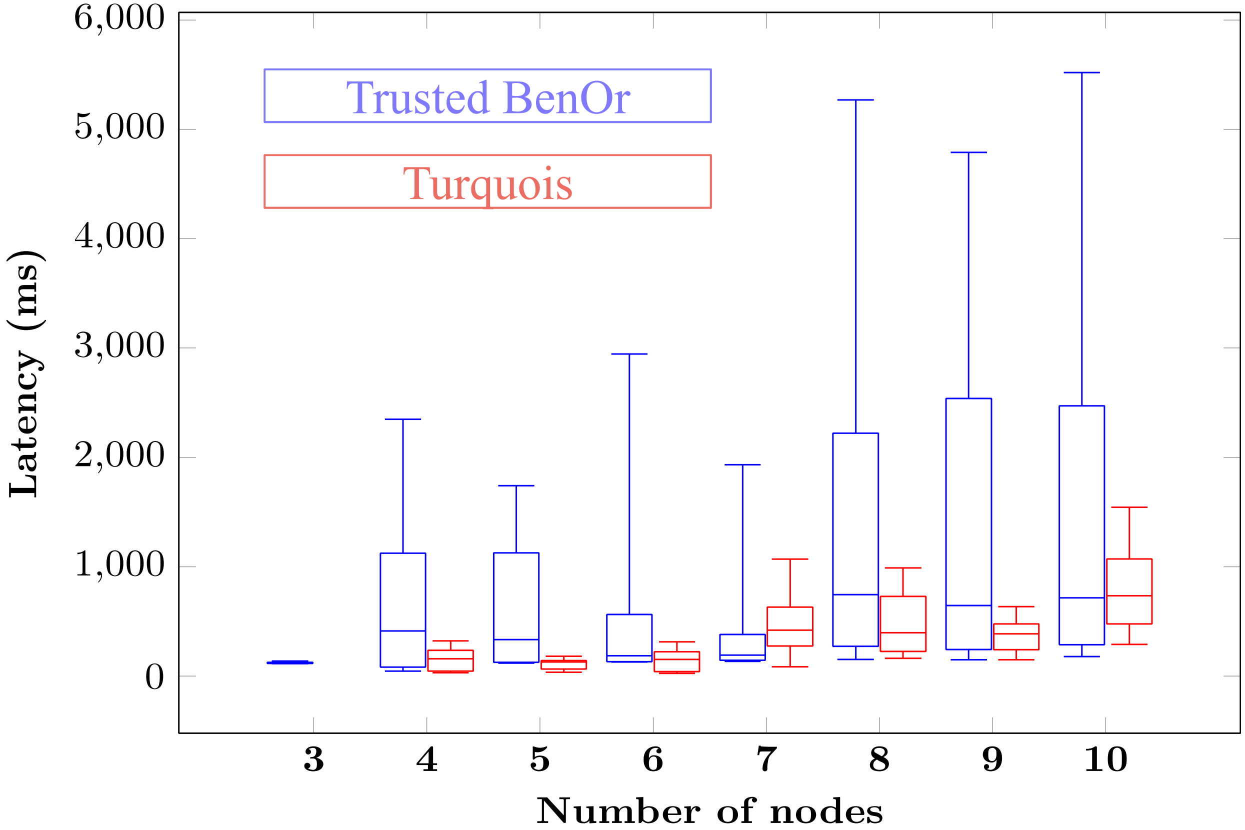
Experiments: Settings

- 3-10 RaspberryPi 3: ARM processor with TrustZone interface, distributed in different rooms in office building
- Wireless ad-hoc mode, UDP multicast
  - ICMP ping delay: (min, average, max) = (5.6 ms, 12.5 ms, >1000 ms)
  - iperf3 test: up to 24% data loss
- Trusted counter implemented on Linaro OPTEE
  - SHA-256 HMAC provided by OPTEE
- Compare with Turquois [1]



[1] Henrique Moniz, Nuno Ferreira Neves, and Miguel Correia. Turquois: Byzantine consensus in wireless ad hoc networks. In *Dependable Systems and Networks (DSN), 2010 IEEE/IFIP International Conference on*, pages 537–546. IEEE, 2010.

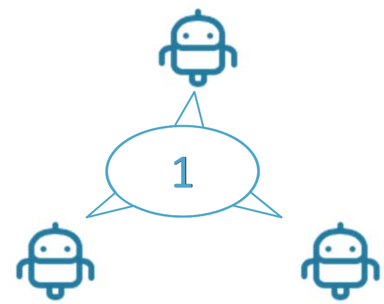
Experiment: Result with Byzantine Faults Injected



- Comparable median
- Higher variance
- Can tolerate more faults

Conclusion

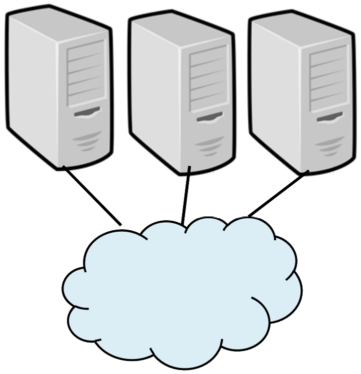
- Randomized binary consensus in asynchronous system
- Trusted monotonic counter for message authentication
- Resilient against strong adversary
- Tailored for embedded wireless systems
- Tolerate more faults with limited overhead (in most cases)

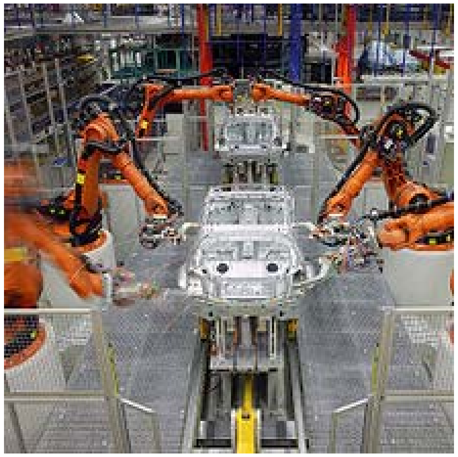


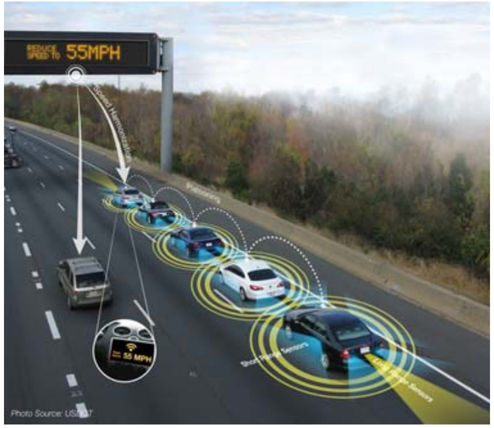
Thank you for your attention!

Motivation: Distributed Consensus

Replication system







Trusted BenOr Algorithm: Overview

//the initial round. Round number is omitted
send <PR, v, D-get>
wait for $\left\lceil \frac{n+1}{2} \right\rceil$ valid PR-messages
if $\left\lceil \frac{n+1}{2} \right\rceil$ <P, v> with the same v
    send <VO, v>
else
    send <VO, $\perp$>
wait for $\left\lceil \frac{n+1}{2} \right\rceil$ valid VO-messages
if $\left\lceil \frac{n+1}{2} \right\rceil$ <VO, v>
    decide v
//new round
if at least one <VO, v>
    send <PR, V, D-get>
else send <PR, \$, R-get>

Message Validity: Legality Certificate

Message type	When to send	Required certificate
<PR, k+1, v, R-get>	$\lceil(n+1)/2\rceil$<VO, k, ⊥>	$\lceil(n+1)/2\rceil$ <VO, k, ⊥>
<PR, k+1, v, D-get>	$\lceil(n+1)/2\rceil$ <VO, k, *> with at least one <VO, k, v>	$\lceil(n+1)/2\rceil$ <PR, k, v, *>
<VO, k+1, v>	$\lceil(n+1)/2\rceil$ <PR, k+1, v, *>	$\lceil(n+1)/2\rceil$ <PR, k+1, v, *> If there is a <PR, k+1, v, D-get>, then add $\lceil(n+1)/2\rceil$ <PR, k+1, v, *>
<VO, k+1, ⊥>	$\lceil(n+1)/2\rceil$ <PR, k+1, *, *> with different values	$\lceil(n+1)/2\rceil$ <PR, k+1, *, *> with different values Plus $\lceil(n+1)/2\rceil$ <VO, k, ⊥>

Proof of Agreement

A correct node decides *v* in round *k*

Exist $\lceil (n+1)/2 \rceil$ valid <VO, k, v>

Exist $\lceil (n+1)/2 \rceil$ <PR, k, v, *>

No valid <PR, k+1, 1-v, D-get>

No $\lceil (n+1)/2 \rceil$ < VO, k, ⊥>

No valid <PR, k+1, *, R-get>

Message type	Required certificate
<PR, k+1, v, D-get>	$\lceil (n+1)/2 \rceil$ <PR, k, v, *>
<VO, k+1, v>	$\lceil (n+1)/2 \rceil$ <PR, k+1, v, *> …

Message type	Required certificate
<PR, k+1, v, R-get>	$\lceil (n+1)/2 \rceil$ <VO, k, ⊥>

Proof of Agreement

A correct node decides *v* in round *k*

Exist $\lceil(n+1)/2\rceil$ valid <VO, k, v>

Exist $\lceil(n+1)/2\rceil$ <PR, k, v, *>

No valid <PR, k+1, 1-v, D-get>

No $\lceil(n+1)/2\rceil$ < VO, k, ⊥>

No valid <PR, k+1, *, R-get>

Only valid <PR, k+1, v, D-get>

Proof of Termination

Correct definition of "luckiness"

- 1 is lucky in round (3k+1)
- In round (3k-1) and (3k), depends on t0:
  - 0 is lucky before t0
  - Since t0

  Case A: a majority proposed 0 in (3k-1) → 0 is lucky

  Case B: no majority proposed 0 in (3k-1) → 1 is lucky

		Node 0	Node 1	Node 2
3k-1	PR			
	VO			
3k	PR	★		
	VO			
3k+1	PR	1,R	1,R	1,R
	VO			

t0 = the first time a correct node tosses a coin

"Luckiness" now only depends on current state and past events.

Trusted Subsystem: BiTrinc

- Restrict Byzantine nodes, not too faulty → Hybrid fault model
  - Most part can still be Byzantine
  - A small trusted part is never Byzantine (crash-fault-only)
- Can be protected by hardware. Example: ARM TrustZone, Intel SGX, other dedicated hardware security modules
- Minimal Trusted Computing Base
  - As simple and small as possible
  - Only critical functions and data