Bee's Strategy Against Byzantines

Replacing Byzantine Participants

by

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Abstract

Schemes for the identification and replacement of two-faced Byzantine processes are presented. The detection is based on the comparison of the (blackbox) decision result of a Byzantine consensus on input consisting of the inputs of each of the processes, in a system containing n processes $p_1, \ldots, p_n$. Process p_i that received a gossiped message from p_j with the input of another process p_k, that differs from p_k's input value as received from p_k by p_i, reports on p_k and p_j being two-faced. If enough processes (where enough means at least $t+1$, $t < n$ is a threshold on the number of Byzantine participants) report on the same participant p_j to be two-faced, participant p_j is eliminated. If less than the required $t+1$ processes threshold report on a participant p_j, both the reporting processes and the reported process are eliminated. If one of them is not Byzantine, its elimination is the price to pay to cope with the uncertainty created by Byzantine processes. The scheme ensures that any two-faced Byzantine participant that prevents fast termination is eliminated and replaced. Such replacement may serve as a preparation for the next invocations of Byzantine agreement possibly used to implement a replicated state machine.

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1 Introduction

The Byzantine Agreement (BA) problem, introduced by Pease, Shostak, and Lamport in [1], is known as a fundamental problem in fault-tolerant distributed computing. The problem has received a lot of attention in the literature and has become the essence of a variety of schemes in distributed computing.

Solving the Byzantine agreement problem is not necessarily tied to the detection of the Byzantine processes, the only success criterion of the agreement is whether all correct processes agree on the same value. In this work, we focus on detecting two-faced Byzantine processes for the sake of eliminating (replacing) them for the next invocations of a Byzantine agreement, possibly as part of implementing (Byzantine Paxos) replicated state machine. Such indication of two-faced behavior may facilitate (possibly machine learning based) decisions for replacing malfunctioning version (say Linux, Java version) by another (say Windows, Python-based) version. The goal is to prepare for the future invocations of the agreement, trying to ensure that the next invocation of the Byzantine agreement will cope with a smaller number of two-faced Byzantine processes.

The Byzantine Agreement Problem. In the Byzantine Agreement Problem, there are n processes, $\Pi = p_1, \ldots, p_n$ with unique names over $N = 1, ..., n$ and at most $t < n$ of the processes can be Byzantine. Each process starts with an input value v from a set of values V[1]. The goal is to ensure that all non-faulty processes eventually output the same value. The output of a non-faulty process called the *decision value*.
More formally, an algorithm solves the Byzantine Agreement if the following conditions hold:

- **Agreement.** All non-faulty processes agreed on the same value. i.e., there are no two non-faulty processes that decide on different values.
- **Validity.**[2] If all non-faulty processes start with the same value v, the decision value of all non-faulty participants is v.
- **Termination.** Eventually, all non-faulty processes decide on a value.

Achieving consensus in presence of Byzantine processes is expensive as the number of messages grows quadratically with the number of participants n and the number of rounds (time) grows linearly with $t < \frac{1}{3}n$, the threshold on the number of Byzantine participants.

Applications may repeatedly invocate consensus instances (e.g., as part of implementing a replicated state machine). Typically, the presence of Byzantine activity is rare, and it is desirable that the overhead in handling Byzantine activity will be tuned to the actual situation. Hence, we want to adjust the time it takes for each consensus invocation to run according to the actual situation at the time. In addition, when the system is interactive and never stops (as in the case of a replicated state machine) the number of Byzantine participants may be accumulated to exceed any threshold. To avoid the accumulation of Byzantine participants over time, we suggest a detection and replacements of Byzantine participants. Thus, we suggest to couple the consensus algorithm with a detection mechanism. As soon as we detect a Byzantine activity, we will eliminate and replace the processes that are responsible for the Byzantine activity.

The rest of the paper is organized as follows. In Section 2, we describe shortly our system settings. In Section 3, we introduce our approach of the detection process, and in Section 4 we

[1] Binary Agreement is defined with the set $V = \{0, 1\}$.

[2] There is an alternative, stronger property for *Validity* [2]. The decision value v has to be an input value of at least one non-faulty process.

present solutions for the detection process. Due to space limitations, some of the proofs appear in the Appendix contains. In addition, run scenario examples for the part of the suggested solutions can be found in the appendix.

2 System Settings

We consider a distributed system composed of n processes, each having a unique identifier $p_1, p_2, ..., p_n$. We assume that up to $t < \frac{1}{3}n$ processes can be Byzantine. A process is said to be *Byzantine* when it deviates from the protocol, otherwise it is said to be *correct*. Processes communicate trough message exchanges. A reliable communication is assumed, where a point-to-point channel exists for every pair of processes. More precisely, if a correct process p_i sends a message m to a process p_j, then m will be delivered by process p_j. Channels are authenticated, i.e., when a process p_j receives a message m from a process p_i, p_j knows that m has been generated by p_i.

We consider a particular type of Byzantine failure called *two-faced Byzantine* i.e., when a message needs to be sent to all the system and a process is faulty, this faulty process may send different values to different processes (instead of sending the same value). In the sequel, we use the term *process acting as Byzantine* to refer to a process that exhibits two-faced behavior.

The system is synchronous and evolves in sequential synchronous rounds $r_1, r_2, \ldots r_i \ldots$. Every round is divided into three steps: (i) *send step* where the processes send all the messages for the current round, (ii) *receive step* where the processes receive all the messages sent at the beginning of the current round[3] and (iii) *computation step* where the processes process the received messages and prepare new messages to be sent in the next round. We assume the existence of a trusted entity component (or components), called *hypervisor*. The *hypervisor* can only receive messages from the processes but cannot send them messages. The hypervisor can eliminate or replace a process with a different process instance. The *hypervisor* is assumed to be correct all the time. We consider two different types in which the hypervisor integrated into the system:

- **Global hypervisor.** There exists just one global hypervisor that controls all the processes in the system.
- **Local hypervisor.** There is a hypervisor that controls p for each process p. Each local hypervisor can communicate with the other local hypervisors.

3 Byzantine Detection and Replacement

Many various algorithms exist for solving different problems given Byzantine processes (some of the algorithms require a restriction on the number of Byzantine participants). In order to detect Byzantine processes, the processes should report each other. Let us observe that given $t+1$ or more testimonies for process p_j as faulty, p_j is Byzantine. On the other hand, in case there are at least one and less than $t + 1$ testimonies on p_j being Byzantine, then at least one process is Byzantine among the reporting processes and p_j.
In the heart of the detection, we expect two main parts, fast and slow. The fast part is run by the processes as long as there is no Byzantine activity. When Byzantine activity is discovered the slow part takes place and eliminates the Byzantine processes that acted in a two faced fashion, enforcing

[3]Let us note, that in round-based computations, all deliver() events happen during the receive step.

the system to continue beyond the fast part. We use the term *fast termination* for a scenario in which the fast part is successfully completed.

Thus, our problem and fitting solutions definition can be summarised by adding the following properties to the specification of the original Byzantine agreement problem.

- **Completeness.** A process p_i acting two-faced in a manner that eliminates fast termination is suspected by some correct process p_j.
- **Sacrifice.** If process p_i is suspected by at least $t + 1$ processes, p_i is the only one to be restarted. Otherwise, p_i and the processes that suspect p_i are restarted.

Note, that the *completeness* above somewhat resembles game theory consideration, enforcing Byzantine process that would like to survive to allow the system to terminate fast, and the best global utility is achieved.

4 Byzantine Free Fast Termination

We suggest a Byzantine agreement protocol composed of *fast* and *slow* parts. As long as there is no indication of a Byzantine activity, the fast algorithm takes place (Algorithm 1). Contrarily, when a testimony of Byzantine activity has been discovered, processes start to execute the slow algorithm (Algorithms 3 or 4).

Optimistically, all processes are assumed to be correct and start with the fast algorithm. When a Byzantine activity is detected by a correct process, the correct process notifies other processes, essentially, invoking the slow algorithm.

Preliminaries. In our schemes, a process p is restarted whenever enough testimonies of a two-faced behavior of p are collected. When there is no sufficient number of testimonies for a two-faced behavior of a particular process p, several restarts may take place. A restart may be scheduled for the processes that provide the testimonies (possibly as a sacrifice action), and also for the process that is blamed to be two-faced.

A *consensus vector* of n inputs is required for maintaining the replicated state machine as described, for example in [3]. We are interested in providing a *consensus vector* solution with Byzantine detection, as we define next. The properties of the consensus vector task are defined in terms of n inputs. In a more formal way:

- **Agreement.** All non-faulty processes agreed on the same vector. There are not two non-faulty processes that decide on different vectors.
- **Validity.** Let V be the decision vector. $\forall i \in N$, if p_i is correct then $vector[i]$ is the input value of p_i.
- **Completeness.** A process p_i acting in a two-faced manner that causes the system not to decide in a *fast termination* fashion is suspected by some correct process p_j (and eventually restarted by the hypervisor).
- **Sacrifice.** If process p_i is suspected by at least $t + 1$ processes, p_i is the only one to be restarted. Otherwise, p_i and the processes that suspect p_i are restarted.

The Fast Algorithm (Algorithm 1). The processes run for three rounds following a consensus invocation. In the first round (lines $1 - 2$) each process sends its input value, and in the second

round (lines $3-5$) each process sends the values it received in the previous round. After these two rounds, each process looks for conflicting messages as an indication for Byzantine activity, and collect a suspect list. In the third round, a process sends a bit (an indication bit) with value of 1 (*suspect message*) as an indication for Byzantine activity if such activity is detected. The processes start a new binary consensus invocation (phase 2 line 9). The input value is determined as follows, if a process receives suspect message, the process uses 1 as an input value, and uses 0 otherwise.

When the decision value is 0, the processes use the received vector of round 1 as the decision value. Otherwise, they move to the *slow algorithm* that supposes to take care of Byzantine processes and eliminate them, while keeping the suspect list that has been achieved in the *fast algorithm* to be used in the slow one.

An *early stopping* Byzantine agreement is used to agree on the indication bit. For example, one may use the algorithm suggested in [4, 5]. Such an *early stopping* algorithm terminates in $min\{t+1, f+1\}$ rounds, where t is the maximum number of Byzantine and f is the actual Byzantine processes.

Algorithm 1 Fast Algorithm for process p_i, Denote by N the group of processes' identities, by v_i, the input value of process p_i:

Process fields (initialized with each invocation):
$vector_i = [\perp, \ldots, \perp]$
$vectors_i = [\perp, \ldots, \perp]$
$slow = 0$
Phase 1:
Round 1:
1: $\forall j \in N$: send v_i to p_j
2: on **receive** of v_j from p_j: $vector[j] = v_j$
Round 2:
3: $\forall j \in N$: send $vector$ to p_j
4: on **receive** of $vector_j$ from p_j: $vectors[j] = vector_j$
Round 3:
5: $suspects = getSuspects(vectors)$ ▷ check for conflicts
6: **if** $(|suspects| \geq 1)$ **then** $\forall j \in N$: send $'1'$ to p_j ▷ indication for suspicion
7: on **receive** of $'1'$ from p_j: $slow = 1$

Phase 2:
8: **if** $BA.decide(slow) = 1$ **then**
9: apply *SLOW algorithm* with *suspects* list
10: **else**
11: **return** $vector_i$

The function *getSuspected* is used in the third round of the first phase. This function is used to detect Byzantine processes based on the received messages of the first two rounds. The function input is $vectors_i$, a vector of vectors that represents all the received messages of the two rounds. The value of $vectors_i[k][j]$, $k, j \in N$, represents the value of p_j as received by p_k in the first round. The value of $vectors_i[k][j]$ has been sent to p_i by p_k during the second round (if $k = i$ then $vectors_i[i][j]$ is known after the first round).

At the beginning, the function finds Byzantine processes and removes their values from $vectors_i$. Then the function searches for suspected processes. By examining the vector we can calculate a majority vote for each process' value based on the values received from the others. Majority of process p_j is the most frequent value in $\{vectors[i][j] : i \in N\}$, where N is the unique processes' identifier.

In order to find faulty processes based on $vectors_i$, the *getSuspects* function checks for each process p_k if there are at least $n - t$ processes that send the same value in the second round, otherwise p_k is faulty. This check is done by examining the kth entry of each vector in $vectors_i$. Then the function counts how many times p_k provides a value v for p_j (given by $vectors_i[k][j]$), such that v and the majority value for p_j are different. If it counts more than t occurrences, p_k is faulty. The function then checks, that the value received from p_k in the first round equals the majority value for p_k. After finding faulty process (or processes), their value is removed from $vectors_i$. However, when at least one faulty process had been found, less than $t + 1$ testimonies are required to discover additional faulty processes. Finally, when no more faulty processes can be discovered, the remaining processes' conflicts are considered to be the *suspected* processes only. The function returns a union of the faulty and suspect groups.

Algorithm 2 Description of the function **getSuspects**(vectors)

```
1:  procedure getSuspects(vectors)
2:      maxFaults = t
3:      faulty = ∅
4:      repeat
5:          newFaulty = ∅
6:          for k ∈ N/faulty do
7:              majorityDiff = {j ∈ N/faulty : vectors[k][j] ≠ majority(j)}
8:              if (majority(k) = ⊥) OR (vectors[i][k] ≠ majority(k))
                                        OR (|majorityDiff| ≥ maxFaulty + 1) then
9:                  newFaulty = newFaulty ∪ {k}
10:         for k ∈ newFaulty do
11:             vectors[k] = [⊥, ..., ⊥]
12:             ∀j ∈ N : vectors[j][k] = ⊥
13:         maxFaults = t − |faulty|
14:         faulty = faulty ∪ newFaulty
15:     until (newFaulty = ∅ OR |faulty| = t)
16:     suspects = {k : k ∈ {i, j} s.t. ∃_{j,i∈N/faulty} vectors[j][i] ≠ majority(i)}
17:     return faulty ∪ suspects

18: procedure majority(k)
19:     if vectors[i][k] = ⊥ then
20:         return ⊥
21:     return v s.t. |{j ∈ N : vectors[j][k] = v :}| ≥ n − t, ⊥ otherwise
```

The first two rounds of the algorithm are based on the exponential information gathering (EIG) Byzantine agreement algorithm introduced in [6]. In the first round, each process sends its own input value. In round $r > 1$, each process sends all the messages it receives in round $r - 1$.

The following definitions and proofs are used to explain the detection process of the fast algorithm. The main detection process is done by the function *getSuspects* (Algorithm 2) after collecting messages of two rounds. The function starts with identification of the Byzantine processes, then the function finds suspect processes using p_i messages (i.e., from p_i's point of view). The definitions *c-order lie with respect to* p_i and *A c-discoverability with respect to* p_i are used to explain the detection of Byzantine process and the definition p_i *co-suspects* p_j *and* p_k is used for explaining the detection of suspected processes. Then lemmas are used, based on those definitions, to prove the correctness of the detection algorithm. First, *getSuspects* function tries to identify Byzantine processes by finding *A c-discoverability with respect to* p_i processes. Then, identifies the suspects process by looking for processes p_j, p_k such that p_i *co-suspects* p_j *and* p_k.

Definition 4.1. p_i **co-suspects** p_j **and** p_k**.** Let $r > 1$, process p_i *co-suspects* p_j *and* p_k if in round r, p_j has sent to p_i value v, which supposed to be the value that p_k sent in round $r-1$, while a majority of processes have sent value $v' \neq v$ to p_i as the value sent by p_k in round $r-1$.

Definition 4.2. *c*-**order lie with respect to** p_i**.** Let $c \geq 1$, C - a group of correct processes of size c, called the *lied group*, $p_i \in C$. There are two kinds of *c-order lie*:

- **Two-faced.** Process $p_j, j \in N/C$ sends value v to processes in C and a different value (or values) to others not in C.
- **Anomalous.** $\forall p_i \in C$, p_i *co-suspects* p_j and p_k, $k \in N$

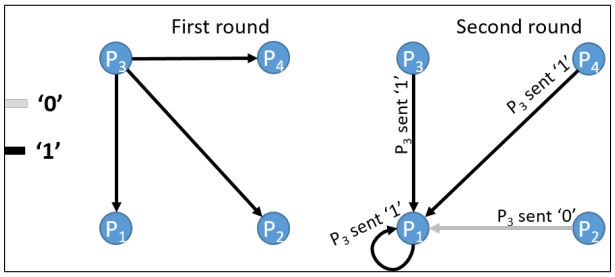
A better understanding of the difference between two-faced and anomalous requires a look in Algorithm 1. In the first round only one value, the input value, is sent. In the second round, n values are sent (as a single message). A two-faced lie can be made in the first round and be discovered in the second round. In that case, in the first round, the process may send v as its initial value to $0 < c < n$ processes and value v', $v \neq v'$, to others, but it can only lie concerning a single value in its message. On the other hand, an anomalous lie can be made in the second round, where there are n possibilities to lie for each one of the n values.

c-order lie leads to the *c-discoverable* definition. Usually, given $t+1$ testimonies for process p to be Byzantine, process p is doomed to be Byzantine. However, if we already count x Byzantine processes, then only $t+1-x$ testimonies are required to discover another Byzantine process. Using this fact, the algorithm starts looking for Byzantine processes using $t+1$ testimonies to find x Byzantine processes, then uses $t-x+1$ testimonies, and so on, as long as new Byzantine processes are found. Note, that both lies are two-faced, but the way of detecting those lies is different.

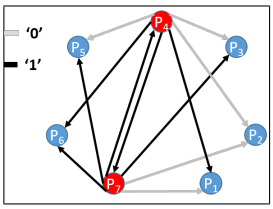
Definition 4.3. A c-discoverability with respect to p_i **process.** Let $1 \leq c \leq t+1$, a process p_j is *c-discoverable with respect to* p_i if $i \neq j$, and p_j made a *c-order lie* to the *lied group* C, $p_i \in C$ and:

- $c = t+1$ or
- $c < t+1$, and there is a group $G = \{k \in N : p_k$ is a *c′-discoverable* with respect to p_i, $c' > c\}$, such that $|G| > t-c$

In Figure (1a), we focused only on messages involving p_3, even though other messages are sent as well. In the first round p_1, p_2 and p_4 receive the value 1 from p_3. In the second round, p_4 and p_1 notify p_1 (p_1 sends the message to itself), that p_3 sent 1 in the first round, while p_2 claims that the value 1 had been sent by p_3. In that case, p_1 has two processes, including itself, that report 1, and one process that reports 0. p_1 cannot identify whether p_3 or p_2 are faulty and p_1 suspects



(a) We focus only on messages regarding process p_3. p_1 co-suspects p_2 and p_3. Three processes (including p_1) notify p_1 that p_3 sent 1 at the first round and p_2 tells p_1 that p_3 sent 0 at the first round.



(b) p_4 sends different values to different processes. p_4 is 3-discoverable ($C = \{5, 3, 2\}$) and P_7 is 2-discoverable ($C = \{1, 2\}$). p_4 and p_7 will cause the processes to run the slow algorithm. p_4 and p_7 will be restarted by the hypervisor then.

Figure 1: *Co-suspect* and *c-discoverable* examples

them both. p_1 *co-suspects* p_2 and p_3. Figure (1b) depicts the case in which p_4 and p_7 are 4 and 3-discoverable, respectively. The algorithm first detects p_4 and only then can detect p_3.

Lemma 4.1. If p is a *c-discoverable with respect to* p_i, then p is detected as Byzantine by p_i.

Proof. The proof is given by decreasing induction on the value of c, $1 \leq c \leq t+1$, starting with $c = t+1$ as the base case. Let $c = t+1$, p_i has $t+1$ testimonies claiming p_j as faulty. Since there are at most t faulty processes, at least one of them is correct. Thus p_j is faulty.

The inductive step. Assuming the claim is correct for $c < t+1$, we show its correctness for $c' = c-1$. By definition, there is a group of processes G wherein, each process is c''*-discoverable with respect to* p_j, such that $c'' > c'$. Therefore, by the induction assumption, all processes in G will be detected as faulty by p_i. $|G| > t - c'$ means that p_i has already discovered at least $t - c'$ faulty processes. By definition of *c-order lie with respect to* p_i, c refers to the number of correct processes that have been lied to. Consider the case in which $N' = N/G$, in such a case any group of c' processes in N' includes at least one correct process. Now, given c' testimonies claiming p_j as faulty, there is at least one correct process, therefore p_j is faulty and discovered by p_i. □

The following lemmas can be used for the exponential information gathering (EIG) Byzantine agreement algorithm [6] where the algorithm terminates in $t+1$ rounds. In our algorithm, these lemmas hold for the first two rounds of the fast algorithm.

Lemma 4.2. Let p_j be a *c-discoverable with respect to* p_i in round $r \geq 1$. If p_j is *two-faced*, assuming at least one round left, p_i detects p_j as faulty in round $r+1$.

Lemma 4.3. Let p_j be a *c-discoverable with respect to* p_i in round $r \geq 1$. If $r > 1$ and p_j is *anomalous*, p_i detects p_j as faulty in round r.

Remark. Lines $5-9$ in Algorithm 2 are searching for $two-faced$ or $anomalous$ processes with $maxFaults$ testimonies.

Remark. Line 16 in Algorithm 2 when applied with $vectors_i$ is searching for p_j, p_k such that p_i co-suspects p_j and p_k.

Lemma 4.4. Let p_j a *c-discoverable with respect to* p_i, then $getSuspects(vectors_i)$ for p_i will return p_j as faulty.

Lemma 4.5. Let p_j be a *c-discoverable with respect to* p_i, with $two-faced$ in round 1 or *anomalous* in round 2, where p_i is a correct process. Then all processes moved to the *slow algorithm*, where at least one process has non-empty suspect list.

Claim 1. After applying $getSuspects(vectors_i)$ for each correct process p_i the following holds:

- Each correct process has a faulty list of size at most t.
- Let p_j be a Byzantine process that exhibits Byzantine behavior. If p_j is a *c-discoverable with respect to* p_i, p_j will be included in p_i's faulty list, where p_i is a correct process. Otherwise, if p_i co-suspects p_j and $p_k, k \in N$, p_j will be included in p_i's suspect list, where p_i is correct process.

Proof. Suppose p_j acts in a Byzantine two-faced fashion in the first two round of the *fast algorithm*. In case p_j acts in a *c-discoverable* fashion, then by Lemma 4.4 p_j will be discovered as faulty. Otherwise, suppose p_i co-suspects p_j and $p_k, k \in N$, by Remark 4 it will be discovered as suspected. □

Lemma 4.6. If there is no Byzantine activity, while running the *fast algorithm*, the algorithm satisfies Agreement, validity, and termination.

5 Using Byzantine Agreement Objects

5.1 Global Hypervisor

The Slow Algorithm (Algorithm 3). The algorithm consists of n stages that run one after another, one for each process. The stage computation steps are presented in Algorithm 3 and composed of 3 phases. The first 2 phases are done by the processes, and the third phase is done by the *global hypervisor*, a single hypervisor for controlling all the processes as defined earlier. In stage s, phase 1 (lines $1-7$), process p_i, such that $(s \ mod \ n) + 1 = i$, is the sender. The sender sends its input value, v_i, to all the other processes. Then the processes invoke an initialized version of a Byzantine consensus on v_i. Process p_j sets the *suspect* variable to 1 (line 7) if an agreement is reached, but the decision value is differed from the received value or p_j had suspect p_i in the *fast algorithm* already. In that cases, p_j suspects p_i. In phase 2 (lines $8-10$) each process, with *suspect* variable set to 1, sends a suspect message to the *global hypervisor* (line 10).

The hypervisor can decide to eliminate or restart a process based on the testimonies of other processes. In phase 3 (lines $11-14$), if the hypervisor receives at least $t+1$ testimonies claiming that process p_i is faulty, p_i is doomed to be a Byzantine process since at least one non-faulty process's testimony exists. If the number of testimonies is less than $t+1$, it is unclear whether p_i is Byzantine or not. Either the testimonies are correct and p_i is Byzantine, or the t Byzantine processes worked together to incriminate p_i. Thus, in this case, the hypervisor has to eliminate them all, i.e., p_i and the other processes that sent the testimonies.

By this approach, once Byzantine activity occurs by sender process p_i, it will be eliminated by the hypervisor. Still, sometimes some correct processes would be restarted along with p_i. As a conclusion, the addition of third party (the hypervisor) cannot identify Byzantine process p_i unless there are at least $t+1$ processes that claim p_i is Byzantine. Otherwise, in the worst case scenario, the only possibility left is to suspect all the $t+1$ processes. That way, in all cases Byzantine process p_i that has been discovered in the fast part is doomed to be eliminated at stage s', such

that $(s' \ mod \ n)+1 = i$. At the end of the n stages, each Byzantine process that has been discovered in the fast algorithm will be eliminated and each non-faulty process will have the same vector of values. The next theorem (for which the proof appears in the appendix) summarizes the above observations.

Theorem 5.1. Algorithm 3 satisfies agreement, validity, and termination.

Algorithm 3 Code for process p_i and hypervisor in stage s, each process starts with suspect list it discovered in the fast algorithm:

Process fields: $in_i[1 \dots n]$ initially [null, ... ,null],
$suspect = 0$
$suspects$ = initialized from *fast algorithm*
$BA[1 \dots n]$ initially [null, ... ,null]

Phase 1 **of stage** s:
1: **if** $s \ (mod \ n)+1 = i$ **then**
2: send $val(v_i)$ to all processes
3: **else** ▷ upon receiving v_j from p_j
4: $in_i[j] = v_j$
5: $dec_i[j] = BA[j].decide(v_j)$
6: **if** $dec_i[j] \neq in_i[j]$ **OR** $j \in suspects$ **then**
7: turn on *hypervisor* **;** $suspect = 1$

Phase 2 **of stage** s:
8: **if** $s \ (mod \ n)+1 \neq i$ **AND** $suspect = 1$ **then**
9: $j = s \ (mod \ n)+1$
10: send $suspect(j)$ to hypervisor

Hypervisor code:

Phase 3 **of stage** s: ▷ Let $P = \{i_1, \dots, i_k\}$ group of processes that send $suspect(i)$ messages.
11: **if** $(k > t)$ **then**
12: restart p_i
13: **else**
14: $\forall j \in P \cup \{i\}$: restart p_j

5.2 Local Hypervisor

In this part, we assumed the existent of a different definition of a hypervisor, a *local hypervisor* for each process. The *local hypervisor* can be turned on by its process and assumed to be correct all the time. The local hypervisors can send and receive suspects messages (as explained in the sequel) but cannot send messages to the processes. The *hypervisor* can restart the process based on the suspect messages.

Algorithm 4. The algorithm starts the same as Algorithm 3, in phase 1 there is a sender process sending its own input value to all processes, following by Byzantine consensus invocation for the received value, and suspect if the decision value is different from the received value or if the sender had already suspected in the *fast algorithm*. Algorithm 4 differs from Algorithm 3 following the detection part. A process that suspects the sender turns on its local hypervisor as an indication for the detection. In phase 2, the *local hypervisor* sends suspect messages to all other hypervisors. During phase 3, after all suspects messages of phase 2 have been received, the local hypervisor that controls the sender restarts the sender as a consequence of receiving at least one suspect message. The local hypervisor of the other processes, different from the sender, restarts their hosted process only when there are less than $t + 1$ suspect messages.

Theorem 5.2. Algorithm 4 satisfies agreement, validity, and termination.

Algorithm 4 Code for separated hypervisors and process p_i in stage s, each process starts with suspect list it discovered in the fast algorithm:

---

local hypervisor *turned off* except for p_i, such that $s \pmod n + 1 = i$
Process fields:
$in_i[1 \dots n]$ initially [null, ... ,null],
$BA[1 \dots n]$ initially [null, ... ,null]
$suspects$ = initialized from *fast algorithm*

Phase 1 **of stage** s:
1: **if** $s \pmod n + 1 = i$ **then**
2: send $val(v_i)$ to all processes
3: **else** ▷ *upon receiving* v_j *from* p_j
4: $in_i[j] = v_j$
5: $dec_i[j] = BA[j].decide(v_j)$
6: **if** $dec_i[j] \neq in_i[j]$ **OR** $j \in suspects$ **then**
7: turn on *local hypervisor*

Hypervisor code (for p_i's turned on (active) local hypervisor):

Phase 2 **of stage** s:
8: **if** $s \pmod n + 1 \neq i$ **then**
9: $j = s \pmod n + 1$
10: send *suspect(j)* to all active *hypervisor*s
11: **else** ▷ *counter-testimony for all active hypervisors*
12: $\forall j \in N$ such that p_j's *hypervisor* is active: send *suspect(j)* to p_j's *local hypervisor*

Phase 3 **of stage** s: ▷ k - amount of received $suspect(i)$ messages.
13: **if** $s \pmod n + 1 = i$ **AND** $k > 0$ **then**
14: restart p_i
15: **else if** $k \leq t$ **then** ▷ *upon receiving* k ***suspect(j)*** *messages*
16: restart p_i

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A Proofs

Lemma 4.2. Let p_j be a *c-discoverable with respect to* p_i in round $r \geq 1$. If p_j is *two-faced*, assuming at least one round left, p_i detects p_j as faulty in round $r+1$.

Proof. Let p_j be a *c-discoverable with respect to* p_i in round r with a *two-faced* lie. It follows that p_j sends a value v to group C of c correct processes while sending a different value (or values) to other correct processes. Processes in C will identify the different value sent to the other processes only in the next round when all the processes send their receiving value of the previous round. □

Lemma 4.3. Let p_j be a *c-discoverable with respect to* p_i in round $r \geq 1$. If $r > 1$ and p_j is *anomalous*, p_i detects p_j as faulty in round r.

Proof. Let process p_j be a *c-discoverable with respect to* p_i in round $r > 1$ with an *anomalous* lie. It follows that p_j claims that it received certain messages from processes in C (of c correct processes), while these messages are different from the messages received by p_i from the processes in C. Since processes in C are correct, they sent the same message to all processes, including the $n-t$ correct processes. Let $p_k \in C$, when p_i checks the received messages from all processes for p_k, p_i will identify at least $n-t$ messages carrying the same value as p_i got last round from p_k. Giving the fact that p_j is *c-discoverable with respect to* p_i, p_i has c testimonies claiming p_j for being faulty. Thus, p_i can detect p_j as faulty. □

Lemma 4.4. Let p_j a *c-discoverable with respect to* p_i, then $getSuspects(vectors_i)$ for p_i will return p_j as faulty.

Proof. Let p_j be a *c-discoverable with respect to* p_i, then there is a group $G = \{k \in N : p_k$ is a c'-discoverable with respect to p_i, $c' > c\}$, such that $|G| > t - c$.
Lines $5-9$ of *getSuspects* (Algorithm 2) search for $(maxFaults + 1)$ testimonies of $two - faced$ or *anomalous* for each process.
The proof is given by decreasing induction on the value of c, $1 \leq c \leq t+1$, starting with $c = t+1$ as the base case. Let $c = t+1$, p_i has $t+1$ testimonies claiming p_j as faulty. In line 2, $maxFaults$ is initialized to t, then lines $5-9$ searching for $t+1$ testimonies of $two - faced$ or *anomalous*. A *(t+1)-discoverable with respect to* p_i process is discovered after executing lines $5-9$.

After discovering a group of *c-discoverable with respect to* p_i, $maxFaults$ is decreased by the size of this group (line 13).

The inductive step. Assuming the claim is correct for $c < t+1$, we show its correctness for $c' = c-1$. By definition, there is a group of processes G wherein, each process is *c''-discoverable with respect to* p_j, such that $c'' > c'$. Therefore, by the induction assumption, all processes in G will be detected as faulty by p_i. $|G| > t - c'$ means that p_i has already discovered at least $t - c'$ faulty processes. Thus, $maxFault$ eventually is updated to be $t - |G|$ and lines $5-9$ will search for at least $maxFault + 1$ $(t - c' + 1)$ testimonies and p_j will be discovered. □

Lemma 4.5. Let p_j be a *c-discoverable with respect to* p_i, with $two-faced$ in round 1 or *anomalous* in round 2, where p_i is a correct process. Then all processes moved to the *slow algorithm*, where at least one process has non-empty suspect list.

Proof. Let p_j be a *c-discoverable with respect to* p_i, by Lemma 4.4 p_i will discover p_j by round 3 and will send indication bit $'1'$ to all processes. Then in phase 3 a Byzantine agreement will be

executed. Since p_i is correct, all correct processes' input value will be $'1'$, the decision value will be $'1'$ and all correct processes will move to the *slow algorithm* □

Lemma 4.6. If there is no Byzantine activity, while running the *fast algorithm*, the algorithm satisfied: Agreement, validity, and termination.

Proof. Suppose there is no Byzantine activity while running the *fast algorithm*.
Agreement. Each correct processes received the same messages for creating $vector_i$. Hence, they agreed on the same vector.
Validity. Since no Byzantine activity done, the value at entry i of the vector (aka $vector[i]$) is the input value of p_i.
Termination. The algorithm composed of two phases. The first phase (lines $1-7$) contains three rounds and the second phase (lines $8-11$) composed of Byzantine agreement execution (line 8), which is finite due to the Byzantine agreement termination property, then the algorithm terminates. After termination, the slow algorithm might be applied (a separate proof for the slow algorithm in the sequel). □

Theorem 5.1. Algorithm 3 satisfies agreement, validity, and termination.

Proof. Agreement. The algorithm consists of n stages, at each stage, all the correct processes agree on the same value for process p_i with $s(mod\ n)+1=i$ through a Byzantine consensus (line 5). Eventually, after n stages, all correct processes received the same n values representing the vector of size n.
Validity. For each entry i in the vector a consensus had been made at stage s, such that $i(mod\ n)+1=i$. *Validity*, by definition, concerns only the input value of correct processes. If the sender is correct, it sent the same value, v to all processes in phase 1 (line 2). Then Byzantine agreement is invoked and all correct processes hold the same input value v. By validity property of Byzantine consensus, the decision value is v.
Termination. The algorithms consist of n stages. Each stage composed of three phases. The first phase contains one round and Byzantine agreement execution (lines $1-7$), which is finite due to the Byzantine agreement termination property. The second phase lasts for one round (lines $8-10$) and finally, the third phase (lines $11-14$) contains the hypervisor part which requires one round. Given that stage is finite, n stages are also finite, thus the algorithm terminates. □

Theorem 5.2. Algorithm 4 satisfies agreement, validity, and termination.

Proof. Agreement. The algorithm consists of n stages, at each stage, all the correct processes agree on the same value for process p_i with $s(mod\ n)+1=i$ through a Byzantine consensus (line 5). Eventually, after n stages, all correct processes receive the same n values representing the vector of size n.
Validity. For each entry i in the vector a consensus had been made at stage s, such that $i(mod\ n)+1=i$. *Validity*, by definition, concerns only the input value of correct processes. If the sender is correct, it sent the same value, v, to all processes in phase 1 (line 2). Then Byzantine agreement is invoked and all correct processes hold the same input value v. By validity property of Byzantine consensus, the decision value is v.
Termination. The algorithms consist of n stages. Each stage composed of three phases. The first phase contains one round and Byzantine agreement execution (lines $1-7$), which is finite due to the Byzantine agreement termination property. The second phase lasts for one round (lines $8-12$)

and finally, the third phase (lines $13 - 16$) which requires one round. Given that stage is finite, n stages are also finite, thus the algorithm terminates

□

B Slow Algorithm Run Scenarios

B.1 Global Hypervisor.

Figures 2 to 5 describe the various scenarios for the case of $n = 4, t = 1$.

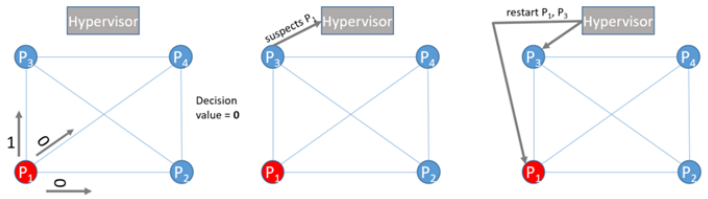

Figure 2: P_1 sends wrong value to P_3. P_3 suspects P_1 and both restarted by the hypervisor.

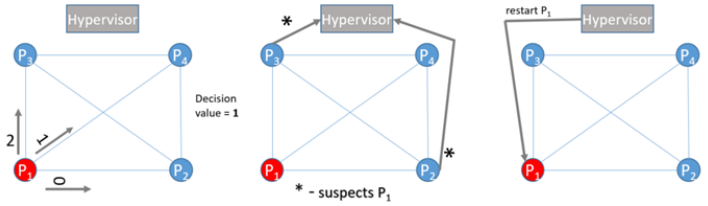

Figure 3: P_1 sends different values such that P_2, P_3 suspect P_1, and P_1 restarted by the hypervisor.

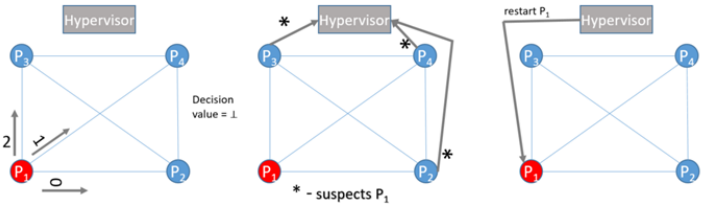

Figure 4: P_1 sends different values such that there is no agreement, and P_1 restarted by the hypervisor.

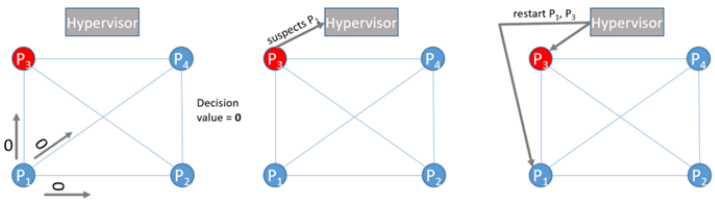

Figure 5: P_1 non-faulty, but incriminated by P_3. Both restarted by the hypervisor.

B.2 Local Hypervisors.

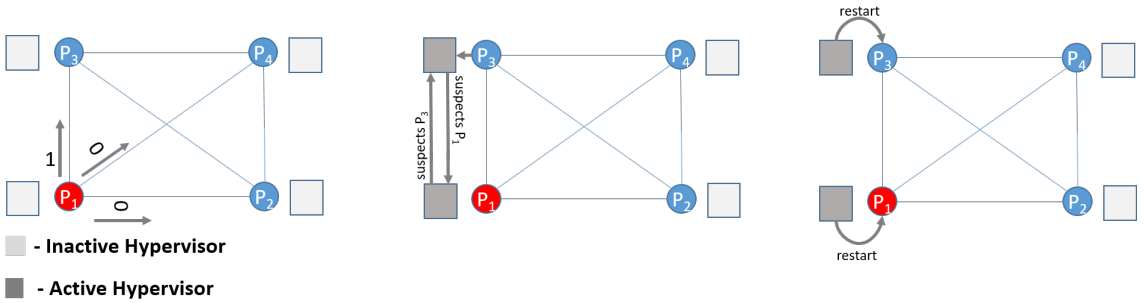

Figure 6: P_1 sends wrong value to P_3. P_3 suspects P_1 and both restarted by their local hypervisors.

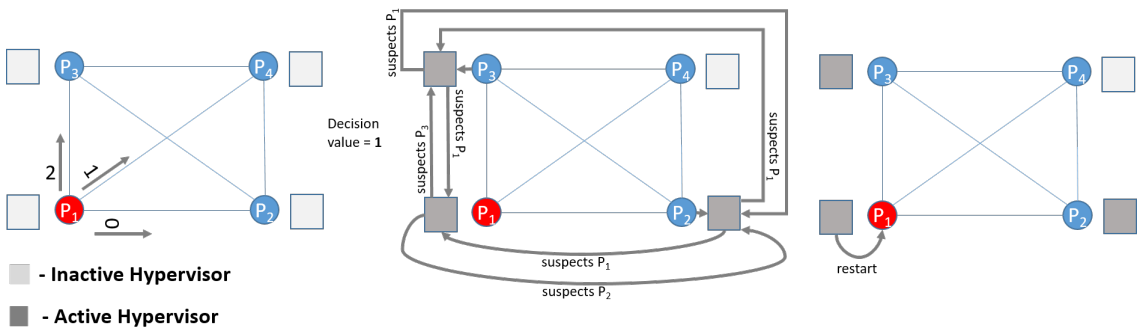

Figure 7: P_1 sends different values such that P_2, P_3 suspect P_1, and P_1 restarted by its local hypervisor.

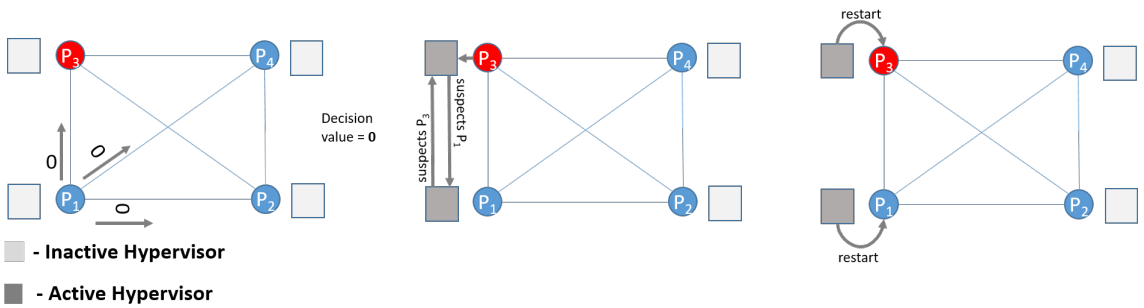

Figure 8: P_1 non-faulty, but incriminated by P_3. Both restarted by their local hypervisors.