

# Parallel Consensus is Harder than Set Agreement in Message Passing\*

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## Abstract

In the traditional consensus task, processes are required to agree on a common value chosen among the initial values of the participating processes. It is well known that consensus cannot be solved in crash-prone, asynchronous distributed systems. Two generalizations of the consensus tasks have been introduced:  $k$ -set agreement and  $k$ -parallel consensus.

The  $k$ -set agreement task has the same requirements as consensus except that processes are allowed to decide up to  $k$  distinct values. In the  $k$ -parallel consensus task, each process participates simultaneously in  $k$  instances of consensus and is required to decide in at least one of them; any two processes deciding in the same instance must decide the same value.

It is known that both tasks are equivalent in the wait-free shared memory model. Perhaps surprisingly, this paper shows that this is no longer the case in the  $n$ -process asynchronous message passing model with at most  $t$  process crashes. Specifically, the paper establishes that for parameters  $t, n, k$  such that  $t > \frac{n+k-2}{2}$ ,  $k$ -parallel consensus is strictly harder than  $k$ -set agreement.

The proof compares the information on failures necessary to solve each task in the failure detector framework and relies on a result in topological combinatorics, namely, the chromatic number of Kneser graphs. The paper also introduces the new failure detector class  $V\Sigma_k$ , which is a generalization of the quorum failures detector class  $\Sigma$  suited to  $k$ -parallel consensus.

## 1 Introduction

**The  $k$ -set agreement problem:** The  $k$ -set agreement problem (Chaudhuri, [1]) is one of the fundamental problems in fault tolerant distributed computing. Each process proposes a value and every non-faulty process is required to decide a value (termination) such that every decided value has been proposed (validity) and no more than  $k$  distinct values are decided (agreement). The problem generalizes the consensus problem, which corresponds to the case where  $k = 1$ . In asynchronous systems, it is well known that 1-set agreement is impossible as soon as at least one process may fail by crashing [2], whereas the case  $k = n$  does not require any coordination at all. For intermediate values of  $k$  ( $1 < k < n$ ), asynchronous  $k$ -set agreement tolerating  $t$  process crash failures is possible if and only if  $k > t$  [3, 4, 5], in shared memory or message-passing systems.

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\*This work was supported in part by the DIGITEO project PACTOLE and by the ANR project DISPLEXITY.

**The  $k$ -parallel consensus problem:** The  $k$ -parallel consensus problem [6]<sup>1</sup> is another generalization of consensus. Each process proposes a value and is required to decide a pair  $(c, v)$ , where  $c$  is an integer  $1 \leq c \leq k$  and  $v$  is a proposed value (validity). Each non-faulty process has to decide (termination) and, for any two pairs with the same first component, the second component must be the same, i.e., for any decided pairs  $(c, v), (c', v'), c = c' \implies v = v'$  (agreement). Intuitively, processes are trying to solve simultaneously  $k$  instances of the consensus problem in such a way that each process decides in at least one instance. For any instance, decisions occurring in that instance must be consistent with the validity and agreement requirements of consensus. A decided pair  $(c, v)$  may thus be interpreted as follows: value  $v$  is decided in the  $c$ th instance of consensus.

While  $k$ -set agreement weakens the safety property of consensus by allowing  $k$  values to be decided,  $k$ -parallel consensus may be thought as weakening its liveness property by considering  $k$  instances in parallel, and allowing some instances to remain undecided. Practically, parallel consensus might be useful in situations where processes participate concurrently in  $k$  different applications: a  $k$ -parallel consensus protocol can guarantee progress in at least one application [9, 10].

**Failure detectors:** A failure detector is a distributed oracle that provides processes with possibly unreliable information on failures [11]. According to the quality of the information, several classes of failure detectors can be defined and may be used to solve otherwise impossible problems. For example, an eventual leadership failure detector  $(\Omega, [12])$  provides the processes with an id which is eventually 1) the same at each process and, 2) the id of a non-faulty process. Whereas  $k$ -set agreement cannot be solved in asynchronous message passing systems in which at most  $t$  processes may fail if  $k \leq t$ , [13] presents an asynchronous  $\Omega$ -based  $k$ -set agreement protocol that tolerates up to  $t$  process failures, for any  $t, k \leq t < \frac{kn}{k+1}$ .

A failure detector  $D$  is *necessary* for solving a distributed problem  $P$  if given any failure detector  $D'$  that can be used to solve  $P$ , it is possible to emulate  $D$ . It has been shown that a failure detector called  $\Sigma_k$  is necessary for  $k$ -set agreement in message passing systems [14].

**$k$ -set agreement vs.  $k$ -parallel consensus:** The paper investigates the relative hardness of  $k$ -set agreement and  $k$ -parallel consensus in  $n$ -process asynchronous messages passing systems with crash failures. Let  $t < n$  denote the bound on the number of failures.

Clearly, if a protocol for  $k$ -parallel consensus is provided, one can solve  $k$ -set agreement. A fundamental result in [6] is that the converse is true in asynchronous shared memory system. That is, both problems are computationally *equivalent* in shared memory: given any wait-free<sup>2</sup> protocol for  $k$ -set agreement (respectively, for  $k$ -parallel consensus), one can construct a wait-free protocol for  $k$ -parallel (respectively, for  $k$ -set agreement).

The equivalence has been instrumental in determining the weakest failure detector for  $k$ -set agreement in asynchronous shared memory systems [15, 16], a question which is still unsolved for message passing systems. In addition, while many  $k$ -set agreement protocols for messages passing systems with various synchrony assumptions or augmented with failure detectors have been proposed, e.g., [17, 18, 13, 19, 20, 21, 22], to the best of our knowledge no specific protocol is known for  $k$ -parallel consensus. A first step to remedy this situation will consist in a generic

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<sup>1</sup>In this paper,  $k$ -parallel consensus problem is called  $k$ -simultaneous consensus. However, there is a body of work on simultaneous consensus, e.g. [7, 8], in which simultaneity refers to when agreement is reached. We use the terminology  $k$ -parallel consensus to avoid confusion.

<sup>2</sup>A wait-free protocol tolerates any number of crash failures.

transformation for turning any  $k$ -set agreement protocol into a  $k$ -parallel consensus protocol, if such a transformation exists.

The equivalence extends to asynchronous process message passing systems when a majority of processes are non-faulty (i.e.,  $t < \frac{n}{2}$ ), as in this case shared memory can be emulated  $t$ -resiliently [23]. The question addressed in this paper is whether the equivalence between the two problems extends beyond the majority threshold. Our main result is that the answer is “no”: we show that if  $t > \frac{n+k-2}{2}$ ,  $k$ -parallel consensus is *strictly harder* than  $k$ -set agreement in an asynchronous  $n$ -process messages passing systems in which at most  $t$  processes can fail by crashing.

**Contributions of the paper:** We study both problems through the lens of the *amount of information on failures* required to solve them. This is usually captured in the framework of failure detectors. On one hand, it is known that failure detector  $(\Sigma_k \times \Omega)$  is sufficient for  $k$ -set agreement [13]. On the other hand, we identify a new class of failure detectors, namely  $V\Sigma_k$ , and show that it is necessary for  $k$ -parallel consensus (Section 4). The question of whether  $k$ -parallel consensus can be solved  $t$ -resiliently using a  $k$ -set agreement protocol thus boils down to whether  $V\Sigma_k$  can be emulated  $t$ -resiliently from  $\Sigma_k \times \Omega$  (Section 6). If  $t$  is small enough, namely  $t < \frac{kn}{k+1}$ ,  $\Sigma_k$  can be emulated  $t$ -resiliently without relying on any failure detector. In this case, it is enough to study for which values of  $t$  failure detector  $V\Sigma_k$  can be implemented  $t$ -resiliently (Section 5). It is shown that  $\frac{n-k+2}{2}$  is a tight threshold. Interestingly, the proof relies on the chromatic number of a certain class of graphs, namely Kneser graphs. Finally, Section 7 presents our main impossibility results, obtained by assembling the various pieces from the previous sections.

Table 1 summarizes the main contributions of the paper.  $k$ -SA and  $k$ -PC are shorthands for  $k$ -set agreement and  $k$ -parallel consensus respectively.  $\mathcal{MP}_{n,t}$  denotes a message passing system made of  $n$  processes,  $t$  of which may crash.  $\mathcal{MP}_{n,t}[\Omega]$  stands for system  $\mathcal{MP}_{n,t}$  equipped with a failure detector  $\Omega$ .  $X \simeq X'$ ,  $X \prec X'$ ,  $X \preceq X'$  mean respectively that  $X$  and  $X'$  implements each other,  $X'$  implements  $X$  but  $X'$  does not implement  $X$ ,  $X'$  implements  $X$ . See Section 2 for more details about the notations.

$t$	0	$\frac{n}{2}$	$\frac{n+k-2}{2}$	$\frac{kn}{k+1}$	$n$	
$\mathcal{MP}_{n,t}$	$\Sigma_k$ implementable			$\Sigma_k$ not implementable		[14], Section 5
	$V\Sigma_k$ implementable			$V\Sigma_k$ not implementable		Section 5
	$\Sigma_k \simeq V\Sigma_k$			$\Sigma_k \prec V\Sigma_k$		Section 6
	$k$ -SA $\simeq$ $k$ -PC		$k$ -SA $\preceq$ $k$ -PC	$k$ -SA $\prec$ $k$ -PC		[6], Section 7
$\mathcal{MP}_{n,t}[\Omega]$	$k$ -PC solvable			$k$ -PC not solvable		Section 7
	$k$ -SA solvable			$k$ -SA not solvable		[13]

Table 1: Contributions of the paper.

## 2 Preliminaries

**Message passing asynchronous distributed system:** We consider a distributed system made of a set  $\Pi$  of  $n$  asynchronous processes  $\{p_1, \dots, p_n\}$ . Each process runs at its own speed, independently of the other processes.

Processes communicate by sending and receiving messages over a reliable but asynchronous network. Each pair of processes  $\{p_i, p_j\}$  is connected by a bi-directional channel. Channels are

reliable and asynchronous, meaning that each message sent by  $p_i$  to  $p_j$  is received by  $p_j$  after some finite, but unknown, time; there is no global upper bound on message transfer delays.

The system is equipped with a global clock whose ticks range  $\mathbb{T}$  is the set of positive integers. This clock is not available to the processes, it is used from an external point of view to state and prove properties about executions.

**Failures:** Processes may fail by *crashing*. A process that crashes prematurely halts and never recovers. In an execution, a process is *faulty* if it fails and *correct* otherwise. A *failure pattern* is a function  $\mathcal{F}$  from  $\mathbb{T}$  to  $\Pi$  where  $\mathcal{F}(\tau)$  is the set of processes that have failed by time  $\tau$ . We define  $Correct(\mathcal{F})$  and  $Faulty(\mathcal{F}) = \Pi \setminus Correct(\mathcal{F})$  to be the set of correct processes and the set of faulty processes according to  $\mathcal{F}$ , respectively. When  $\mathcal{F}$  is clear from the context, we simply write *Faulty* and *Correct* instead of  $Faulty(\mathcal{F})$  and  $Correct(\mathcal{F})$  respectively.

An *environment* (or *adversary* [24]) is a set of failure patterns. The *wait-free* environment consists in all failure patterns in which at least one process is correct. For  $1 \leq t \leq n - 1$ , the *t-resilient* environment contains every failure pattern in which no more than  $t$  processes are faulty (the  $(n - 1)$ -resilient environment is the wait-free environment).

**Failure detectors:** Informally, a failure detector [11] is a distributed oracle that provides (perhaps inaccurate) hints on the current failure pattern of the execution. Operationally, a failure detector provides at each process  $p_i$  a read-only variable  $FD_i$ , whose value at time  $\tau$  is denoted  $FD_i^\tau$ . This value is the output of the failure detector for process  $p$  at time  $\tau$ .

We recall next the main features of the framework in which failure detectors are defined, as introduced in [11]. A *failure detector history*  $H$  with range  $\mathcal{R}$  is a function  $H : \Pi \times \mathbb{T} \rightarrow \mathcal{R}$ .  $H(p_i, \tau)$  may be seen as the output of the local failure detector module of process  $p_i$  at time  $\tau$ . A *failure detector*  $D$  with range  $\mathcal{R}_D$  is a function that maps each failure pattern to set of failure detector histories with range  $\mathcal{R}_D$ . Given a failure pattern  $\mathcal{F}$ ,  $D(\mathcal{F})$  denotes the set of failure detector histories allowed by  $D$  when the failure pattern is  $\mathcal{F}$ .

For example, the range of the *quorum failure detector*  $\Sigma$ , defined in [25] is  $2^\Pi$ , the set of all subsets of  $\Pi$ .  $H : \Pi \times \mathbb{T} \rightarrow 2^\Pi \in \Sigma(\mathcal{F})$  iff  $\forall \tau, \tau' \in \mathbb{T}, \forall p_i, p_j \in \Pi : H(p_i, \tau) \cap H(p_j, \tau') \neq \emptyset$  and  $\exists \tau_c \in \mathbb{T} : \forall p_i \in Correct(\mathcal{F}), \forall \tau \geq \tau_c, H(p_i, \tau) \subseteq Correct(\mathcal{F})$ . That is, any two sets output by the failure detector intersect and eventually, for every correct process, the output of  $\Sigma$  contains only correct processes.

**Comparing failure detectors:** Let  $D1, D2$  denote two failure detectors. Failure detector  $D1$  is *weaker than*  $D2$  in environment  $\mathcal{E}$ , denoted  $D1 \preceq D2$ , if there exists a distributed algorithm  $\mathcal{T}_{D2 \rightarrow D1}$  that uses  $D2$  to emulate the output of  $D1$ . More specifically, algorithm  $\mathcal{T}_{D2 \rightarrow D1}$  maintains at each process  $p_i$  a variable  $OUT_{D1}$  intended to emulate the output of  $D1$  at  $p_i$ ; The variable can be used at each process to replace the actual output of  $D1$ : in any execution,  $p_i$  cannot distinguish between reading the variable  $OUT_{D1}$  or querying the failure detector  $D1$ . If  $D1$  is weaker than  $D2$  and  $D2$  weaker than  $D1$  in environment  $\mathcal{E}$ ,  $D1$  and  $D2$  are said to be *equivalent* in  $\mathcal{E}$  (denoted  $D1 \simeq D2$ ). On the contrary, if  $D2$  is not weaker than  $D1$ ,  $D1$  is *strictly weaker* than  $D2$  (denoted  $D1 \prec D2$ ).

Given a distributed task  $T$ , such as consensus, failure detector  $D$  is a *weakest failure detector* for  $T$  in environment  $\mathcal{E}$  if (1) there exists an algorithm  $\mathcal{A}_D$  for  $T$  in  $\mathcal{E}$  that uses  $D$  and (2) for every failure detector  $D'$  that can be used to solve  $T$  in  $\mathcal{E}$ , there exists an algorithm  $\mathcal{T}_{D' \rightarrow D}$  that uses  $D'$  to emulate  $D$ . Note that if  $D1$  and  $D2$  are weakest failure detectors for  $T$ , then  $D1 \simeq D2$ .

**Comparing tasks:** Given two distributed tasks  $T1$  and  $T2$  defined for  $n$  processes, task  $T1$

implements task  $T2$  in environment  $\mathcal{E}$  if, given a protocol for  $T1$ , one can construct a protocol for  $T2$  in  $\mathcal{E}$  by interleaving steps of a message passing protocol with calls to any number of instances of the protocol for  $T1$ . The protocol for  $T1$  is a “black-box”: it is only required that it solves  $T1$  in  $\mathcal{E}$ . We say that  $T1$  is *harder* than  $T2$  in  $\mathcal{E}$  if  $T1$  implements  $T2$  whereas  $T2$  does not implement  $T1$ .

**Notations:** Given  $var_i$  a local variable of process  $p_i$ , we denote by  $var_i^\tau$  its value at time  $\tau$ .  $\mathcal{MP}_{n,t}$  denotes a  $n$ -process asynchronous message passing system in which at most  $t$  processes may fail.  $\mathcal{MP}_{n,t}[D]$  denote the same system equipped with a failure detector of the class  $D$ . Given two failure detectors  $D, D'$  with ranges  $R_D$  and  $R_{D'}$  respectively,  $D \times D'$  denote the failure detector with range  $R_D \times R_{D'}$  and histories  $D(\mathcal{F}) \times D'(\mathcal{F})$  for any failure pattern  $\mathcal{F}$ .

### 3 The failure detectors $\Sigma_k$ , $V\Sigma_k$ and $\Omega$

This section recalls the definition of the failure detector classes  $\Sigma_k$ ,  $\Omega$  and introduces the new class  $V\Sigma_k$ . For each process  $p_i$ ,  $FD_i^\tau$  denotes the value output by the failure detector at time  $\tau$ .

**The family  $\{\Sigma_k\}_{1 \leq k \leq n}$**  A failure detector of the class  $\Sigma_k$  maintains at each process a variable  $QUORUM_i$  that contains at any time a set of process ids. The sets output, called *quorums*, satisfy the following properties:

- *Intersection.* Any set containing at least  $k + 1$  quorums has two intersecting quorums. Formally, let  $Q$  be the set of *all* quorums output at all the processes at all times. That is,  $Q = \{B \mid \exists p_i \in \Pi, \exists \tau \in \mathbb{T} : QUORUM_i^\tau = B\}$ . Then, for every  $X \subseteq Q$  with  $|X| > k : \exists B, B' \in X : B \cap B' \neq \emptyset$ .
- *Liveness.* Eventually, for each correct process, every quorum contains only correct processes ids. That is,  $\exists \tau \in \mathbb{T} : \forall p_i \in Correct, \forall \tau' \geq \tau : quorum_i^{\tau'} \subseteq Correct$

$\Sigma_k$  was introduced in [14] where it is shown to be necessary to solve  $k$ -set agreement in message passing systems. A  $(\Sigma_k \times \Omega)$ -based protocol tolerating any number of process crashes that solves  $k$ -set agreement is presented in [13]. The class  $\Sigma_1$  is the same as  $\Sigma$ , the weakest failure detector to implement a register in crash-prone message passing systems [25].

**The eventual leader failure detector  $\Omega$**  A failure detector of the class  $\Omega$  maintains at each process  $p_i$  a variable  $LEADER_i$  that contains a process id. It satisfies the following property:

- *Eventual leadership.* Eventually, for every correct process  $p_i$ ,  $LEADER_i$  contains forever the same identity of a correct process. That is,  $\exists p_\ell \in Correct, \exists \tau \in \mathbb{T} : \forall \tau' \geq \tau, \forall p_i \in Correct, LEADER_i^{\tau'} = \ell$ .

$(\Omega \times \Sigma)$  is the weakest failure detector for consensus in message passing systems in any environment [12, 25].

**The family  $\{V\Sigma_k\}_{1 \leq k \leq n}$**  The failure detector  $V\Sigma_k$  (read Vector- $\Sigma_k$ ) outputs at each process  $p_i$  an array  $QUORUMS_i$  of size  $k$ . At any time, each component  $QUORUMS_i[c]$ ,  $1 \leq c \leq k$  of the array contains a set of process ids (a quorum). Intuitively, a failure detector  $V\Sigma_k$  may be seen as  $k$  instances of a failure detector of the class  $\Sigma$ . In each instance, the intersection property of the

class  $\Sigma$  is satisfied, whereas the liveness property may not hold. It is only required that liveness is satisfied in at least one instance. Formally:

- *Intersection.* Any two quorums output in the same entry  $c$  at the same process or at distinct processes intersect. That is,  $\forall c, 1 \leq c \leq k, \forall \tau, \tau' \in \mathbb{T}, \forall p_i, p_{i'} \in \Pi : \text{QUORUMS}_i^\tau[c] \cap \text{QUORUMS}_{i'}^{\tau'}[c] \neq \emptyset$ .
- *Liveness.* There exists some entry  $c$  such that, eventually, every quorum output in this entry at any correct process contains only correct processes. That is,  $\exists \tau \in \mathbb{T}, \exists c, 1 \leq c \leq k : \forall p_i \in \text{Correct}, \forall \tau' \geq \tau, \text{QUORUMS}_i^{\tau'}[c] \subseteq \text{Correct}$ .

## 4 Necessity of $V\Sigma_k$ for $k$ -parallel consensus

This section shows that failure detector  $V\Sigma_k$  is necessary for solving  $k$ -parallel consensus. That is, failure detector  $\mathcal{D}$  can be used to solve  $k$ -parallel consensus, then  $V\Sigma_k$  can be emulated using  $\mathcal{D}$ .

**Theorem 4.1.** *For all  $t, k, 1 \leq t, k \leq n$ , for any protocol  $\mathcal{A}$  and any failure detector  $\mathcal{D}$ , if  $\mathcal{A}$  solves  $k$ -parallel consensus in  $\mathcal{MP}_{n,t}[\mathcal{D}]$  then  $V\Sigma_k \preceq \mathcal{D}$ .*

The strategy of the proof is similar to the one in [14]. There, it is shown that failure detector  $\Sigma_k$  is necessary to solve  $k$ -set agreement in message passing systems. The proof is simple and elegant, and, as we are about to see, can be generalized to the case of  $k$ -parallel consensus.

A protocol that emulates a failure detector  $V\Sigma_k$  is described in Figure 1. Recall that we are given an algorithm  $\mathcal{A}$  and a failure detector  $\mathcal{D}$  such that  $\mathcal{A}$  solves  $k$ -parallel consensus in  $\mathcal{MP}_{n,t}[\mathcal{D}]$ . We assign for each set  $S \in 2^\Pi$  an instance of  $\mathcal{A}$  denoted  $\mathcal{A}^S$ . Each process  $p_i$  participates in instance  $\mathcal{A}^S$  only if  $p_i \in S$ . The value proposed by  $p_i$  in this instance is  $\langle S, i \rangle$ . In more details, algorithm  $\mathcal{A}$  consists in  $n$  automata  $\mathcal{A}_1, \dots, \mathcal{A}_n$ , one per process. Process  $p_i$  starts  $2^{n-1}$  copies of  $\mathcal{A}_i$ , one copy, denoted  $\mathcal{A}_i^S$ , for each set  $S \in 2^\Pi : i \in S$ . The proposal of  $p_i$  in  $\mathcal{A}_i^S$  is  $\langle S, i \rangle$  and each message sent by  $\mathcal{A}_i^S$  is tagged for the purpose of not confusing messages sent in different instances of  $\mathcal{A}$ . When a receive step is performed in  $\mathcal{A}_i^S$ , a message with tag  $S$  (if any) is selected from  $p_i$ 's input message buffer and delivered to the automata. Failure detector queries are performed normally: when a failure detector value is needed by  $\mathcal{A}_i^S$ , the local failure detector module of  $p_i$  is queried.  $p_i$  performs steps of each automata  $\mathcal{A}_i^S, i \in S$  in any fair way, for example in a round-robin fashion.

The output of the failure detector  $V\Sigma_k$  at process  $p_i$  consists in a  $k$ -component array  $\text{OUT}_i$ . Process  $p_i$  maintains in addition a  $k$ -component array of sets denoted  $Q_i$ . If  $p_i$  decides  $(c, d)$  in instance  $\mathcal{A}^S$ , set  $S$  is added to the  $c$ th component of  $Q_i[c]$ .

For each  $c, 1 \leq c \leq k$ ,  $p_i$  periodically strives to assign to the  $c$ th component of  $\text{OUT}_i$  a set  $S \in Q_i[c]$  that contains only correct process (if  $Q_i[c]$  contains such a set). To that end, each process periodically broadcasts HEARTBEAT messages (task T2). HEARTBEATS are used to rank processes id. Process  $p_i$  maintains an ordered list  $\text{order}_i$  of processes ids. Each time a HEARTBEAT from process  $p_j$  is received,  $j$  is moved at the beginning of the list (Task T3). As each faulty process sends finitely many HEARTBEATS, there exists a time after which each correct process id appears before any faulty process id. Therefore, given two sets  $S, S'$  of process,  $S \subseteq \text{Correct}$  and  $S' \not\subseteq \text{Correct}$ , the largest rank of the ids of the processes in  $S$  is eventually always smaller than the largest rank of the ids in  $S'$ . When  $p_i$  updates  $\text{OUT}_i[c]$ , it selects a set  $S$  that has the smallest largest rank of its ids among the sets currently in  $Q_i[c]$  output by  $V\Sigma_k$  (lines 5–7). If  $Q_i[c]$  contains a set of correct processes, this guarantees that eventually  $\text{OUT}_i[c] \subseteq \text{Correct}$ .

Process  $p_i$  may not decide in every instance  $\mathcal{A}^S$  in which it participate, as it may wait forever for messages from some process  $p_j, j \notin S$ . However, for any  $S$  such that  $Correct \subseteq S$ , every correct process that participates in  $\mathcal{A}^S$ , must eventually decide since  $\mathcal{A}$  correctly solves  $k$ -parallel consensus. Hence, some component  $c_i$  of  $Q_i$  eventually contains a set of correct processes, and therefore,  $OUT_i[c_i]$  is eventually a subset of the correct processes. Moreover, the protocol ensures that when a set  $S$  is added to  $Q_i[c_i]$ , it is eventually added to the  $c_i$ th component of every  $Q_j$ , for every correct process  $p_j$  (tasks T1 and T4). It thus follows that eventually at each correct process  $p_j$ ,  $OUT_j[c] \subseteq Correct$  for some  $c, 1 \leq c \leq k$ , thereby ensuring the liveness property of the class  $V\Sigma_k$ .

For the intersection property of the class  $V\Sigma_k$ , it remains to see that for any two sets  $S, S'$  assigned to the  $c$ th component of the emulated failure detector output, perhaps at different processes,  $S \cap S' \neq \emptyset$ , for any  $c, 1 \leq c \leq k$ . Note that  $S, S'$  are assigned to the  $c$ th component of the emulated failure detector only if  $(c, d)$  and  $(c, d')$  are decided in instances  $\mathcal{A}^S$  and  $\mathcal{A}^{S'}$  respectively.

Let  $S, S'$  be two disjoint subsets of  $\Pi$ . Suppose that processes  $p \in S$  and  $p' \in S'$  decide the pairs  $(c, d)$  and  $(c', d')$  in  $\mathcal{A}^S$  and  $\mathcal{A}^{S'}$  respectively. We demonstrate that, in this case,  $c \neq c'$ . First, as any value proposed in  $\mathcal{A}^S$  (respectively, in  $\mathcal{A}^{S'}$ ) is of the form  $\langle S, j \rangle$  (respectively,  $\langle S', j \rangle$ ), where  $p_j \in S$  (respectively,  $p_j \in S'$ )  $d \neq d'$  by the validity of property of  $k$ -parallel consensus. Second, because  $S' \cap S = \emptyset$ , prefixes of the executions of  $\mathcal{A}^S$  and  $\mathcal{A}^{S'}$  can be “merged” in a single execution of  $\mathcal{A}$  in which the set of participating processes is  $S \cup S'$ . That is, there exists a single execution  $\alpha$  of  $\mathcal{A}$  that is indistinguishable from the execution of  $\mathcal{A}^S$  (respectively, of  $\mathcal{A}^{S'}$ ) for  $p$  (respectively, for  $p'$ ).  $p$  and  $p'$  thus decide respectively  $(c, d)$  and  $(c', d')$  in  $\alpha$ . As  $d \neq d'$ , it thus follows that  $c' \neq c$ .

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init  $Q_i[1..k] \leftarrow [\{\Pi\}, \dots, \{\Pi\}]$ ; /* array of set of sets */
       $order_i \leftarrow (1, \dots, n)$ ; /* ordered list of processes ids */
       $OUT[1..k] \leftarrow [\Pi, \dots, \Pi]$ ; /*  $V\Sigma_k$  output */
for each  $S \in 2^\Pi : i \in S$  do
  launch an instance  $\mathcal{A}_i^S$  of  $\mathcal{A}_i$  with input  $\langle S, i \rangle$  enddo
  /* instances run in parallel independently */
  start tasks T1,T2,T3,T4

task T1: when  $p_i$  decides in  $\mathcal{A}_i^S$ :
(1) let  $(c, d)$  be the decision of  $p_i$ ;  $Q_i[c] \leftarrow Q_i[c] \cup \{S\}$ ;
(2) send  $(c, S)$  to all /*  $d = \langle S, j \rangle$  for some  $j \in S$  */

task T2: repeat periodically
(3) send HEARTBEAT( $i$ ) to all

task T3: when HEARTBEAT( $j$ ) is received:
(4) move  $j$  at the head of the list  $order_i$ 
(5) for each  $c : 1 \leq c \leq k$  do  $OUT_i[c] \leftarrow E$ 
(6)   where  $E \in Q_i[c]$  and  $\forall S \in Q_i[c]$ ,
(7)    $\max_{j \in E} rank(j, order_i) \leq \max_{j \in S} rank(j, order_i)$ 
/*  $rank(j, order_i)$ : rank of  $j$  in the ordered list  $order_i$  */

task T4: when  $(c, S)$  is received:
(8)  $Q_i[c] \leftarrow Q_i[c] \cup \{S\}$ ;

```

Figure 1: Emulation of  $V\Sigma_k$  from an algorithm  $\mathcal{A}$  that uses a failure detector  $\mathcal{D}$  to solve  $k$ -parallel consensus (code for  $p_i$ )

**Proof:** The proof is essentially the same as the proof of Bonnet and Raynal [14]. In order for the paper to be self-contained, a complete proof is provided next.

If  $var_i$  a variable local to process  $p_i$ , let  $var_i^\tau$  denote the value of the variable at time  $\tau$ . We consider an arbitrary infinite execution  $\alpha$  of the protocol described in Figure 1. For each process  $p_i$ , the output of the emulated failure detector  $V\Sigma_k$  is stored in the array  $OUT_i$ ;  $OUT_i^\tau[c]$  thus denotes the  $c$ th quorum output at process  $p_i$  by the emulated failure detector at time  $\tau$ , for any  $c, 1 \leq c \leq k$ , and any  $p_i \in \Pi$ . The proof is divided in two parts. We first establish that the protocol ensures the Liveness property of the class  $V\Sigma_k$  (Lemma 4.2) and then show that the Intersection property is also ensured (Lemma 4.3). The correctness of the emulation then immediately follows (Theorem 4.1).

**Lemma 4.2** (Liveness). *For each correct process  $p_i$ , there exists a time  $\tau_i$  and  $\ell_i, 1 \leq \ell_i \leq k$ :  $\forall \tau \geq \tau_i, OUT_i^\tau[\ell_i] \subseteq Correct$ .*

*Proof.* Let  $p_i$  denote a correct process in  $\alpha$ . Recall that  $\mathcal{A}$  is an asynchronous algorithm that solves the  $k$ -parallel consensus problem in  $\mathcal{MP}_{n,t}[\mathcal{D}]$ . This implies that every correct process eventually decides in every instance  $\mathcal{A}^S$ , where  $Correct \subseteq S$ . In particular,  $p_i$  decides in the instance  $\mathcal{A}^{Correct}$ . Let  $(\ell_i, v_i)$  be the pair eventually decided by  $p_i$  in this instance. It thus follows from the protocol (task T1), that, after some time  $\tau_1$ ,  $Correct \in Q_i[\ell_i]$ .

If no set containing faulty process is ever inserted in  $Q_i[\ell_i]$ , then  $OUT_i^\tau[\ell_i]$  is a set of the correct processes in  $\alpha$ , for any time  $\tau$ . Otherwise, let  $S$  be any set containing a faulty process that is included in  $Q_i[\ell_i]$ . That is, after some time  $\tau_2$ , we have  $S \in Q_i^\tau[\ell_i]$ , for any  $\tau \geq \tau_2$ . Let  $p_f$  denote a faulty process in  $S$ .  $p_f$  sends finitely many HEARTBEAT messages to  $p_i$ . Therefore,  $p_f$  is moved finitely many times at the head of the list  $order_i$ . On the contrary,  $p_i$  receives infinitely many HEARTBEAT messages from each correct process, and thus each correct process is moved infinitely often at the head of the list  $order_i$ . It thus follows that after some time  $\tau_3$ , we always have

$$\max_{p_j \in Correct} rank(j, order_i) < \max_{p_j \in S} rank(j, order_i)$$

Hence, after time  $\max(\tau_1, \tau_2, \tau_3)$ , the set stored in  $OUT_i[\ell_i]$  cannot be  $S$  (lines 5–8, task T3). As this is true for any set  $S$  containing a faulty process,  $OUT_i[\ell_i]$  eventually always contain a set of correct processes.  $\square$

**Lemma 4.3.** *For any  $p_i, p_j$  pair of (not necessarily distinct) processes, for any times  $\tau, \tau'$ , for any  $c, 1 \leq c \leq k$ :  $OUT_i^\tau[c] \cap OUT_j^{\tau'}[c] \neq \emptyset$*

*Proof.* Let  $S, S'$  be the values of  $OUT_i[c]$  and  $OUT_j[c]$  at times  $\tau$  and  $\tau'$  respectively. Assume for contradiction that  $S \cap S' = \emptyset$ . Note that  $S, S' \neq \Pi$  and thus neither  $S$  nor  $S'$  are the initially values of  $OUT_i[c]$  and  $OUT_j[c]$  respectively. Therefore, by the code (Task T3),  $S$  must have been inserted in  $Q_i[c]$  by  $p_i$  and  $S'$  inserted in  $Q_j[c]$  by  $p_j$ . This implies that  $p_i$  has decided  $(c, v)$  in the instance  $\mathcal{A}^S$  and  $p_j$  has decided  $(c, v')$  in  $\mathcal{A}^{S'}$ , where  $v, v'$  are the  $c$ th entry of a vector proposed in  $\mathcal{A}^S$  and  $\mathcal{A}^{S'}$  respectively.

Any value proposed in  $\mathcal{A}^S$  has the form  $\langle S, \ell \rangle$ , where  $p_\ell \in S$ . Similarly, any value proposed in  $\mathcal{A}^{S'}$  has the form  $\langle S', \ell' \rangle$ , where  $p_{\ell'} \in S'$ . Hence, by the validity requirement of the  $k$ -parallel problem and the fact that  $S \neq S', v \neq v'$ .

We next construct an execution  $\beta$  of  $\mathcal{A}$  in which  $p_i$  decides  $(c, v)$  and  $p_j$  decides  $(c, v')$ . Since  $v \neq v'$ , this is a contradiction. Intuitively,  $\beta$  is obtained by merging steps of  $\mathcal{A}^S$  and  $\mathcal{A}^{S'}$  taken by the processes in  $S \cup S'$  in  $\alpha$  in a single execution.



More precisely, the failure pattern is the same in  $\beta$  and  $\alpha$ . The failure detector history of the underlying failure detector  $\mathcal{D}$  is also the same in  $\alpha$  and  $\beta$ . In  $\beta$ , only processes in  $S \cup S'$  take steps. Let  $\sigma$  (respectively,  $\sigma'$ ) be the sequence of steps taken by the processes in  $S$  (resp.  $S'$ ) while executing  $\mathcal{A}^S$  (resp.,  $\mathcal{A}^{S'}$ ) in  $\alpha$ . The sequence of steps  $\mu$  taken by the processes in  $S \cup S'$  in  $\beta$  is obtained by merging  $\sigma$  and  $\sigma'$  respecting the real order occurrence of the steps in  $\alpha$ . Note that  $\beta$  is a valid execution of  $\mathcal{A}$ , as the history of  $\mathcal{D}$  is the same in  $\alpha$  and  $\beta$ .

Since  $p_i$  (resp.,  $p_j$ ) takes the same steps in  $\beta$  and in the execution of  $\mathcal{A}^S$  (resp.,  $\mathcal{A}^{S'}$ ) in  $\alpha$ , it decides  $(c, v)$  (resp.,  $(c, v')$ ) in  $\beta$ . This is a contradiction as  $v \neq v'$  and  $\mathcal{A}$  solves the  $k$ -parallel problem in  $\mathcal{MP}_{n,t}[\mathcal{D}]$ .  $\square$

It thus follows from Lemma 4.2 and Lemma 4.3 that the protocol of Figure 1 emulates failure detector of the class  $V\Sigma_k$  given a protocol  $\mathcal{A}$  using a failure detector  $\mathcal{D}$  to solve  $k$ -parallel consensus.

## 5 $t$ -resilient protocols for $V\Sigma_k$ and $\Sigma_k$

This section investigates whether there is a  $t$ -resilient protocol for implementing a failure detector  $\Sigma_k$  or  $V\Sigma_k$ . For the class  $\Sigma_k$ , the answer is known [13]. For completeness, the result is recalled at the end of this section (Theorem 5.5).

For the class  $V\Sigma_k$ , we show that the existence of a protocol emulating a failure detector  $V\Sigma_k$  is strongly related to the chromatic number of a certain family of graphs, namely, Kneser graphs. We show that there exists a  $t$ -resilient protocol that emulates a failure detector  $V\Sigma_k$  if and only if the Kneser graph  $KG_{n,n-t}$  has a proper vertex  $k$ -coloring.

### 5.1 $t$ -resilient emulation of $V\Sigma_k$

This section is devoted to the proof of the following Theorem:

**Theorem 5.1.** *Let  $n, k, t$  be integers such that  $1 \leq t, k \leq n$ . There exists a protocol that emulates a failure detector of the class  $V\Sigma_k$  in  $\mathcal{MP}_{n,t}$  if and only if  $t \leq \frac{n+k-2}{2}$ .*

**Preliminaries:** A *coloring* of a graph is a labelling of the graph's vertices with colors drawn from the integers  $\{1, 2, 3, \dots\}$ . A coloring is called a  *$k$ -coloring* if it uses at most  $k$  colors and *proper* if no two adjacent vertices share the same color. The *chromatic number* of a graph  $G$ , denoted  $\chi(G)$ , is the smallest number of colors needed to properly color  $G$ , *i.e.* the smallest value of  $k$  for which a proper  $k$ -coloring of  $G$  is possible.

The *Kneser graph*  $KG_{n,k}$  is the undirected graph whose vertices are the subsets of  $k$  elements of a set of size  $n$ , and where two vertices share an edge whenever the two corresponding sets are disjoint. For example,  $KG_{n,1}$  is the complete graph, and  $KG_{5,2}$  is isomorphic to the Petersen graph. An important result about Kneser graphs is their chromatic number. The chromatic number  $\chi(KG_{n,k})$  of the Kneser graph is exactly  $n - 2k + 2$  if  $n \geq 2k$ , and 1 otherwise. This result was conjectured by Martin Kneser early in 1955 and proved for the first time by Lovász[26] in 1978. His proof was the first one using algebraic topology to solve a problem in combinatorics, giving rise to the field of topological combinatorics. Simpler proofs were later given by Bárány [27], Greene [28] and Matoušek [29].

Kneser graphs, and their chromatic number are central to show that it is impossible to emulate  $t$ -resiliently  $V\Sigma_k$  for certain values of  $n, k$  and  $t$ . We reduce the existence of a protocol that

emulates  $V\Sigma_k$  in  $\mathcal{MP}_{n,t}$  to the problem of whether  $k$  colors are sufficient to properly color  $KG_{n,n-t}$  (Lemma 5.2). Conversely, we show that if  $V\Sigma_k$  can be emulated in  $\mathcal{MP}_{n,t}$ , there is a  $k$ -coloring of  $KG_{n,n-t}$  (Lemma 5.3).

**A  $t$ -resilient protocol emulating  $V\Sigma_k$ :** A simple algorithm that emulates a failure detector of the class  $V\Sigma_k$  in  $\mathcal{MP}_{n,t}$  is described in Figure 2. The algorithm requires that  $t \leq \frac{n+k-2}{2}$ .

The algorithm relies on a  $k$ -coloring of the Kneser graph  $KG_{n,n-t}$ . As seen in the preliminaries, the chromatic number of  $KG_{n,n-t}$  is  $\chi(KG_{n,n-t}) = n - 2(n-t) + 2 = 2t - n + 2 \leq k$  if  $n \geq 2(n-t)$  and 1 otherwise. Therefore, for  $t \leq \frac{n+k-2}{2}$ , the graph  $KG_{n,n-t}$  can be properly colored with  $k$  colors.

The processes are initially provided with a function *color* that maps each subset of  $\Pi$  of size  $n-t$  to an integer in the range  $[1, k]$  such that any two disjoint sets are mapped to distinct integers. That is, *color* is a  $k$ -coloring of  $KG_{n,n-t}$ . Since the chromatic number of this graph is  $\chi(KG_{n,n-t}) = 2t - n + 2$  if  $n \geq 2(n-t)$  and 1 otherwise, the function *color* does exist as  $t \leq \frac{n+k-2}{2}$ .

Each process  $p_i$  maintains a vector of sets of processes  $\text{OUT}_i[1..k]$  intended to contain the output of the emulated failure detector  $V\Sigma_k$ . Each entry of  $\text{OUT}_i$  is initially equal to  $\Pi$ , the set of processes ids in the system. To ensure the liveness property of  $V\Sigma_k$ , i.e., the existence for each correct process  $p_i$  of an entry  $\ell_i$  such that eventually, the  $\ell_i$ th entry of  $\text{OUT}_i$  contains only correct processes ids, each process periodically broadcasts HEARTBEAT (line 1). When a HEARTBEAT is received from some process  $p_j$ , the identity of  $p_j$  is added to the local set  $Q_i$  (line 2). Whenever  $n-t$  distinct ids have been accumulated in  $Q_i$ , the output of  $V\Sigma_k$  is updated as follows. The current set  $S$  of ids in  $Q_i$  is assigned to the  $c$ th entry of  $\text{OUT}_i$ , where  $c$  is the color of  $S$  (line 3). Then  $p_i$  broadcasts  $Q_i$  together with its color  $c$  in a QUORUM message. Finally,  $Q_i$  is reset to the empty set. When a QUORUM( $Q_j, c$ ) message is received from  $p_j$ , the  $c$ th element of  $\text{OUT}_i$  is updated to  $Q_i$ .

Note that it thus follows that eventually, some entry of the output of  $V\Sigma_k$  at all processes contains only correct processes, as every faulty process eventually stops sending HEARTBEATs messages, and thus its id eventually stops occurring in  $Q_i$ . Moreover, using the map *color* to assign sets of  $(n-t)$  processes ids to entries of the vector  $\text{OUT}_i$  guarantees the intersection property of  $V\Sigma_k$ . Indeed, by definition of the map *color*, two sets are assigned to the same entry only if they intersect.

**Lemma 5.2.** *Let  $n, t, k$  be integers such that  $1 \leq t, k \leq n$  and  $t \leq \frac{n+k-2}{2}$ . The algorithm described in Figure 2 implements a failure detector  $V\Sigma_k$  in  $\mathcal{MP}_{n,t}$ .*

*Proof.* The proof is divided in two parts corresponding to the two properties of the class  $V\Sigma_k$ , namely liveness and intersection.

*Liveness.* Define  $\tau$  to be the time at which: (i) all faulty processes have already crashed, (ii) all messages sent by them have already been received by correct processes. There exists a time  $\tau' \geq \tau$  such that for every correct process  $p_i$ , the processes that are accumulated in  $Q_i$  at any time after  $\tau'$  are correct. This is because there are at least  $n-t$  correct processes, and each of them never stops sending HEARTBEAT messages (line 1). Let  $Q \subseteq \text{Correct}$  be any set of  $n-t$  ids accumulated by a given correct process  $p_\ell$  after  $\tau'$ , say at  $\tau_\ell$ . Let  $c$  denote  $\text{color}(Q)$ . Every process  $p_j \in \text{Correct} \setminus \{p_\ell\}$  will receive the message QUORUM( $c, Q$ ) from  $p_\ell$ , say at  $\tau_j$ . Hence for every  $p_i \in \text{Correct}$ ,  $\text{OUT}_i[c]$  contains  $Q$  at  $\tau_i$ . After  $\tau_i$ , since  $\tau_i \geq \tau'$ , whether  $\text{OUT}_i[c]$  is updated (as a result of accumulating a new set of ids by  $p_i$  or receiving a QUORUM message) or not, its value is necessarily a subset of  $\text{Correct}$ .

```

init  OUTi[1..k] ← [Π, …, Π]; /* output of VΣk */
        color : {S ⊆ Π : |S| = n - t} → {1, …, k};
                /* k-coloring of KGn,n-t */
        Qi ← ∅; /* set of processes ids, initially empty */
        start task T1,T2,T3

task T1: repeat periodically
(1) send HEARTBEAT(i) to all

task T2: when HEARTBEAT(j) is received:
(2) Qi ← Qi ∪ {j};
(3) if |Qi| = n - t then let c = color(Qi); OUTi[c] ← Qi;
(4)   send QUORUM(Qi, c) to all; Qi ← ∅ endif

task T3: when QUORUM(Q, c) is received:
(5) OUTi[c] ← Q

```

Figure 2: Emulation of  $V\Sigma_k$  in  $\mathcal{MP}_{n,t}$ ,  $t \leq \frac{n+k-2}{2}$  (code for  $p_i$ )

*Intersection.* Let  $\ell, 1 \leq \ell \leq k$  and let  $S_i, S_j$  be two sets of processes ids corresponding to the  $\ell$ th entry of the output of the emulated failure detector at some processes  $p_i$  and  $p_j$  (with  $p_i$  not necessarily distinct from  $p_j$ ). That is, at some time  $\tau_i$  (respectively,  $\tau_j$ ),  $\text{OUT}_i[\ell] = S_i$  (respectively,  $\text{OUT}_j[\ell] = S_j$ ). If  $S_i$  or  $S_j$  is equal to  $\Pi$ ,  $S_i \cap S_j \neq \emptyset$  as  $\text{OUT}_i[\ell]$  and  $\text{OUT}_j[\ell]$  always contain processes ids. Otherwise,  $S_i$  is the value of the variable  $Q_i$  at some time, and  $\ell$  is the color assigned to the set  $S_i$  by the map  $color$ . Similarly,  $color$  maps  $S_j$  to  $\ell$ . Since disjoint sets are mapped to distinct colors, it follows that  $S_i \cap S_j \neq \emptyset$ .  $\square$

**An impossibility result:** We now prove that the condition linking  $t, k$  and  $n$  of Lemma 5.2 is tight for the existence of a protocol that emulates  $V\Sigma_k$  in  $\mathcal{MP}_{n,t}$ :

**Lemma 5.3.** *Let  $n, t, k$  be integers such that  $1 \leq t, k \leq n$  and  $\frac{n+k-2}{2} < t$ . There is no algorithm that emulates a failure detector of the class  $V\Sigma_k$  in  $\mathcal{MP}_{n,t}$ .*

We actually prove this Lemma as a corollary of a slightly more general result:

**Lemma 5.4.** *Let  $n, t, k$  be integers such that  $1 \leq t, k \leq n$  and  $\frac{n+k-2}{2} < t$ . There is no algorithm that emulates a failure detector of the class  $V\Sigma_k$  in  $\mathcal{MP}_{n,t}[\Omega]$ .*

*Proof.* The proof is by contradiction. Assume that there exists an algorithm  $\mathcal{A}$  that implements a failure detector  $V\Sigma_k$  in  $\mathcal{MP}_{n,t}[\Omega]$  with  $\frac{n+k-2}{2} < t$ , i.e,  $k < 2t - n + 2$ . We show that we can use  $\mathcal{A}$  to properly color  $KG_{n,n-t}$  with  $k$  colors. This contradicts the fact that the chromatic number of  $KG_{n,n-t}$  is  $\chi(KG_{n,n-t}) = 2t - n + 2$  when  $t \geq \frac{n}{2}$  and 1 otherwise.

Let  $\mathcal{S} = S_1, \dots, S_u, u = \binom{n}{n-t}$  be an enumeration of all subsets of  $\Pi$  of size  $n-t$ . We construct an execution  $\alpha$  of  $\mathcal{A}$  from which we derive a proper  $k$ -coloring of  $KG_{n,n-t}$ . The construction proceeds inductively by forming longer and longer prefix  $\alpha_i$  of  $\alpha$ . At the end of  $\alpha_i$ , each set  $S_j, 1 \leq j \leq i$  has received a color  $c_j, 1 \leq c_j \leq k$  such that any two disjoint sets receive distinct colors.

*Base step.* Let  $\alpha'_1$  be an execution of  $\mathcal{A}$  in which the set of correct processes is  $S_1$ . Moreover, the faulty processes are initially crashed in  $\alpha'_1$ . At each process  $p_i \in S_1$ , the output of the failure

detector  $\Omega$  is the same process id  $\ell_1$ , where  $p_{\ell_1} \in S_1$ . Let  $p_j$  be a process in  $S_1$ . By the liveness property of  $V\Sigma_k$ , there exists a time  $\tau_1$  and an entry  $c_1$  such that, at time  $\tau_1$ , the  $c_1$ th entry of the failure detector output at process  $p_j$  is a set  $S \subseteq S_1$ . This is because  $S_1$  is the set of correct processes in  $\alpha'_1$  and eventually one entry of the vector output by  $V\Sigma_k$  at each correct process must contain only correct processes ids.

In execution  $\alpha_1$ , no process fails. However, processes in  $\Pi \setminus S_1$  do not take a step before time  $\tau_1$ . Moreover, execution  $\alpha_1$  and  $\alpha'_1$  are indistinguishable up to time  $\tau_1$  for every process in  $S_1$ . In particular, for every process in  $S_1$ , the output of  $\Omega$  until time  $\tau_1$  is  $\ell_1$ . Hence, as in execution  $\alpha'_1$ , process  $p_j \in S_1$  output at time  $\tau_1$  a vector whose  $c_1$ th entry is a set contained in  $S_1$ . We then let every process take enough steps for every message sent before  $\tau_1$  to be received. The color  $c_1$  is assigned to  $S_1$ .

*Induction step.* Suppose that the prefix  $\alpha_i$  has been constructed, for some  $i, 1 \leq i < u$ . We describe how to extend  $\alpha_i$  to form the prefix  $\alpha_{i+1}$ .

Let  $\alpha'_{i+1}$  be an execution of  $\mathcal{A}$  that extends  $\alpha_i$  and in which the set of correct processes is  $S_{i+1}$ . More precisely,  $\alpha_i$  is a prefix of  $\alpha'_{i+1}$  and every process in  $\Pi \setminus S_{i+1}$  fails immediately after  $\alpha_i$ . Processes in  $S_{i+1}$  then keep taking steps forever and, after  $\alpha_i$ , the output of  $\Omega$  at each process in  $S_{i+1}$  is the same id  $\ell_{i+1}$  for some process  $p_{\ell_{i+1}} \in S_{i+1}$ . The eventual leadership property of the class  $\Omega$  is thus satisfied. Let  $p_j$  be an arbitrary process in  $S_{i+1}$ . As in the base case, it follows from the liveness property of the class  $V\Sigma_k$  that there exists an entry  $c_{i+1}$  such that eventually the  $c_{i+1}$ th entry of the vector output by  $\mathcal{A}$  at  $p_j$  is included in  $S_{i+1}$ , which is the set of correct processes in that execution. Let  $\tau_{i+1}$  be a time following  $\alpha_i$  at which this occurs.

Execution  $\alpha_{i+1}$  and  $\alpha'_{i+1}$  are indistinguishable for every process in  $S_{i+1}$  up to time  $\tau_{i+1}$ . In particular, for every process in  $S_{i+1}$ , the output of  $\Omega$  is  $\ell_{i+1}$  after  $\alpha_i$  and until time  $\tau_{i+1}$ , and processes in  $\Pi \setminus S_{i+1}$  take no step after  $\alpha_i$  and until  $\tau_{i+1}$ . After  $\tau_{i+1}$ , we let each process takes enough step in order to every message sent before  $\tau_{i+1}$  to be received. As  $\alpha_{i+1}$  and  $\alpha'_{i+1}$  are indistinguishable for every process in  $S_{i+1}$ , the  $c_{i+1}$ th entry of the vector output by  $\mathcal{A}$  at process  $p_j$  at time  $\tau_{i+1}$  is the same as in  $\alpha'_{i+1}$ , that is a set included in  $S_{i+1}$ . We assign the color  $c_{i+1}$  to  $S_{i+1}$ .

*Final step.* Suppose we have constructed prefix  $\alpha_u$  as described above. Execution  $\alpha$  is an infinite execution with prefix  $\alpha_u$ . After  $\alpha_u$ , each process takes infinitely many steps, for example in round-robin fashion; the output of  $\Omega$  at each process is the same id of some arbitrary correct process. Every message sent is eventually received.

Note that execution  $\alpha$  is a valid execution of  $\mathcal{A}$  in  $\mathcal{MP}_{n,t}[\Omega]$  with no failure. In particular, note that since after prefix  $\alpha_u$ , the underlying failure detector outputs the same correct process id at every process, the failure detector history is a valid history for a failure detector of the class  $\Omega$ . The output of  $\mathcal{A}$  must therefore fulfill the properties of the class  $V\Sigma_k$ . We claim that the coloring of each  $S_i, 1 \leq i \leq u$  with  $c_i, 1 \leq i \leq u$ , as indicated in the construction is a proper  $k$ -coloring of  $KG_{n,n-t}$ .

Notice first that each  $c_i$  is an entry of the vector of size  $k$  output by  $\mathcal{A}$ , i.e.,  $1 \leq c_i \leq k$ . Finally, let  $S_i, S_j$  be two sets such that  $S_i \cap S_j = \emptyset$ . By construction, at time  $\tau_i$ , the  $c_i$ th entry of the vector output by  $\mathcal{A}$  at some process is a set  $s_i \subseteq S_i$ . Similarly, at time  $\tau_j$ , the  $c_j$ th entry of the vector output by  $\mathcal{A}$  at some process is a set  $s_j \subseteq S_j$ . As  $S_i \cap S_j = \emptyset$ , we have  $s_i \cap s_j = \emptyset$ . It thus follows from the intersection property of  $V\Sigma_k$  that  $c_i \neq c_j$ , as desired.

As  $1 \leq k$ , and  $\frac{n+k-2}{2} < t$ , it follows that  $2(n-t) \leq n$ . The chromatic number of  $KG_{n,n-t}$  is thus  $\chi(KG_{n,n-t}) = n - 2(n-t) + 2 = 2t - n + 2$ . This is a contradiction since we have  $k < 2t - n + 2$ .  $\square$

Lemma 5.3 is a consequence of Lemma 5.4, as any protocol emulating  $V\Sigma_k$  in  $\mathcal{MP}_{n,t}$  emulates  $V\Sigma_k$  in any system in which a failure detector is available. Theorem 5.1 then immediately follows from Lemma 5.2 and Lemma 5.3.

## 5.2 $t$ -resilient emulation of $\Sigma_k$

For completeness, we recall here the condition linking the parameters  $t, k$  and  $n$  under which there exists a  $t$ -resilient protocol emulating a failure detector  $\Sigma_k$ :

**Theorem 5.5** ([13]). *Let  $n, k, t$  be integers such that  $1 \leq t, k \leq n$ . There exists a protocol that emulates a failure detector  $\Sigma_k$  in  $\mathcal{MP}_{n,t}$  if and only if  $t < \frac{kn}{k+1}$ .*

*Proof.* The proof considers two cases, according to the value of  $t$ .

- $t < \frac{kn}{k+1}$ . A simple protocol to emulate a failure detector of the class  $\Sigma_k$  in  $\mathcal{MP}_{n,t}$  is as follows: Every process periodically broadcasts HEARTBEAT messages. Whenever a process has collected  $n - t$  “fresh” HEARTBEAT from a set  $S$  of  $n - t$  distinct processes, it updates the output of  $\Sigma_k$  with this set  $S$ . The intersection property of the class  $\Sigma_k$  is ensured since, as  $(k+1)(n-t) > n$ , among any  $k+1$  sets of size  $n-t$  of processes, at least two sets intersect. Liveness follows from the fact that faulty processes eventually stop broadcasting heartbeats.
- $t \geq \frac{kn}{k+1}$ . In that case, it is not possible to emulate  $\Sigma_k$  in  $\mathcal{MP}_{n,t}$ . The proof is by contradiction and relies on a partitioning argument.

Assume for contradiction that there exists an algorithm  $\mathcal{A}$  that emulates a failure detector  $\Sigma_k$  in  $\mathcal{MP}_{n,t}$ . We construct an execution  $\alpha$  of  $\mathcal{A}$  in which the intersection property of the class  $\Sigma_k$  is violated.

As  $t \geq \frac{kn}{k+1}$ , i.e.,  $(k+1)(n-t) \leq n$ , there exists a collection  $\mathcal{S}$  of  $k+1$  pairwise disjoint subsets of  $\Pi$  of size  $n-t$ ,  $\mathcal{S} = \{S_1, \dots, S_{k+1}\}$ . That is, for all  $1 \leq i \neq j \leq k+1$ ,  $S_i \cap S_j = \emptyset$  and  $|S_i| = |S_j| = n-t$ . We construct inductively longer and longer prefix  $\alpha_i$  of  $\alpha$ .

- Base case. Let  $\alpha'_1$  denote an execution of  $\mathcal{A}$  in which every process, but the  $n-t$  processes of  $S_1$  initially fail. By the liveness property of the class  $\Sigma_k$ , there exists a time  $\tau_1$  at which the output of  $\Sigma_k$  is a set  $s_1 \subseteq S_1$  at some process  $p_j \in S_1$ .  
In the prefix  $\alpha_1$ , no process fails. Every process in  $\Pi \setminus S_1$  does not take any step before  $\tau_1$  and, for every process in  $S_1$ ,  $\alpha_1$  and  $\alpha'_1$  are indistinguishable up to time  $\tau_1$ . Hence, as in  $\alpha'_1$ , the output of  $\Sigma_k$  at process  $p_j \in S_1$  is  $s_1 \subseteq S_1$ . After  $\tau_1$ , we then let every process take enough steps such that every message sent before  $\tau_1$  is received, and every process in  $\Pi \setminus S_1$  takes at least one step.
- Induction base. Suppose that the prefix  $\alpha_i$  has been constructed, for some  $i, 1 \leq i < k+1$ . Let  $\alpha'_{i+1}$  be an execution of  $\mathcal{A}$  that extends  $\alpha_i$  and in which the set of correct processes is  $S_{i+1}$ . More precisely, after  $\alpha_i$ , every process in  $\Pi \setminus S_{i+1}$  fails and every process in  $S_{i+1}$  keeps taking steps forever. By the liveness property of the class  $\Sigma_k$ , there exists a time  $\tau_{i+1}$  after  $\alpha_i$  at which the output of  $\Sigma_k$  is some set  $s_{i+1} \subseteq S_{i+1}$  at some process  $p_j \in S_{i+1}$ . Execution  $\alpha_{i+1}$  and  $\alpha'_{i+1}$  are indistinguishable for every process until  $\tau_{i+1}$ . As in the base case, after time  $\tau_{i+1}$ , we let every process take enough steps for every message sent before  $\tau_{i+1}$  to be delivered. Note that, as in  $\alpha'_{i+1}$ , the output of  $\Sigma_k$  at process  $p_j \in S_{i+1}$  is  $s_{i+1} \subseteq S_{i+1}$  at time  $\tau_{i+1}$  in execution  $\alpha_{i+1}$ .

- Final case. Suppose that prefix  $\alpha_{k+1}$  has been constructed.  $\alpha$  is an infinite execution of  $\mathcal{A}$  with no faulty process. After  $\alpha_{k+1}$ , every process takes infinitely many steps in some arbitrary order in such a way that every message sent is eventually received.

$\alpha$  is a valid execution of  $\mathcal{A}$  in  $\mathcal{MP}_{n,t}$  in which the emulated failure detector output sets  $s_1, \dots, s_{k+1}$ . As for each  $i, 1 \leq i \leq k+1, s_i \subseteq S_i$  and  $\{S_1, \dots, S_{k+1}\}$  is a family of pairwise disjoint sets, the intersection property of the class  $\Sigma_k$  is violated in  $\alpha$ .  $\square$

## 6 $\{V\Sigma_k\}_{1 \leq k \leq n}$ vs. $\{\Sigma_k\}_{1 \leq k \leq n}$

This section compares the two families  $\{V\Sigma_k\}_{1 \leq k \leq n}$  and  $\{\Sigma_k\}_{1 \leq k \leq n}$ . For establishing that  $k$ -set agreement is weaker than  $k$ -parallel consensus, we are mainly interested in the values of parameters  $n, t, k$  for which  $V\Sigma_k$  can be emulated in  $\mathcal{MP}_{n,t}[\Sigma_k]$ . This is because  $\Sigma_k$  can be used to solve  $k$ -set agreement and  $V\Sigma_k$  is necessary for  $k$ -parallel consensus. Hence, a protocol that uses a  $k$ -set agreement protocol to solve  $k$ -parallel consensus in  $\mathcal{MP}_{n,t}$  implies that  $V\Sigma_k$  can be emulated in  $\mathcal{MP}_{n,t}[\Sigma_k]$ . Nevertheless, for completeness, we also study for which values of the parameters  $n, t$  and  $k$  a failure detector  $\Sigma_k$  can be emulated in  $\mathcal{MP}_{n,t}[V\Sigma_k]$  (Section 6.2).

### 6.1 Emulation of $V\Sigma_{k'}$ in $\mathcal{MP}_{n,t}[\Sigma_k]$

The values of  $t, n, k$  and  $k'$  for which a failure detector  $V\Sigma_{k'}$  can be emulated in  $\mathcal{MP}_{n,t}[\Sigma_k]$  are completely characterized by the following theorem:

**Theorem 6.1.** *Let  $n, t, k, k', 1 \leq k, k', t < n$ . There is a protocol that emulates a failure detector  $V\Sigma_{k'}$  in  $\mathcal{MP}_{n,t}[\Sigma_k]$  if and only if  $k = 1$  or  $t \leq \frac{n+k'-2}{2}$ .*

*Proof.* If  $t \leq \frac{n+k'-2}{2}$ , we know from Lemma 5.2 that there is a protocol that emulates  $V\Sigma_{k'}$  in  $\mathcal{MP}_{n,t}$ , and thus also in  $\mathcal{MP}_{n,t}[\Sigma_k]$ . If  $k = 1$ ,  $V\Sigma_{k'}$  can be emulated in  $\mathcal{MP}_{n,t}[\Sigma]$  by simply replicating  $k'$  times the outputs of  $\Sigma$ .

Suppose now that  $k \geq 2$  and  $t > \frac{n+k'-2}{2}$ . Assume for contradiction that there exists a protocol  $\mathcal{A}$  that emulates  $V\Sigma_{k'}$  in  $\mathcal{MP}_{n,t}[\Sigma_k]$ .

Let  $S_1, \dots, S_u, u = \binom{n}{n-t}$  be every subset of  $\Pi$  of size  $n - t$ . For every  $S_i \in \mathcal{S}$ , let  $\alpha_i$  be an execution of  $\mathcal{A}$  in which (1) the set of correct processes is  $S_i$ , (2) each faulty process fails initially and (3) the output of the underlying failure detector  $\Sigma_k$  is always  $S_i$ , at every process. By the liveness property of the class  $V\Sigma_{k'}$ , there exists a time  $\tau_i$  and  $c_i, 1 \leq c_i \leq k'$  such that the  $c_i$ th entry of the vector output by  $V\Sigma_{k'}$  at some correct process in  $\alpha_i$  is a set  $s_i \subseteq S_i$ .

Now, we show that there exists  $S_j, S_\ell$  such that  $S_i \cap S_j = \emptyset$  and  $c_j = c_\ell = c$ . Assume not for contradiction. This means that  $f : S_i \mapsto c_i$  is a  $k'$ -coloring of  $KG_{n,n-t}$ . Therefore, the chromatic number of  $KG_{n,n-t}$  is  $\chi(KG_{n,n-t}) \leq k'$ . As  $t > \frac{n+k'-2}{2}$ , it follows that  $k' < 2t - n + 2$ . Contradiction!

Let  $\alpha$  be an execution of  $\mathcal{A}$  defined as follows. The set of correct processes in  $\alpha$  is  $S_j \cup S_\ell$ . At each process in  $S_j$  (respectively,  $S_\ell$ ), the output of  $\Sigma_k$  is always  $S_j$  (respectively,  $S_\ell$ ). Since  $k \geq 2$ , this is a valid output for  $\Sigma_k$  in an execution where the set of correct processes is  $S_j \cup S_\ell$ . Faulty processes do not take a step in  $\alpha$ . As for correct processes, each message sent by the processes in  $S_j$  (respectively,  $S_\ell$ ) before time  $\tau = \max(\tau_j, \tau_\ell)$  is delayed if it is sent to a process in  $S_\ell$  (respectively,  $S_j$ ). Otherwise it is received as in  $\alpha_j$  (respectively,  $\alpha_\ell$ ). After time  $\tau$ , every delayed message is received, and every message sent after that time is eventually received.

Up to time  $\tau$ ,  $\alpha$  and  $\alpha_j$  are thus indistinguishable for any processes in  $S_j$  and, similarly,  $\alpha$  and  $\alpha_\ell$  are indistinguishable for any processes in  $S_\ell$ . Therefore, in  $\alpha$ , the  $c$ th ( $= c_j = c_\ell$ ) entry of the vector output by  $\mathcal{A}$  is a set  $s_j \subseteq S_j$  at some process, and a set  $s_\ell \subseteq S_\ell$  at some other process. As  $S_j \cap S_\ell = \emptyset$ , this contradicts the intersection property of the class  $V\Sigma_{k'}$ .  $\square$

The impossibility part of the Theorem can be extended to the case in which a failure detector  $\Omega$  is available:

**Corollary 6.2.** *Let  $n, t, k, k', 1 \leq k, k', t < n$ . There is no protocol that emulates a failure detector  $V\Sigma_{k'}$  in  $\mathcal{MP}_{n,t}[\Sigma_k \times \Omega]$  if  $k \geq 2$  and  $t > \frac{n+k'-2}{2}$ .*

*Proof.* Essentially the same strategy as in the previous proof can be reused. What is left undefined in the executions  $\alpha_i$  considered there is the output of the failure detector  $\Omega$ . In each  $\alpha_i$ ,  $1 \leq i \leq u$ ,  $\Omega$  may always outputs the same process  $q \in S_i$  at each process. Then, in the definition of  $\alpha$ , the output of  $\Omega$  is the same as in  $\alpha_j$  (respectively,  $\alpha_\ell$ ) up to time  $\tau$  for each process in  $S_j$  (respectively,  $S_\ell$ ). After time  $\tau$ , the output of  $\Omega$  is the same process  $\in S_i \cup S_\ell$  at every correct process in  $\alpha$ . This is consistent with the eventual leadership property of the class  $\Omega$  and does not help each process in  $S_j$  (respectively,  $S_\ell$ ) to distinguish until time  $\tau$  between  $\alpha_j$  (respectively,  $\alpha_\ell$ ) and  $\alpha$ .  $\square$

## 6.2 From $V\Sigma_k$ to $\Sigma_k$

Next theorem complements Theorem 6.1 by characterizing the values of the parameters  $t, n$  and  $k'$  for which it is possible to  $t$ -resiliently emulate  $\Sigma_{k'}$  when a failure detector  $V\Sigma_k$  is available.

**Theorem 6.3.** *Let  $n, t, k, k', 1 \leq k, k', t < n$ . There is a protocol that emulates a failure detector  $\Sigma_{k'}$  in  $\mathcal{MP}_{n,t}[V\Sigma_k]$  if and only if  $k \leq k'$  or  $t < \frac{k'n}{k'+1}$ .*

*Proof.* The proof of the theorem is divided in two parts. We first establish that for  $k \leq k'$  or when  $t < \frac{k'n}{k'+1}$ , failure detector  $\Sigma_{k'}$  can be emulated in  $\mathcal{MP}_{n,t}[V\Sigma_k]$ . For the case  $k \leq k'$ , a simple protocol emulating a failure  $\Sigma_{k'}$  is presented (Figure 3). When  $t < \frac{k'n}{k'+1}$ ,  $\Sigma_{k'}$  can be emulated in  $\mathcal{MP}_{n,t}$  (Theorem 5.5), and thus also in  $\mathcal{MP}_{n,t}[V\Sigma_k]$ . We then prove that if  $k > k'$  and  $t \geq \frac{k'n}{k'+1}$ , it is not possible to emulate  $\Sigma_{k'}$  (Lemma 6.5). The proof is based on a simple partitioning argument.  $\square$

**Emulation of  $\Sigma_{k'}$  in  $\mathcal{MP}_{n,n-1}[V\Sigma_k]$ ,  $k' \geq k$**  A protocol that emulates a failure detector  $\Sigma_{k'}$  is described in Figure 3. The protocol tolerates any number of failures, i.e.,  $t \leq n - 1$ . Each process  $p_i$  maintains a variable  $\text{QUORUM}_i$  that contains the output of the emulated failure detector  $\Sigma_{k'}$ .

Recall that the underlying failure detector  $V\Sigma_k$  provides at each process  $p_i$  an array  $VQ_i[1..k]$  of sets of processes. By the intersection property of the class  $V\Sigma_k$ , the sets output at any time and at any process in the  $c$ th entry intersect, for any  $c, 1 \leq c \leq k$ . So, any collection of  $k' + 1$  sets  $Q_1, \dots, Q_{k'+1}$  output by failure detector  $V\Sigma_k$  contains at least two sets with a non-empty intersections since  $k' \geq k$ . That is, if for each  $Q_i, 1 \leq i \leq k' + 1$  there exists a process  $p_i$ , a time  $\tau_i$  and an entry  $c_i$  such that  $VQ_i[c_i] = Q_i$  at time  $\tau_i$ , then two sets  $Q_j, Q_\ell, 1 \leq j \neq \ell \leq k' + 1$  are output in the same entry  $c = c_j = c_\ell$  and thus are not disjoint. Therefore, the intersection property of the class  $\Sigma_{k'}$  is satisfied if for each process  $p_i$ ,  $\text{QUORUM}_i$  always contains some set output by  $V\Sigma_k$ . This is what is done in the protocol of Figure 3: periodically, the underlying failure detector is queried, and one of the sets output by  $V\Sigma_k$  is selected as the new output of  $\Sigma_{k'}$  (Task T1, lines 3–5).

```

init  $order_i \leftarrow (1, \dots, n)$ ; /* ordered list of processes ids */
       $QUORUM_i \leftarrow \Pi$ ; /*  $\Sigma_k$  emulated output */
      start task T1,T2,T3

task T1:
  (1) repeat periodically
  (2) send HEARTBEAT( $i$ ) to all processes;
  (3)  $VQ_i \leftarrow V\Sigma_k\text{-query}()$ ;
  /* query  $V\Sigma_k$ ;  $VQ_i$  is an array of  $k$  sets of procs. ids */
  (4) let  $Q \subseteq \Pi : \exists j : Q = VQ_i[j]$  and  $\forall c, 1 \leq c \leq k :$ 
       $\max_{\ell \in Q} rank(\ell, order_i) \leq \max_{\ell \in VQ_i[c]} rank(\ell, order_i)$ 
      /*  $rank(j, order)$  is the rank of  $j$  in the ordered list  $order_i$  */
  (5)  $QUORUM_i \leftarrow Q$ 
  (6) end repeat

task T2: when HEARTBEAT( $j$ ) is received:
  (7) move  $j$  at the head of the list  $order_i$ 

task T3: when  $\Sigma_{k'}$  is queried:
  (8) return  $QUORUM_i$ 

```

Figure 3: Emulation of  $\Sigma_{k'}$  in  $\mathcal{MP}_{n,n-1}[V\Sigma_k]$ ,  $k' \geq k$  (code for  $p_i$ )

It is also required that the output of the emulated failure detector eventually always contains at each correct process a set of correct processes. By the liveness property of the class  $V\Sigma_k$ , for each correct process  $p_i$ , there exist an entry  $\ell_i, 1 \leq \ell_i \leq k$  such that  $VQ_i[\ell_i]$  eventually always contains a set of correct processes. In order to eventually select one of the sets of correct processes output by  $V\Sigma_k$ , each process periodically broadcasts HEARTBEAT messages (task T1). As in the extraction protocol (Figure 1), HEARTBEAT are used to rank processes id. Each process  $p_i$  maintains an ordered list  $order_i$  of processes ids. Each time a HEARTBEAT from process  $p_j$  is received,  $j$  is moved at the beginning of the list (Task T2). As each faulty process sends finitely many HEARTBEAT messages, there exists a time after which each correct process id appears before any faulty process id. Therefore, given two sets  $S, S'$  of process,  $S \subseteq Correct$  and  $S' \not\subseteq Correct$ , the largest rank of the ids of the processes in  $S$  is eventually always smaller than the largest rank of the ids in  $S'$ . When  $p_i$  updates  $QUORUM_i$ , it selects a set  $S$  that has the smallest largest rank of its ids among the sets currently output by  $V\Sigma_k$  (line 4). Since the sets output by  $V\Sigma_k$  eventually contain a subset of the correct processes, this guarantees that eventually  $QUORUM_i \subseteq Correct$ . A proof of the protocol follows.

**Lemma 6.4.** *For all  $k, k' : 1 \leq k \leq k' \leq n$  and  $t : 1 \leq t \leq n - 1$ , the protocol described in Figure 3 implements a failure detector of the class  $\Sigma_{k'}$  in  $\mathcal{MP}_{n,t}[V\Sigma_k]$ .*

*Proof.* We show that the values of the variables  $QUORUM_i$ , for each process  $p_i$ , fulfill the specification of the class  $\Sigma_{k'}$ .

- *Intersection.* Let us consider  $k' + 1$  set  $Q_1, \dots, Q_{k'+1}$  output by the emulated failure detector. We have to show that at least two of them have a non-empty intersection.

$Q_1, \dots, Q_{k'+1}$  are the values of the variables  $QUORUM_{i_1}, \dots, QUORUM_{i_{k'+1}}$  at some times  $\tau_1, \dots, \tau_{k'+1}$  respectively for some (not necessarily distinct) processes  $p_{i_1}, \dots, p_{i_{k'+1}}$ . By the



code of the protocol (line 4), each  $Q_j$  is output by the underlying failure detector  $V\Sigma_k$ . More precisely, for each  $Q_j$ , there exists an integer  $c_j, 1 \leq c_j \leq k$  and a time at which at process  $p_{i_j}$ , the  $c_j$ th entry of the output of  $V\Sigma_k$  is  $Q_j$ . As  $k' \geq k$ , for at least two sets  $Q_j, Q_\ell, \ell \neq j$ ,  $c_j = c_\ell$  by the pigeonhole principle. Therefore, it follows from the intersection property of  $V\Sigma_k$  that  $Q_j \cap Q_\ell \neq \emptyset$ .

- *Liveness* Let  $p_i$  denote a correct process. Periodically, the value of the variable  $\text{QUORUM}_i$  is refreshed with one of the sets currently output by the underlying failure detector  $V\Sigma_k$ . The set is chosen according to the current order on the processes ids given by the ordered list  $\text{order}_i$  (lines 3–4).

Let  $S, S'$  denote two sets of processes ids. The set  $S$  has higher rank than  $S'$  if every id in  $S$  appears before at least one id in  $S'$  in the list  $\text{order}_i$ . Suppose that  $S \subseteq \text{Correct}$  whereas  $S'$  contains the id of a faulty process. A faulty process is moved finitely many times at the head of the list (line 7) since it sends finitely many HEARTBEAT messages. On the contrary, a correct process is moved infinitely many times at the beginning of the list (line 7). Hence,  $S$  is eventually always ranked before  $S'$ .

By the liveness property of the class  $V\Sigma_k$ , there is a time after which the vector of sets output by the failure detector at  $p_i$  always contains a set of correct processes ids. It thus follows that eventually, a set of correct processes ids is selected each time line 4 is executed, from which we conclude that  $\text{QUORUM}_i$  eventually contains a set of correct processes ids.  $\square$

**Impossibility of  $t$ -resilient emulation of  $\Sigma_{k'}$  for  $k < k'$  and  $\frac{k'n}{k+1} \leq t$ :** To complete the proof of Theorem 6.3, we establish the following impossibility result:

**Lemma 6.5.** *Let  $n, t, k, k', 1 \leq k' < k < n$  and  $\frac{k'n}{k+1} \leq t$ . There is no protocol that emulates a failure detector  $\Sigma_{k'}$  in  $\mathcal{MP}_{n,t}[V\Sigma_k]$ .*

*Proof.* The proof is based on a partition argument. Assume for contradiction that there exists a protocol  $\mathcal{A}$  that emulates a failure detector  $\Sigma_{k'}$  in  $\mathcal{MP}_{n,t}[V\Sigma_k]$ .

As  $\frac{k'n}{k+1} \leq t$ , i.e.,  $(k'+1)(n-t) \leq n$ , there exists  $k'+1$  pairwise disjoint sets  $S_1, \dots, S_{k'+1} \subseteq \Pi$  of size  $n-t$ . Let  $VQ$  be the vector of size  $k$   $[S_1, \dots, S_{k'+1}, \Pi, \dots, \Pi]$ . Note that  $VQ$  is a valid output for a failure detector of the class  $V\Sigma_k$  in any execution in which the set of correct processes is  $\Pi$  or  $S_i$ , for any  $i, 1 \leq i \leq k'+1$ .

Let  $\alpha_1, \dots, \alpha_{k'+1}$  denote  $k'+1$  executions of  $\mathcal{A}$  as follows. For each  $i, 1 \leq i \leq k'+1$ , the set of correct processes in execution  $\alpha_i$  is  $S_i$ ; the output of the underlying failure detector  $V\Sigma_k$  is always  $VQ$ , for every process  $p_\ell \in S_i$ . Processes in  $\Pi \setminus S_i$  fail before taking any step. Observe that  $n-t$  processes are correct in  $S_i$ .

Consider execution  $\alpha_i$ , for some  $i, 1 \leq i \leq k'+1$ . By the correctness of the emulation  $\mathcal{A}$ , there exists a time  $\tau_i$  at which the output of  $\Sigma_{k'}$  is a set  $s_i \subseteq S_i$ , for some process in  $S_i$ . This follows from the liveness property of the class  $\Sigma_{k'}$ .

To establish a contradiction, we construct an execution  $\alpha$  of  $\mathcal{A}$  by “merging” execution  $\alpha_1, \dots, \alpha_{k'+1}$ . Let  $\tau = \max_{1 \leq i \leq k'+1} \tau_i$ . No processes fail in  $\alpha$ . As in each execution  $\alpha_i$ , the output of the underlying failure detector  $V\Sigma_k$  is always  $VQ = [S_1, \dots, S_{k'+1}, \Pi, \dots, \Pi]$  as in  $\alpha_i, 1 \leq i \leq k'$ . This is a valid output for a failure detector of the class  $V\Sigma_k$ , as no processes fail in  $\alpha$ . Moreover, for each  $i, 1 \leq i \leq k$ , each message sent by the processes in  $S_i$  before time  $\tau$  is delayed if it is sent to a

process outside  $S_i$ , or received as in  $\alpha_i$ . After time  $\tau$ , we let every delayed messages be received in any order. Also, each message sent after time  $\tau$  is eventually received.

It thus follows that run  $\alpha$  and  $\alpha_i$  are indistinguishable up to time  $\tau$  by each process in  $S_i$ . Therefore, by construction of  $\alpha_i$ , at time  $\tau_i$  and at some process  $S_i$ , the output of  $\mathcal{A}$  is a quorum  $s_i \subseteq S_i$ . As  $S_1, \dots, S_{k'+1}$  is a family of pairwise disjoint sets, so is the family  $s_1, \dots, s_{k'+1}$ . Therefore, the intersection property of  $\Sigma_{k'}$  is violated: a contradiction.  $\square$

## 7 Separation results

This section glues together the results presented in Section 4, Section 5 and Section 6 to establish the following main theorem:

**Theorem 7.1.** *Let  $n, t, k, k', 1 \leq k, k' \leq t < n$  such that  $2 \leq k$  and  $\frac{n+k'-2}{2} < t$ . There is no protocol for  $k'$ -parallel consensus in  $\mathcal{MP}_{n,t}[k\text{-SA}]$ .*

The proof strategy is as follows: On one hand, it has been shown in [13] that  $k$ -set agreement can be solved in  $\mathcal{MP}_{n,t}[\Omega \times \Sigma_k]$ , for any value of  $t$ . On the other hand, we have seen that  $V\Sigma_{k'}$  is necessary for solving  $k'$ -parallel consensus (Theorem 4.1). The impossibility of a  $t$ -resilient solution to  $k'$ -parallel consensus using a  $k$ -set agreement protocol thus reduces to the impossibility of a  $t$ -resilient emulation of  $V\Sigma_{k'}$  based on  $\Omega \times \Sigma_k$ . The latter has been answered in the previous Section (Corollary 6.2).

*Proof.* Let  $k \geq 2$  and  $t > \frac{n+k'-2}{2}$ . The proof is by contradiction. Assume that there exists a  $k'$ -parallel consensus protocol  $\mathcal{A}$  in  $\mathcal{MP}_{n,t}[k\text{-SA}]$ . More precisely,  $\mathcal{A}$  uses any number of copies of a  $k$ -set agreement protocol  $\mathcal{B}$  to solve  $k'$ -parallel consensus. Protocol  $\mathcal{B}$  is any  $t$ -resilient protocol for  $k$ -set agreement. No assumption is made regarding the internals of protocol  $\mathcal{B}$ . In particular,  $\mathcal{B}$  might be a failure detector-based protocol.

It is known that  $k$ -set agreement can be solved in  $\mathcal{MP}_{n,t}[\Omega \times \Sigma_k]$  [13] – the protocol presented there imposes no requirement on  $t$  and  $k$ .  $\mathcal{B}$  may thus be the protocol presented in [13]. Therefore, by combining protocol  $\mathcal{A}$  and  $\mathcal{B}$ , it follows that  $k'$ -parallel consensus can be solved in  $\mathcal{MP}_{n,t}[\Omega \times \Sigma_k]$ .

In section 4, we have shown that  $V\Sigma_k$  is necessary for  $k'$ -parallel consensus. That is, if there is a  $k'$ -parallel consensus protocol using a failure detector  $\mathcal{D}$ , then one may use  $\mathcal{D}$  to emulate a failure detector of the class  $V\Sigma_k$ . As  $k'$ -parallel consensus can be solved in  $\mathcal{MP}_{n,t}[\Omega \times \Sigma_k]$  by combining protocols  $\mathcal{A}$  and  $\mathcal{B}$ , it thus follows that there exists a protocol  $\mathcal{T}$  that emulates  $V\Sigma_k$  in  $\mathcal{MP}_{n,t}[\Omega \times \Sigma_k]$ .

However, by corollary 6.2, there is no protocol that emulates  $V\Sigma_k$  in  $\mathcal{MP}_{n,t}[\Omega \times \Sigma_k]$  if  $k \geq 2$  and  $t > \frac{n+k'-2}{2}$ : a contradiction.  $\square$

The relative hardness of  $k$ -set agreement and  $k$ -parallel consensus is also expressed by the following theorem. The theorem gives tight bounds on  $t$  for  $k$ -set agreement and  $k$ -parallel consensus to be solvable when an eventual leader is available:

**Theorem 7.2.** *Let  $1 \leq k \leq t < n$ . In  $\mathcal{MP}_{n,t}[\Omega]$ ,*

1. *There is a  $k$ -set agreement protocol if and only if  $t < \frac{kn}{k+1}$ ;*
2. *There is a  $k$ -parallel consensus protocol if and only if  $t \leq \frac{n+k-2}{2}$ .*

*Proof.* 1) Bonnet and Raynal[14] have shown that  $\Sigma_k$  is necessary for  $k$ -set agreement. Moreover,  $\Sigma_k$  can be emulated in  $\mathcal{MP}_{n,t}[\Omega]$  if and only if  $t < \frac{kn}{k+1}$ . Hence, the existence of an  $\Omega$ -based  $k$ -set agreement protocol tolerating  $t$  implies a  $t$ -resilient emulation of  $\Sigma_k$  in  $\mathcal{MP}_{n,t}[\Omega]$ . This is not possible if  $t \geq \frac{kn}{k+1}$ . A  $k$ -set agreement protocol in  $\mathcal{MP}_{n,t}[\Sigma_k \times \Omega]$  is presented in [13]. Since  $\Sigma_k$  can be emulated in  $\mathcal{MP}_{n,t}$  provided that  $t < \frac{kn}{k+1}$ ,  $k$ -set agreement can be solved in  $\mathcal{MP}_{n,t}[\Omega]$  for  $t < \frac{kn}{k+1}$ .

2) Similarly, we have shown that  $V\Sigma_k$  is necessary for  $k$ -parallel (Section 4) and that  $V\Sigma_k$  can be emulated in  $\mathcal{MP}_{n,t}[\Omega]$  if and only if  $t \leq \frac{n+k-2}{2}$  (Lemma 5.4). Therefore, no protocol solves  $k$ -parallel consensus in  $\mathcal{MP}_{n,t}[\Omega]$  if  $t > \frac{n+k-2}{2}$ .

For  $t \leq \frac{n+k-2}{2}$ ,  $k$ -parallel consensus can be solved in  $\mathcal{MP}_{n,t}[\Omega]$  as follows: Each process  $p_i$  participates parallelly in  $k$  instances  $\mathcal{A}^1, \dots, \mathcal{A}^k$  of an  $(\Omega \times \Sigma)$ -based consensus protocol  $\mathcal{A}$ .  $p_i$  proposes its initial value in each instance; if  $p_i$  decides  $v$  in instance  $\mathcal{A}^c$ , the pair  $(c, v)$  is returned by  $p_i$  as its output for  $k$ -parallel consensus. Emulation of  $\Sigma$  in instance  $j$  consists in outputting the  $j$ th component of the vector provided by  $V\Sigma_k$ .

The liveness property of the class  $V\Sigma_k$  ensures that for some  $c, 1 \leq c \leq k$ , the  $c$ th entry of the vector output by  $V\Sigma_k$  eventually contains a subset of the correct processes. Moreover, for any entry  $j$ , every pair of sets in the  $j$ th entry of the vector provided by  $V\Sigma_k$  have a non-empty intersection. Therefore, the  $c$ th entry of the output of  $V\Sigma_k$  satisfy the same property as the output of a failure detector  $\Sigma$ . It thus follows that every correct process eventually decides in  $\mathcal{A}^c$ .

Since in every instance  $\mathcal{A}^j, 1 \leq j \leq k$ , the emulation of  $\Sigma$  preserves the intersection property, no two process decide different values in  $\mathcal{A}^j$ . This is because the safety property of consensus relies only on the fact that the intersection of any two sets output by  $\Sigma$  is non-empty. Hence, if  $(j, v)$  and  $(j, v')$  are decided, then  $v = v'$ , for any  $j, 1 \leq j \leq k$ .  $\square$

## 8 Conclusion

The paper has investigated the relationship linking the  $k$ -set agreement and the  $k$ -parallel consensus problems in asynchronous crash-prone message-passing systems. While  $k$ -parallel consensus  $t$ -resiliently implements  $k'$ -set agreement for any value of  $t < n$ , and any  $k' \leq k$ , the paper has shown that  $k$ -set agreement does not implement  $k'$ -parallel consensus for any  $k', 1 \leq k' \leq n$  if  $\frac{n+k'-2}{2} < t$  and  $2 \leq k$ . In addition, when an eventual leader  $\Omega$  is available, it has established that  $k$ -parallel consensus can be solved if and only if  $t \leq \frac{n+k-2}{2}$ . This is to be compared with  $k$ -set agreement, which can be solved if and only if  $t < \frac{kn}{k+1}$ .

The paper leaves open the following question: For  $\frac{n}{2} \leq t \leq \frac{n+k-2}{2}$ , what is the smallest value of  $k'$  for which  $k$ -set agreement  $t$ -resiliently implements  $k'$ -parallel consensus in message passing? As a starting point, we demonstrate below that given a  $k$ -set agreement protocol and assuming  $t \leq \frac{n+k-2}{2}$ ,  $(2k-1)$ -parallel consensus can be achieved. Note that this is not trivial: for example, if  $2(2k+1) < n, 2k-1 \leq t$  for every  $t, \frac{n}{2} \leq t \leq \frac{k+n-2}{2}$ .

Partition the set of processes in two sets  $A = \{p_1, \dots, p_{k-1}\}$  and  $B = \{p_k, \dots, p_n\}$ . Each  $p_i$  in  $A$  broadcasts  $(i, v_i)$  where  $v_i$  is  $p_i$ 's initial value before deciding that pair. The  $n-k+1$  remaining processes emulate a shared memory reduction of  $k$ -parallel consensus to  $k$ -set agreement, as described in [6], assuming that no more than  $t_B = \lfloor \frac{n-k}{2} \rfloor$  processes among them fail. If  $p_i \in A$  obtains a decision  $(c, d)$ , it broadcast the pair  $(c + (k-1), d)$  before deciding it. Any process that receives a pair  $(c, d)$  decides this pair. Note that we have  $1 \leq c \leq 2k-1$ , and if pairs  $(c, d), (c, d')$  are

decided,  $d = d'$ . If the number of actual failures in  $B$  exceeds  $t_B$ , the emulation may not terminate, but safety is not violated (that is, a simulated write or read operation may not terminate).

For termination, let  $f_A, f_B$  be the actual number of failures in sets  $A$  and  $B$  respectively. If  $f_A < k - 1$ , the protocol terminates as  $A$  contains a correct process. Otherwise,  $f_A = k - 1$  and consequently  $f_B \leq t - (k - 1) \leq \frac{n+k-2}{2} - (k - 1) = \frac{n-k}{2}$ . That is, a majority of the processes in  $A$  are correct. The emulation of the shared memory protocol thus terminates, which enables every correct process to decide.

Another avenue for future research is to determine the weakest failure detector for  $k$ -parallel consensus. A candidate is the (new) failure detector class  $\mathcal{W}_k$ : the output of  $\mathcal{W}_k$  is a  $k$ -component array. Each component contains the same output as a failure detector  $\Omega \times \Sigma$ , except that the eventual leadership property of  $\Omega$  and the liveness property of  $\Sigma$  are only required to hold in a single component. This component must be the same for both properties and for every process. More details appear in Appendix A.

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## A Failure Detector $\mathcal{W}_k$

Intuitively, a failure detector of the class  $\mathcal{W}_k$  provides the processes with  $k$  instances of failure detectors  $\Omega \times \Sigma$ . In each copy, the *safety* property of the class  $\Omega \times \Sigma$  holds. That is, the intersection property of the class  $\Sigma$  in each copies is always satisfied: any two quorums output possibly at distinct processes by the same copy of  $\Sigma$  intersect. The *liveness* properties of  $\Omega \times \Sigma$ , however, is may not be satisfied in every copy. It may be the case that in some copies the output of  $\Omega$  never converges towards a correct leader, or that the quorums output by  $\Sigma$  include infinitely often faulty processes. Nevertheless, in at least one, unknown, copy both the eventual leadership property of  $\Omega$  and liveness of  $\Sigma$  hold.

More formally, a detector  $\mathcal{W}_k$  provides each process  $p_i$  with two  $k$ -component denoted  $\text{LEADERS}_i$  and  $\text{QUORUMS}_i$  that satisfy the following properties:

- *Validity.* At any time, each component of  $\text{LEADERS}_i$  stores a process identity and each component of  $\text{QUORUMS}_i$  stores a set of process ids.  
 $\forall p_i \in \Pi, \forall \tau \in \mathbb{T}, \forall c, 1 \leq c \leq k : (\text{LEADERS}_i^\tau[c] \in \Pi) \wedge (\text{QUORUMS}_i^\tau[c] \subseteq \Pi)$ .
- *Intersection.* Any two quorums output in the same component  $c$  of the array  $\text{QUORUMS}$  at the same process or at distinct processes intersect. Formally,  
 $\forall c, 1 \leq c \leq k, \forall \tau, \tau' \in \mathbb{T}, \forall p_i, p_{i'} \in \Pi : \text{QUORUMS}_i^\tau[c] \cap \text{QUORUMS}_{i'}^{\tau'}[c] \neq \emptyset$ .
- *Liveness.* There exists  $c, 1 \leq c \leq k$  and a correct process  $p_\ell$  such that eventually (i)  $\text{LEADERS}_i[c] = \ell$ , and and, (ii)  $\text{QUORUMS}_i[c] \subseteq \text{Correct}$  for every correct process  $p_i$ . That is,  $\exists c, 1 \leq c \leq k, \exists p_\ell \in \text{Correct}, \exists \tau_\ell \in \mathbb{T}$  such that:
  - (i) *Eventual leadership.*  $\forall p_i \in \text{Correct}, \forall \tau \geq \tau_\ell : \text{LEADERS}_i^\tau[c] = \ell$ .
  - (ii) *Quorum liveness.*  $\forall p_i \in \text{Correct}, \forall \tau \geq \tau_\ell : \text{QUORUMS}_i^\tau[c] \subseteq \text{Correct}$ .

Clearly,  $k$ -simultaneous consensus can be solved in  $\mathcal{MP}_{n,t}[\mathcal{W}_k]$ . Every process participates simultaneously in  $k$  instances of an  $(\Omega \times \Sigma)$ -based consensus protocol. For each instance  $j, 1 \leq j \leq k$ , the output of  $\Omega \times \Sigma$  is provided by the  $j$ th component of  $\mathcal{W}_k$ . By the validity and intersection properties of  $\mathcal{W}_k$ , at most one value is decided in each instance, whereas the liveness guarantees that decision occur in at least one instance.

Finally, we rank the power of  $\mathcal{W}_k$  among two other failure detectors that combine in different way the properties of  $\Omega$  and  $\Sigma$ . Recall that a failure detector  $\bar{\Omega}_k$  [16, 15] outputs a  $k$ -component array of processes ids; it is guaranteed that the eventual leadership property is satisfied in at least one component.

**Lemma A.1.**  $V\Sigma_k \times \bar{\Omega}_k \preceq \mathcal{W}_k \preceq V\Sigma_k \times \Omega$ .

- Proof.*
1.  $\bar{\Omega}_k \times V\Sigma_k \preceq \mathcal{W}_k$ . Simply observe that the arrays  $\text{LEADERS}$  and  $\text{QUORUMS}$  comply with the specification of  $\bar{\Omega}_k$  and  $V\Sigma_k$  respectively.
  2.  $\mathcal{W}_k \preceq V\Sigma_k \times \Omega$ . The failure detector  $\mathcal{W}_k$  can be emulated as follows. The algorithm outputs two arrays  $\text{LEADERS}$  and  $\text{QUORUMS}$  at each process. The former contains  $k$  copies of  $\Omega$  and the latter is a copy of the output of  $V\Sigma_k$ .

The emulated failure detector complies with the validity requirement of  $\mathcal{W}_k$ . The intersection property of  $\mathcal{W}_k$  follows from the eponymous property of the underlying failure detector  $V\Sigma_k$ .

The liveness property of  $V\Sigma_k$  also ensures the quorums liveness property of  $\mathcal{W}_k$ . That is, there exists  $c \in [1, k]$  and a time after which  $\text{QUORUMS}_i[c]$  at each correct process  $p_i$  is a subset of *Correct*. Note that by definition of  $\Omega$ , the content of  $\text{LEADERS}[c]$  eventually complies with the leadership liveness property of  $V\Sigma_k$ .  $\square$