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# *t*-résilient snapshot immédiat<sup>†</sup>

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Dans un système de  $n$  processus communiquant par mémoire partagée, un *snapshot immédiat* est un état de la mémoire assurant que si l'écriture réalisée par  $q$  est dans le snapshot de  $p$  alors le snapshot de  $p$  contient le snapshot obtenu par  $q$ . Un snapshot immédiat peut être réalisé dans un système où au plus  $n - 1$  processus peuvent tomber en panne. Dans un système où  $t$  processus peuvent tomber en panne, un processus peut obtenir un snapshot contenant les valeurs écrites par jusqu'à  $n - t$  processus. On définit ainsi le *t*-résilient snapshot immédiat et on établit des liens entre ce problème et les problèmes d'accord comme le consensus et le  $k$ -accord.

**Mots-clefs :** Mémoire partagé, snapshot immédiat, tolérance aux pannes, consensus,  $k$ -accord.

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## 1 Introduction

We consider a distributed computing model of  $n$  asynchronous processes among which any subset of up to  $t$  processes may crash communicating by shared memory.

The snapshot object was first proposed over a decade ago [1, 2] and has since been intensively studied by the distributed algorithms community. A snapshot object can be seen as a data structure initially empty, which can then contain at most  $n$  pairs (one per process), each made up of a process index and a value. This object provides the processes with two operations denoted `update` and `snap`. The invocation `update(v)` by a process  $p_i$  adds the pair  $\langle i, v \rangle$  to the data structure and the operation `snap` returns all the pairs already written in the data structure.

The immediate snapshot (IS) object has been introduced in [3, 11], and later investigated in [5, 15]. It is a variant of the snapshot object. An immediate snapshot provides the processes with a single operation `write_snapshot()` that a process may invoke at most once. The invocation `write_snapshot(v)` by a process  $p_i$  adds the pair  $\langle i, v \rangle$  to the object and returns a set of pairs  $view_i$  belonging to the object such that if  $\langle j, w \rangle$  is in  $view_i$  then  $view_j \subseteq view_i$ .

The noteworthy feature of the iterated immediate snapshot model is the following. It has been shown by Borowsky and Gafni in [5], that this model is equivalent to the usual read/write wait-free model ( $(n - 1)$ -crash model) for task solvability with the wait-freedom progress condition (any non-faulty process obtains a result). Its advantage lies in the fact that its runs are more structured and easier to analyze than the runs in the basic read/write shared memory model [14]. It is also the basis of the combinatorial topology approach for distributed computing (e.g., [10]). Hence, IS objects constitute the algorithmic foundation of distributed iterated computing models.

When considering the  $t$ -crash  $n$ -process model where  $t < n$ , and assuming that each correct process writes a value, a process may wait for values written by  $(n - t)$  processes without risking being blocked forever.

This naturally leads to the notion of a  $t$ -immediate snapshot object, which generalizes the basic  $(n - 1)$ -immediate snapshot object. More precisely, when considering a  $t$ -immediate snapshot object in a  $t$ -crash  $n$ -process model, an invocation of `write_snapshot()` by a process returns a set including at least  $(n - t)$  pairs

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<sup>†</sup>This paper is an extended abstract of [7]; the original title is *t-resilient snapshot immédiat*.

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(while it would return a set of  $x$  pairs with  $1 \leq x \leq n$  if the object was an immediate snapshot object). Hence, a  $t$ -immediate snapshot object allows processes to obtain as much information as possible from the other processes while guaranteeing progress.

The obvious question is then the implementability of a  $t$ -immediate snapshot object in the  $t$ -crash  $n$ -process model.

Implementations of an  $(n-1)$ -immediate snapshot object is described in [3]. For the other values of  $t$  ( $0 < t < n-1$ ), this question is answered in this paper, which shows that it is impossible to implement a  $t$ -IS object in a  $t$ -crash  $n$ -process model when  $0 < t < n-1$ . More precisely we prove that implementing a  $t$ -IS object is equivalent<sup>§</sup> to implementing consensus when  $t < n/2$  and enables to implement  $(2t-n+2)$ -Set agreement when  $n/2 \leq t < n-1$ .

At first glance, this impossibility result may seem surprising. First, an IS object is a snapshot object (a) whose operations update and snap are glued together in a single operation `write_snapshot()`, and (b) satisfying an additional property linking the sets of pairs returned by concurrent invocations. Then, as already indicated, a  $t$ -IS object is an IS object such that the sets returned by `write_snapshot()` contain at least  $(n-t)$  pairs. This property on the sets returned by a snapshot object can be trivially implemented in a  $t$ -crash  $n$ -process model. Hence, while a  $t$ -snapshot object can be implemented in the  $t$ -crash  $n$ -process model, a  $t$ -IS object cannot when  $0 < t < n-1$ . Second, because in general smallest is the number of possible faults easiest is the implementation. But in the  $t$ -IS, a small number of failure, induces a harder problem each output set must have the size at least  $n-t$ .

## 2 Model

We consider a distributed computing model of  $n \geq 3$  asynchronous sequential processes denoted  $p_1, \dots, p_n$  among which any subset of up to  $t$  ( $0 < t < n$ ) processes may crash. The processes cooperate by reading and writing Single-Writer Multi-Reader atomic read/write registers [13].

**One-shot immediate snapshot object.** An immediate snapshot object (IS) is a set, initially empty, that will contain pairs made up of a process index and a value. Let us consider a process  $p_i$  that invokes `write_snapshot(v)`. This invocation adds the pair  $\langle i, v \rangle$  to the object, and returns to  $p_i$  a set, called view and denoted  $view_i$ , such that the sets returned to the processes collectively satisfy the following properties.

- Termination. The invocation of `write_snapshot()` by a correct process terminates.
- Self-inclusion.  $\forall i : \langle i, v \rangle \in view_i$ .
- Validity.  $\forall i : (\langle j, v \rangle \in view_i) \Rightarrow p_j$  invoked `write_snapshot(v)`.
- Containment.  $\forall i, j : (view_i \subseteq view_j) \vee (view_j \subseteq view_i)$ .
- Immediacy.  $\forall i, j : (\langle i, v \rangle \in view_j) \Rightarrow (view_i \subseteq view_j)$ .

**$k$ -Set agreement.**  $k$ -Set agreement was introduced by S. Chaudhuri [6], it generalizes consensus which corresponds to the case  $k=1$ . A  $k$ -Set agreement object is a one-shot object that provides the processes with a single operation denoted `proposek(v)`. This operation allows the invoking process  $p_i$  to propose a value it passes as an input parameter (called *proposed* value), and obtain a value (called *decided* value). The object is defined by the following set of properties.

- Termination. The invocation of `proposek(v)` by a correct process terminates.
- Validity. A decided value is a proposed value.
- Agreement. No more than  $k$  different values are decided.

It is shown in [8, 4, 11, 16] that the problem is impossible to solve if  $k \leq t$ .

**$t$ -Immediate Snapshot.** A  $t$ -immediate snapshot object (denoted by  $t$ -IS) is an immediate snapshot object with the following additional property.

- Output size. The set  $view$  obtained by a process is such that  $|view| \geq n-t$ .

## 3 Results

**$t$ -Immediate Snapshot is Impossible if  $0 < t < n-1$ .** This section presents an algorithm Figure 1 to achieve (1) consensus from  $t$ -IS for  $0 < t < n/2$ , and (2)  $k$ -Set agreement (in short  $k$ -SA) from  $t$ -IS for

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§. A is equivalent to B if A can be (computationally) reduced to B and reciprocally.

*t*-resilient immediate snapshot

```

1  PROPOSE(v)
2  begin
3      view ← I.write_snapshot(v) ; /* I shared immediate snapshot*/
4      VIEW[i] ← view ; /* VIEW is a shared array*/
5      wait(|{ j such that VIEW[j] ≠ ⊥ }| = t + 1) ;
6      let view be the smallest of the previous (t + 1) views ;
7      return(smallest proposed value in view)
8  end PROPOSE

```

FIGURE 1: Solving consensus from *t*-IS if  $0 < t < n/2$ (code for  $p_i$ )

```

1  write_snapshot(vi)
2  begin
3      S.update((i, vi) ; /* S shared snapshot*/
4      view ← ⊥ ; dec ← ⊥ ; k ← -1 ; launch the tasks T1 and T2.
5      Task T1 :
6          repeat k ← k + 1
7              do aux ← S.snapshot()
8                  until (dec ⊂ aux ∧ |aux| ≥ n - t)
9                      dec ← CONS[k].propose1(aux)
10                     if ((i, vi) ∈ dec) ∧ (view = ⊥) then view ← dec end if
11                 until |aux| = n
12         end task T1
13     Task T2 : wait(view ≠ ⊥) ; return(view) end task T2.
14 end write_snapshot

```

FIGURE 2: Implementing *t*-IS with consensus (code for  $p_i$ )

$k = 2t - n + 2$  (e.g.,  $(n - 2)$ -SA agreement from  $(n - 2)$ -IS if  $t = n - 2$ ). As these problems are impossible to solve [4, 11, 16], we show that it is impossible to implement a *t*-IS object when  $0 < t < n - 1$ .

Intuitively this algorithm works because there is a set of at least  $\ell \geq n - t$  processes, that obtained the same view *min\_view* (or crashed before returning from *write\_snapshot*()), and this view is the smallest view obtained by a process and its size is  $|\text{min\_view}| = \ell$ . If  $0 < t < n/2$ , as  $\ell \geq n - t$  and  $(n - t) + (t + 1) > n$ , it follows from the waiting predicate, that, any process that executes line 5, obtains a copy of *min\_view*, and consequently we have *view* = *min\_view* at line 5. It follows that no two processes can decide different values. If  $n/2 \leq t < n - 1$ , we have  $n - t \leq t$ . The  $m = (n - t) - 1$  biggest views will never be selected by the processes, and consequently these processes obtain at most  $t - m = t - ((n - t) - 1) = 2t - n + 1$  different smallest views. Hence, these processes may decide at most  $2t - n + 1$  different values.

**Theorem 1** *A t-IS object cannot be implemented if  $0 < t < n - 1$ .*

**From Consensus to *t*-IS if  $0 < t \leq n - 1$ .** While a snapshot object is atomic (operations on a snapshot object can be linearized [12]), an IS object and a *k*-immediate snapshot objects are not atomic (its operations cannot always be linearized).

So we cannot apply the universality result of Herlihy [9], and we have to write a specific algorithm given Figure 2.

***t*-Immediate Snapshot and *k*-Set agreement.** With the algorithms Figures 1 and 2, we get :

**Theorem 2** *Consensus and t-IS are equivalent if  $0 < t < n/2$ .*

We have shown that from *t*-IS when  $n/2 \leq t < n - 2$  we can implement  $(2t - n + 2)$ -Set agreement. Can we do consensus as in the case  $0 < t < n/2$ ? By a simulation argument, we show that consensus is not solvable with *t*-immediate snapshot when  $n/2 \leq t < n$  proving that the computational power of *t*-immediate snapshot when  $0 < t < n/2$  is strictly stronger than the computational power of *t*-immediate snapshot when  $n/2 \leq t < n$ .

**Theorem 3** *If  $0 < t < n/2$  then  $t$ -IS can implement  $(2t - n + 2)$ -Set agreement and cannot implement consensus. Consensus implements  $t$ -IS.*

$1 \leq t < n/2$	$n/2 \leq t < n - 1$
$t$ -IS and consensus are equivalent	$t$ -IS implements $(2t - n + 2)$ -Set agreement $t$ -IS does not implement consensus consensus implements $t$ -IS

**TABLE 1:** Summary of results presented in the paper

## 4 Conclusion

The paper has shown that, while it is possible to build an  $(n - 1)$ -IS object in the asynchronous read/write  $(n - 1)$ -crash model, it is impossible to build a  $t$ -IS object in an asynchronous read/write  $t$ -crash model when  $0 < t < n - 1$ . It follows that the notion of an Iterative immediate snapshot distributed model seems inoperative for these values of  $t$ . The results of the paper are summarized in Table 1.

Interestingly, this study shows that there are two contrasting impossibility results in asynchronous read/write  $t$ -crash  $n$ -process systems. Consensus is impossible as soon as  $t > 0$ , while  $t$ -immediate snapshot is impossible as soon as  $t < n - 1$ .

As a final remark, some computability problems remain open. As an example, is it possible to implement a  $t$ -IS object from  $(2t - n + 2)$ -Set agreement ?

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