

Proving the Correctness of Disk Paxos in Isabelle/HOL

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Abstract

Disk Paxos [GL00] is an algorithm for building arbitrary fault-tolerant distributed systems. The specification of Disk Paxos has been proved correct informally and tested using the TLC model checker, but up to now, it has never been fully formally verified. In this work we have formally verified its correctness using the Isabelle theorem prover and the HOL logic system [NPW02], showing that Isabelle is a practical tool for verifying properties of TLA^+ specifications.

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1 Introduction

Algorithms for fault-tolerant distributed systems were first introduced to implement critical systems. Nevertheless, what good is such an algorithm if it has a design error? We need some kind of guarantee that the algorithm does not have a faulty design. Formal verification of its specification is one such guarantee.

Disk Paxos [GL00] is an algorithm for building arbitrary fault-tolerant distributed systems, that, due to its complexity, is difficult to reason about. It has been proved correct informally, and tested using the TLC model checker [Lam02]. The informal proof is rigorous but, as it is always the case with large informal proofs, it is easy to overlook details. Thus, one of the motivations of this work is to see if such a rigorous proof can be formalized in a contemporary theorem prover.

In [Pac01] part of the correctness proof (invariance of $HInv1$ and $HInv3$) was verified using the theorem prover ACL2 [KMM00]. An implicit assumption of this formalization is that all sets are finite, thus overlooking the fact that there is a missing conjunct in the Disk Paxos invariant (see Section 4).

We set the goal of formally verifying Disk Paxos correctness using the theorem prover Isabelle/HOL [NPW02]. In this way, we could gain more confidence in the correctness of Disk Paxos design and, at the same time, learn to what extent can Isabelle be a useful tool for proving the correctness of distributed systems using a real world example.

In Section 2 we give a brief description of the algorithm and its specification. In Section 3 we describe the translation from TLA⁺ to Isabelle/HOL and the problems that this translation originated. In Section 4 we discuss how our formal proofs relate to the informal ones in [GL00], and in Section 5 we conclude. The entire specification and all formal proofs can be found in the Appendix.

2 The Disk Paxos Algorithm

Disk Paxos is a variant of the classic Paxos algorithm [Lam98] for the implementation of arbitrary fault-tolerant systems with a network of processors and disks. It maintains consistency in the event of any number of non-Byzantine failures. This means that a processor may fail completely or pause for arbitrary long periods and then restart, remembering only that it has failed. A disk may become inaccessible to some or all processors, but it may not be corrupted. We say that a system is *stable* if all processes are either non-faulty or have failed completely (i.e. there are no new failed processes). Disk Paxos guarantees progress if the system is stable and there is at least one non-faulty processor that can read and write a majority of the disks. Consequently, the fundamental difference between Classic Paxos and Disk Paxos is that the former achieves redundancy by replicating processes while the latter replicates disks. Since disks are usually cheaper than processors, it is possible to obtain more redundancy at a lower cost.

Disk Paxos uses the state machine approach to solve the problem of implementing an arbitrary distributed system. The state machine approach [Sch90] is a general method that reduces this problem to solving a consensus problem. The distributed system is designed as a deterministic state machine that executes a sequence of commands, and a consensus algorithm ensures that, for each n , all processors agree on the n^{th} command. Hence, each processor p starts with an input value (a command), and it may output a value (the command to be executed). The problem is solved if all processors eventually output the same value and this value was a value of $input[p]$ for some p (under certain assumptions, in our case that there exists at least one non-faulty processor that can write and read a majority of disks).

Progress of Disk Paxos relies on progress of a leader-election algorithm. It is easy to make a leader-election algorithm if the system is stable, but very hard to devise one that works correctly even if the system is unstable. We are requiring stability to ensure progress, but actually only a weaker requirement is needed: progress of the underlying leader-election algorithm. Disk Paxos ensures that all outputs (if any) will be the same even if the leader-election algorithm fails.

2.1 Informal description of the algorithm.

The consensus algorithm of Disk Paxos is called *Disk Synod*. In it, each processor has an assigned block on each disk. Also it has a local memory that contains its current block (called the *dblock*), and other state variables (see figure 1). When a process p starts it contains an input value $input[p]$ that will not be modified, except possibly when recovering from a failure.

Disk Synod is structured in two phases, plus one more phase for recovering from failures. In each phase, a processor writes its own block and reads each other processor's block, on a majority of the disks. The idea is to execute ballots to determine:

Phase 1: whether a processor p can choose its own input value $input[p]$ or must choose some other value. When this phase finishes a value v is chosen.

Phase 2: whether it can commit v . When this phase is complete the process has committed value v and can output it (using variable *output*).

In either phase, a processor aborts its ballot if it learns that another processor has begun a higher-numbered ballot. The third phase (Phase 0) is for starting the algorithm or recovering from a failure.

In each block, processors maintain three values:

mbal The current ballot number.

bal The largest ballot number for which the processor entered phase 2.

inp The value the processor tried to commit in ballot number *bal*.

For a complete description of the algorithm, see [GL00].

2.2 Disk Paxos and its TLA⁺ Specification

The specification of Disk Paxos is written in the TLA⁺ specification language [Lam02]. As it is usual with TLA⁺, the specification is organized into modules.

The specification of consensus is given in module *Synod*, which can be found in appendix A. In it there are only two variables: *input* and *output*. To formalize the property stating that all processors should choose the same value and that this value should have been an input of a processor, we need variables that represent all past inputs and the value chosen as result. Consequently, an *Inner* submodule is introduced, which adds two variables: *allInput* and *chosen*. Our *Synod* module will be obtained by existentially quantifying these variables of the *Inner* module.

The specification of the algorithm is given in the *HDiskSynod* module. Hence, what we are going to prove is that the (translation to Isabelle/HOL

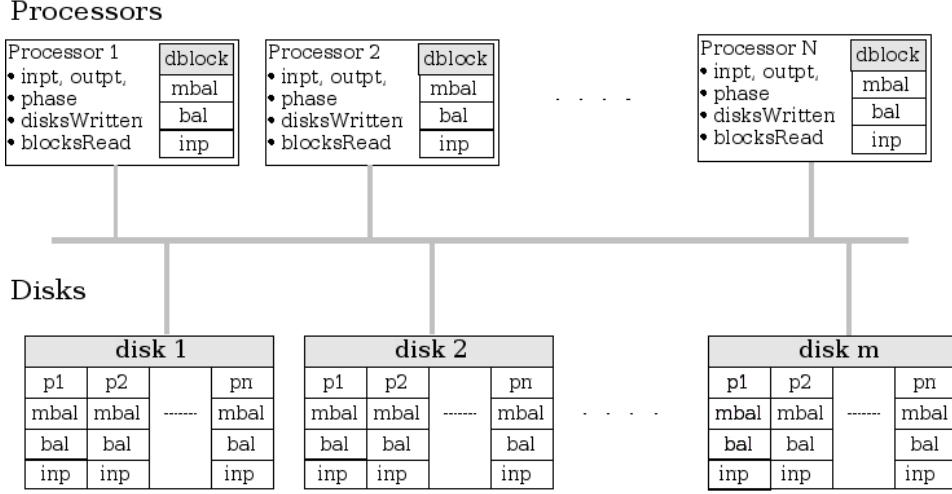


Figure 1: A network of processors and disks.

of the) *Inner* module is implied by the (translation to Isabelle/HOL of the) algorithm module *HDiskSynod*.

More concretely we have that the specification of the algorithm is:

$$HDiskSynodSpec \triangleq HInit \wedge \square[HNext]_{\langle vars, chosen, allInput \rangle}$$

where *HInit* describes the initial state of the algorithm and *HNext* is the action that models all of its state transitions. The variable *vars* is the tuple of all variables used in the algorithm.

Analogously, we have the specification of the *Inner* module:

$$ISpec \triangleq IInit \wedge \square[INext]_{\langle input, output, chosen, allInput \rangle}$$

We define $ivars = \langle input, output, chosen, allInput \rangle$. In order to prove that *HDiskSynodSpec* implies *ISpec*, we follow the structure of the proof given by Gafni and Lamport. We must prove two theorems:

THEOREM *R1* $HInit \Rightarrow IInit$

THEOREM *R2* $HInit \wedge \square[HNext]_{\langle vars, chosen, allInput \rangle} \Rightarrow \square[INext]_{ivars}$

The proof of *R1* is trivial. For *R2*, we use TLA proof rules [Lam02] that show that to prove *R2*, it suffices to find a state predicate *HInv* for which we can prove:

THEOREM *R2a* $HInit \wedge \square[HNext]_{\langle vars, chosen, allInput \rangle} \Rightarrow \square HInv$

THEOREM *R2b* $HInv \wedge HInv' \wedge HNext \Rightarrow INext \vee (\text{UNCHANGED } ivars)$

A predicate satisfying *HInv* is said to be an invariant of *HDiskSynodSpec*. To prove *R2a*, we make *HInv* strong enough to satisfy:

TLA ⁺	Isabelle/HOL
$\exists d \in D : \text{disk}[d][q].\text{bal} = bk$	$\exists d \in D. \text{bal}(\text{disk } s \ d \ q) = bk$
CHOOSE $x.P \ x$	$\varepsilon x. P \ x$
$\text{phase}' = [\text{phase EXCEPT } ![p] = 1]$	$\text{phase } s' = (\text{phase } s)(p := 1)$
UNION $\{\text{blocksOf}(p) : p \in \text{Proc}\}$	$UN \ p. \text{blocksOf } s \ p$
UNCHANGED v	$v \ s' = v \ s$

Table 1: Examples of TLA⁺ formulas and their counterparts in Isabelle/HOL.

THEOREM *I1* $HInit \Rightarrow HInv$
THEOREM *I2* $HInv \wedge HNext \Rightarrow HInv'$

Again, we have TLA proof rules that say that *I1* and *I2* imply *R2a*. In summary, *R2b*, *I1*, and *I2* together imply $HDiskSynodSpec \Rightarrow ISpec$.

Finding a predicate $HInv$ that is strong enough can be rather difficult. Fortunately, Gafni and Lamport give this predicate. In their paper, they present $HInv$ as a conjunction of 6 predicates $HInv1, \dots, HInv6$, where $HInv1$ is a simple “type invariant” and the higher-numbered predicates add more and more information. The proof is structured such that the preservation of $HInv \ i$ by the algorithm’s next-state relation relies on all $HInv \ j$ (for $j \leq i$) being true in the state before the transition. In our proofs we are going to use exactly the same tactic.

Before starting our proofs we have to translate all the specification and theorems above into the formal language of Isabelle/HOL.

3 Translating from TLA⁺ to Isabelle/HOL

The translation from TLA⁺ to Isabelle/HOL is pretty straightforward as Isabelle/HOL has equivalent counterparts for most of the constructs in TLA⁺ (some representative examples are shown in table 1). Nevertheless, there are some semantic discrepancies. In the following, we discuss these differences, some of the options that one has when dealing with them, and the reasons for our choices¹.

3.1 Typed vs. Untyped

TLA⁺ is an untyped formalism. However, TLA⁺ specifications usually have some type information, usually in the form of set membership or set inclusion. When translating these specifications to Isabelle/HOL, which is a typed formalism, one has to invent types that represent these sets of values.

¹There is no point in using the existing TLA encoding in Isabelle. Since the encoding is also based on HOL and we only prove safety, we would have gained nothing.

TLA⁺:

CONSTANT *Inputs*

NotAnInput \triangleq CHOOSE $c : c \notin Inputs$

DiskBlock \triangleq [*mbal* : (UNION *Ballot*(p) : $p \in Proc$) \cup {0},
bal : (UNION *Ballot*(p) : $p \in Proc$) \cup {0},
inp : $Inputs \cup \{NotAnInput\}$]

Isabelle/HOL:

typedecl *InputsOrNi*

consts

Inputs :: *InputsOrNi* set

NotAnInput :: *InputsOrNi*

axioms

NotAnInput: *NotAnInput* $\notin Inputs$

InputsOrNi: (UNIV :: *InputsOrNi* set) = $Inputs \cup \{NotAnInput\}$

record

DiskBlock =

mbal:: nat

bal :: nat

inp :: *InputsOrNi*

Figure 2: Untyped TLA⁺ vs. Typed Isabelle/HOL

This process is not automatic and requires some thought to find the right abstractions. Furthermore, simple types may not be expressive enough to represent exactly the set in the specification. In some cases, these sets could be modelled by algebraic datatypes, but this would make the specification more complex and less directly related to the original one. In this work, we have chosen to stick to simple types and add additional axioms to account for their lack of expressiveness.

For example, see figure 2. The type *InputsOrNi* models the members of the set *Inputs*, and the element *NotAnInput*. We record the fact that *NotAnInput* is not in *Inputs*, with axiom *NotAnInput*. Now, looking at the type of the *inp* field of the *DiskBlock* record in the TLA⁺ specification, we see that its type should be *InputsOrNi*. However, this is not the same type as $Inputs \cup \{NotAnInput\}$, as nothing prevents the *InputsOrNi* type from having more values. Consequently, we add the axiom *InputsOrNi* to establish that the only values of this type are the ones in *Inputs* and *NotAnInput*.

This example shows the kind of difficulties that can arise when trans-

TLA⁺:

$$\begin{aligned}
& \text{Phase1or2Write}(p, d) \triangleq \\
& \wedge \text{phase}[p] \in \{1, 2\} \\
& \wedge \text{disk}' = [\text{disk} \text{ EXCEPT } ![d][p] = \text{dblock}[p]] \\
& \wedge \text{disksWritten}' = [\text{disksWritten} \text{ EXCEPT } ![p] = @ \cup \{d\}] \\
& \wedge \text{UNCHANGED } \langle \text{input}, \text{output}, \text{phase}, \text{dblock}, \text{blocksRead} \rangle
\end{aligned}$$

Isabelle/HOL:

$$\begin{aligned}
& \text{Phase1or2Write} :: \text{state} \Rightarrow \text{state} \Rightarrow \text{Proc} \Rightarrow \text{Disk} \Rightarrow \text{bool} \\
& \text{Phase1or2Write } s \ s' \ p \ d \equiv \\
& \quad \text{phase } s \ p \in \{1, 2\} \\
& \wedge \text{disk } s' = (\text{disk } s) (d := (\text{disk } s \ d) (p := \text{dblock } s \ p)) \\
& \wedge \text{disksWritten } s' = (\text{disksWritten } s) (p := (\text{disksWritten } s \ p) \cup \{d\}) \\
& \wedge \text{inpt } s' = \text{inpt } s \wedge \text{outpt } s' = \text{outpt } s \\
& \wedge \text{phase } s' = \text{phase } s \wedge \text{dblock } s' = \text{dblock } s \\
& \wedge \text{blocksRead } s' = \text{blocksRead } s
\end{aligned}$$

Figure 3: Translation of an action

lating from an untyped formalism to a typed one. Another solution to this matter that is being currently investigated is the implementation of native (untyped) support for TLA⁺ in Isabelle, without relying on HOL.

3.2 Primed Variables

In TLA⁺, to denote the value of a variable in the state resulting from an action, there exists the concept of primed variables. In Isabelle/HOL, there is no built-in notion of state, so we define the state as a record of the variables involved. Instead of defining a “priming” operator, we just define actions as predicates that take any two states, intended to be the previous state and the next state. In this way, $P \ s \ s'$ will be true iff executing an action P in the s state could result in the s' state. In figure 3 we can see how the action *Phase1or2Write* is expressed in TLA⁺ and in Isabelle/HOL.

3.3 Restructuring the specification

There are some minor changes that can be made to specifications to make the proofs in Isabelle easier.

One such change is the elimination of LET constructs by making them global definitions. This has two benefits, as it makes it possible to:

- Formulate lemmas that use these definitions.
- Selectively unfold these definitions in proofs, instead of adding *Let-def* to Isabelle’s simplifier, which unfolds all “let” constructs.

Another change that makes proofs easier is to break down actions into simpler actions (e.g. giving separate definitions for subactions corresponding to disjuncts). By making actions smaller, Isabelle has to deal with smaller formulas when we feed the prover with such an action.

For example, *Phase1or2Read* is mainly a big if-then-else. We break it down into two simpler actions:

$$Phase1or2Read \triangleq Phase1or2ReadThen \vee Phase1or2ReadElse$$

In *Phase1or2ReadThen* the condition of the if-then-else is present as a state formula (i.e. it is an enabling condition) while in *Phase1or2ReadElse* we add the negation of this condition.

Another example is *HInv2*, which we break down into:

$$HInv2 \triangleq Inv2a \wedge Inv2b \wedge Inv2c$$

Not only we break it down into three conjuncts but, since these conjuncts are quantifications over some predicate, we give a separate definition for this predicate. For example for *Inv2a*, and after translating to Isabelle/HOL, instead of writing:

$$Inv2a\ s \equiv \forall p. \forall bk \in blocksOf\ s\ p. \dots$$

we write:

$$\begin{aligned} Inv2a\text{-innermost} &:: state \Rightarrow Proc \Rightarrow DiskBlock \Rightarrow bool \\ Inv2a\text{-innermost}\ s\ p\ bk &\equiv \dots \end{aligned}$$

$$\begin{aligned} Inv2a\text{-inner} &:: state \Rightarrow Proc \Rightarrow bool \\ Inv2a\text{-inner}\ s\ p &\equiv \forall bk \in blocksOf\ s\ p. Inv2a\text{-innermost}\ s\ p\ bk \end{aligned}$$

$$\begin{aligned} Inv2a &:: state \Rightarrow bool \\ Inv2a\ s &\equiv \forall p. Inv2a\text{-inner}\ s\ p \end{aligned}$$

Now we can express that we want to obtain the fact

$$Inv2a\text{-innermost}\ s\ q\ (dblock\ s\ q)$$

explicitly stating that we are interested in predicate *Inv2a*, but only for some process *q* and block (*dblock s q*).

4 Structure of the Correctness Proof

In [GL00], a specification of correctness and a specification of the algorithm are given. Then, it is proved that the specification of the algorithm implies the specification of correctness. We will do the same for the translated specifications, maintaining the names of theorems and lemmas. It should be noted that only safety properties are given and proved.

4.1 Going from Informal Proofs to Formal Proofs

There are informal proofs for invariants $HInv3$ - $HInv6$ and for theorem $R2b$ in [GL00]. These informal proofs are written in the structured-proof style that Lamport advocates [Lam95], and are rigorous and quite detailed. We based our formal proofs on these informal proofs, but in many cases a higher level of detail was needed. In some cases, the steps were too big for Isabelle to solve them automatically, and intermediate steps had to be proved first; in other cases, some of the facts relevant to the proofs were omitted in the informal proofs.

As an example of these omissions, the invariant should state that the set $allRdBlks$ is finite. This is needed to choose a block with a maximum ballot number in action $EndPhase1$. Interestingly, this omission cannot be detected with finite-state model checking. As another example, it was omitted that it is necessary to assume that $HInv4$ and $HInv5$ hold in the previous state to prove lemma $I2f$.

Although our proofs were based on the informal ones, the high-level structure was often different. When proving that a predicate I was an invariant of $Next$, we preferred proving the invariance of I for each action, rather than a big theorem proving the invariance of I for the $Next$ action. As a consequence, a proof for some actions was often similar to the proof of some other action. For example, the proof of the invariance of $HInv3$ for the $EndPhase0$ and $Fail$ actions is almost the same. This means we could have made only one proof for the two actions, shortening the length of the complete proof. Nevertheless, proving each action separately could be tackled more easily by Isabelle, as it had fewer facts to deal with, and proving a new lemma was often a simple matter of copy, paste and renaming of definitions. Once the invariance of a given predicate has been proved for each simple action, proving it for the $Next$ action is easy since the $Next$ action is a disjunction of all actions.

The informal proofs start working with $Next$, and then do a case split in which each case implies some action. The structure of the formal proof was copied from the informal one, in the parts where the latter focused on a particular action. This structure could be easily maintained since we used Isabelle's Isar proof language [Wen02, Nip03], a language for writing human-readable structured proofs.

Lamport's use of a hierarchical scheme for naming subformulas of a formula would have been very useful, as we have to repeatedly extract subfacts from facts. These proofs were always solved automatically by the auto Isabelle tactic, but made the proofs longer and harder to understand. Automatic naming of subformulas of Isabelle definitions would be a very practical feature.

5 Conclusion

We formally verified the correctness of the Disk Paxos specification in Isabelle/HOL. We found some omissions in the informal proofs, including one that could not have been detected with finite-state model checking, but no outright errors. This formal proof gives us a greater confidence in the correctness of the algorithm.

This work was done in little more than two months, including learning Isabelle from scratch. Consequently, this work can be taken as evidence that formal verification of fault-tolerant distributed algorithms may be feasible for software verification in an industrial context.

Isabelle proved to be a very helpful tool for this kind of verification, although it would have been useful to have Lamport's naming of subfacts to make proofs shorter and easier to write.

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A TLA⁺ correctness specification

MODULE <i>Synod</i>
EXTENDS <i>Naturals</i>
CONSTANT <i>N, Inputs</i>
ASSUME $(N \in \text{Nat}) \wedge (N > 0)$
$Proc \triangleq 1..N$
$NotAnInput \triangleq \text{CHOOSE } c : c \notin Inputs$
VARIABLES <i>inputs, output</i>
MODULE <i>Inner</i>
VARIABLES <i>allInput, chosen</i>
$IInit \triangleq \wedge input \in [Proc \rightarrow Inputs]$ $\wedge output = [p \in Proc \mapsto NotAnInput]$ $\wedge chosen = NotAnInput$ $\wedge allInput = input[p] : p \in Proc$
$IChoose(p) \triangleq$ $\wedge output[p] = NotAnInput$ $\wedge \text{IF } chosen = NotAnInput$ $\quad \text{THEN } ip \in allInput : \wedge chosen' = ip$ $\quad \quad \quad \wedge output' = [output \text{ EXCEPT } ![p] = ip]$ $\quad \text{ELSE } \wedge output' = [output \text{ EXCEPT } ![p] = chosen]$ $\quad \quad \quad \wedge \text{UNCHANGED } chosen$ $\wedge \text{UNCHANGED } \langle input, allInput \rangle$
$IFail(p) \triangleq \wedge output' = [output \text{ EXCEPT } ![p] = NotAnInput]$ $\wedge \exists ip \in Inputs : \wedge input' = [input \text{ EXCEPT } ![p] = ip]$ $\quad \quad \quad \wedge allInput' = allInput \cup \{ip\}$
$INext \triangleq \exists p \in Proc : IChoose(p) \vee IFail(p)$
$ISpec \triangleq IInit \wedge \square [INext]_{\langle input, output, chosen, allInput \rangle}$
$IS(chosen, allInput) \triangleq \text{INSTANCE } Inner$
$SynodSpec \triangleq \exists chosen, allInput : IS(chosen, allInput)!ISpec$

B Disk Paxos Algorithm Specification

theory *DiskPaxos-Model* **imports** *Main* **begin**

This is the specification of the Disk Synod algorithm.

typedecl *InputsOrNi*

typedecl *Disk*

typedecl *Proc*

axiomatization

Inputs :: *InputsOrNi* set **and**

NotAnInput :: *InputsOrNi* **and**

Ballot :: *Proc* \Rightarrow nat set **and**

IsMajority :: *Disk* set \Rightarrow bool

where

NotAnInput: *NotAnInput* \notin *Inputs* **and**

InputsOrNi: (*UNIV* :: *InputsOrNi* set) = *Inputs* \cup {*NotAnInput*} **and**

Ballot-nzero: $\forall p. 0 \notin$ *Ballot* *p* **and**

Ballot-disj: $\forall p q. p \neq q \longrightarrow$ (*Ballot* *p*) \cap (*Ballot* *q*) = {} **and**

Disk-isMajority: *IsMajority*(*UNIV*) **and**

majorities-intersect:

$\forall S T. \text{IsMajority}(S) \wedge \text{IsMajority}(T) \longrightarrow S \cap T \neq \{\}$

lemma *ballots-not-zero* [*simp*]:

$b \in$ *Ballot* *p* $\implies 0 < b$

proof (*rule ccontr*)

assume *b*: $b \in$ *Ballot* *p*

and *contr*: $\neg (0 < b)$

from *Ballot-nzero*

have $0 \notin$ *Ballot* *p* ..

with *b* *contr*

show *False*

by *auto*

qed

lemma *majority-nonempty* [*simp*]: *IsMajority*(*S*) $\implies S \neq \{\}$

proof(*auto*)

from *majorities-intersect*

have *IsMajority*({}) \wedge *IsMajority*({}) \longrightarrow {} \cap {} \neq {}

by *auto*

thus *IsMajority* {} \implies *False*

by *auto*

qed

definition *AllBallots* :: nat set

where *AllBallots* = (*UN* *p*. *Ballot* *p*)

record

DiskBlock =

mbal :: nat
bal :: nat
inp :: InputsOrNi

definition *InitDB* :: DiskBlock
where *InitDB* = (| *mbal* = 0, *bal* = 0, *inp* = NotAnInput |)

record
BlockProc =
block :: DiskBlock
proc :: Proc

record
state =
inpt :: Proc ⇒ InputsOrNi
outpt :: Proc ⇒ InputsOrNi
disk :: Disk ⇒ Proc ⇒ DiskBlock
dblock :: Proc ⇒ DiskBlock
phase :: Proc ⇒ nat
disksWritten :: Proc ⇒ Disk set
blocksRead :: Proc ⇒ Disk ⇒ BlockProc set

allInput :: InputsOrNi set
chosen :: InputsOrNi

definition *hasRead* :: state ⇒ Proc ⇒ Disk ⇒ Proc ⇒ bool
where *hasRead* *s p d q* = (∃ *br* ∈ *blocksRead* *s p d*. *proc* *br* = *q*)

definition *allRdBlks* :: state ⇒ Proc ⇒ BlockProc set
where *allRdBlks* *s p* = (UN *d*. *blocksRead* *s p d*)

definition *allBlocksRead* :: state ⇒ Proc ⇒ DiskBlock set
where *allBlocksRead* *s p* = *block* ' (*allRdBlks* *s p*)

definition *Init* :: state ⇒ bool
where
Init *s* =
(range (*inpt* *s*) ⊆ Inputs
& *outpt* *s* = (λ*p*. NotAnInput)
& *disk* *s* = (λ*d p*. *InitDB*)
& *phase* *s* = (λ*p*. 0)
& *dblock* *s* = (λ*p*. *InitDB*)
& *disksWritten* *s* = (λ*p*. {})
& *blocksRead* *s* = (λ*p d*. {}))

definition *InitializePhase* :: state ⇒ state ⇒ Proc ⇒ bool
where
InitializePhase *s s' p* =

$$\begin{aligned} & (disksWritten\ s' = (disksWritten\ s)(p := \{\})) \\ & \& \text{blocksRead } s' = (\text{blocksRead } s)(p := (\lambda d. \{\})) \end{aligned}$$

definition *StartBallot* :: *state* \Rightarrow *state* \Rightarrow *Proc* \Rightarrow *bool*

where

$$\begin{aligned} & \text{StartBallot } s\ s'\ p = \\ & \quad (\text{phase } s\ p \in \{1, 2\}) \\ & \quad \& \text{phase } s' = (\text{phase } s)(p := 1) \\ & \quad \& (\exists b \in \text{Ballot } p. \\ & \quad \quad \text{mbal } (\text{dblock } s\ p) < b \\ & \quad \quad \& \text{dblock } s' = (\text{dblock } s)(p := (\text{dblock } s\ p) \parallel \text{mbal } := b)) \\ & \quad \& \text{InitializePhase } s\ s'\ p \\ & \quad \& \text{inpt } s' = \text{inpt } s \ \& \ \text{outpt } s' = \text{outpt } s \ \& \ \text{disk } s' = \text{disk } s \end{aligned}$$

definition *Phase1or2Write* :: *state* \Rightarrow *state* \Rightarrow *Proc* \Rightarrow *Disk* \Rightarrow *bool*

where

$$\begin{aligned} & \text{Phase1or2Write } s\ s'\ p\ d = \\ & \quad (\text{phase } s\ p \in \{1, 2\}) \\ & \quad \wedge \text{disk } s' = (\text{disk } s)\ (d := (\text{disk } s\ d)\ (p := \text{dblock } s\ p)) \\ & \quad \wedge \text{disksWritten } s' = (\text{disksWritten } s)\ (p := (\text{disksWritten } s\ p) \cup \{d\}) \\ & \quad \wedge \text{inpt } s' = \text{inpt } s \ \wedge \ \text{outpt } s' = \text{outpt } s \\ & \quad \wedge \text{phase } s' = \text{phase } s \ \wedge \ \text{dblock } s' = \text{dblock } s \\ & \quad \wedge \text{blocksRead } s' = \text{blocksRead } s \end{aligned}$$

definition *Phase1or2ReadThen* :: *state* \Rightarrow *state* \Rightarrow *Proc* \Rightarrow *Disk* \Rightarrow *Proc* \Rightarrow *bool*

where

$$\begin{aligned} & \text{Phase1or2ReadThen } s\ s'\ p\ d\ q = \\ & \quad (d \in \text{disksWritten } s\ p) \\ & \quad \& \text{mbal}(\text{disk } s\ d\ q) < \text{mbal}(\text{dblock } s\ p) \\ & \quad \& \text{blocksRead } s' = (\text{blocksRead } s)(p := (\text{blocksRead } s\ p)(d := \\ & \quad \quad (\text{blocksRead } s\ p\ d) \cup \{\parallel \text{block} = \text{disk } s\ d\ q, \\ & \quad \quad \quad \text{proc} = q\ \parallel\})) \\ & \quad \& \text{inpt } s' = \text{inpt } s \ \& \ \text{outpt } s' = \text{outpt } s \\ & \quad \& \text{disk } s' = \text{disk } s \ \& \ \text{phase } s' = \text{phase } s \\ & \quad \& \text{dblock } s' = \text{dblock } s \ \& \ \text{disksWritten } s' = \text{disksWritten } s \end{aligned}$$

definition *Phase1or2ReadElse* :: *state* \Rightarrow *state* \Rightarrow *Proc* \Rightarrow *Disk* \Rightarrow *Proc* \Rightarrow *bool*

where

$$\begin{aligned} & \text{Phase1or2ReadElse } s\ s'\ p\ d\ q = \\ & \quad (d \in \text{disksWritten } s\ p) \\ & \quad \wedge \text{StartBallot } s\ s'\ p \end{aligned}$$

definition *Phase1or2Read* :: *state* \Rightarrow *state* \Rightarrow *Proc* \Rightarrow *Disk* \Rightarrow *Proc* \Rightarrow *bool*

where

$$\begin{aligned} & \text{Phase1or2Read } s\ s'\ p\ d\ q = \\ & \quad (\text{Phase1or2ReadThen } s\ s'\ p\ d\ q) \\ & \quad \vee \text{Phase1or2ReadElse } s\ s'\ p\ d\ q \end{aligned}$$

definition *blocksSeen* :: *state* \Rightarrow *Proc* \Rightarrow *DiskBlock set*

where $blocksSeen\ s\ p = allBlocksRead\ s\ p \cup \{dblock\ s\ p\}$

definition $nonInitBlks :: state \Rightarrow Proc \Rightarrow DiskBlock\ set$

wherenonInitBlks $s\ p = \{bs . bs \in blocksSeen\ s\ p \wedge inp\ bs \in Inputs\}$

definition $maxBlk :: state \Rightarrow Proc \Rightarrow DiskBlock$

where

$maxBlk\ s\ p =$
 $(SOME\ b . b \in nonInitBlks\ s\ p \wedge (\forall c \in nonInitBlks\ s\ p . bal\ c \leq bal\ b))$

definition $EndPhase1 :: state \Rightarrow state \Rightarrow Proc \Rightarrow bool$

where

$EndPhase1\ s\ s'\ p =$
 $(IsMajority\ \{d . d \in disksWritten\ s\ p$
 $\quad \wedge (\forall q \in UNIV - \{p\} . hasRead\ s\ p\ d\ q)\}$
 $\wedge\ phase\ s\ p = 1$
 $\wedge\ dblock\ s' = (dblock\ s)\ (p := dblock\ s\ p$
 $\quad \langle\ bal := mbal(dblock\ s\ p),$
 $\quad inp :=$
 $\quad\quad (if\ nonInitBlks\ s\ p = \{\}$
 $\quad\quad\quad then\ inpt\ s\ p$
 $\quad\quad\quad else\ inp\ (maxBlk\ s\ p))$
 $\quad \rangle)$
 $\wedge\ outpt\ s' = outpt\ s$
 $\wedge\ phase\ s' = (phase\ s)\ (p := phase\ s\ p + 1)$
 $\wedge\ InitializePhase\ s\ s'\ p$
 $\wedge\ inpt\ s' = inpt\ s \wedge disk\ s' = disk\ s)$

definition $EndPhase2 :: state \Rightarrow state \Rightarrow Proc \Rightarrow bool$

where

$EndPhase2\ s\ s'\ p =$
 $(IsMajority\ \{d . d \in disksWritten\ s\ p$
 $\quad \wedge (\forall q \in UNIV - \{p\} . hasRead\ s\ p\ d\ q)\}$
 $\wedge\ phase\ s\ p = 2$
 $\wedge\ outpt\ s' = (outpt\ s)\ (p := inp\ (dblock\ s\ p))$
 $\wedge\ dblock\ s' = dblock\ s$
 $\wedge\ phase\ s' = (phase\ s)\ (p := phase\ s\ p + 1)$
 $\wedge\ InitializePhase\ s\ s'\ p$
 $\wedge\ inpt\ s' = inpt\ s \wedge disk\ s' = disk\ s)$

definition $EndPhase1or2 :: state \Rightarrow state \Rightarrow Proc \Rightarrow bool$

where $EndPhase1or2\ s\ s'\ p = (EndPhase1\ s\ s'\ p \vee EndPhase2\ s\ s'\ p)$

definition $Fail :: state \Rightarrow state \Rightarrow Proc \Rightarrow bool$

where

$Fail\ s\ s'\ p =$
 $(\exists ip \in Inputs . inpt\ s' = (inpt\ s)\ (p := ip)$
 $\wedge\ phase\ s' = (phase\ s)\ (p := 0)$
 $\wedge\ dblock\ s' = (dblock\ s)\ (p := InitDB)$

$$\begin{aligned} &\wedge \text{outpt } s' = (\text{outpt } s) (p := \text{NotAnInput}) \\ &\wedge \text{InitializePhase } s \ s' \ p \\ &\wedge \text{disk } s' = \text{disk } s \end{aligned}$$

definition *Phase0Read* :: *state* \Rightarrow *state* \Rightarrow *Proc* \Rightarrow *Disk* \Rightarrow *bool*

where

$$\begin{aligned} \text{Phase0Read } s \ s' \ p \ d = & \\ & (\text{phase } s \ p = 0 \\ & \wedge \text{blocksRead } s' = (\text{blocksRead } s) (p := (\text{blocksRead } s \ p)) (d := \text{blocksRead } s \ p \ d) \\ \cup \{ & (\text{block} = \text{disk } s \ d \ p, \text{proc} = p \ \}) \\ & \wedge \text{inpt } s' = \text{inpt } s \ \& \ \text{outpt } s' = \text{outpt } s \\ & \wedge \text{disk } s' = \text{disk } s \ \& \ \text{phase } s' = \text{phase } s \\ & \wedge \text{dblock } s' = \text{dblock } s \ \& \ \text{disksWritten } s' = \text{disksWritten } s \end{aligned}$$

definition *EndPhase0* :: *state* \Rightarrow *state* \Rightarrow *Proc* \Rightarrow *bool*

where

$$\begin{aligned} \text{EndPhase0 } s \ s' \ p = & \\ & (\text{phase } s \ p = 0 \\ & \wedge \text{IsMajority } (\{d. \text{hasRead } s \ p \ d \}) \\ & \wedge (\exists b \in \text{Ballot } p. \\ & \quad (\forall r \in \text{allBlocksRead } s \ p. \text{mbal } r < b) \\ & \quad \wedge \text{dblock } s' = (\text{dblock } s) (p := \\ & \quad \quad (\text{SOME } r. \ r \in \text{allBlocksRead } s \ p \\ & \quad \quad \quad \wedge (\forall s \in \text{allBlocksRead } s \ p. \text{bal } s \leq \text{bal } r)) (\text{mbal} := b \ \)) \\ & \wedge \text{InitializePhase } s \ s' \ p \\ & \wedge \text{phase } s' = (\text{phase } s) (p := 1) \\ & \wedge \text{inpt } s' = \text{inpt } s \ \wedge \ \text{outpt } s' = \text{outpt } s \ \wedge \ \text{disk } s' = \text{disk } s \end{aligned}$$

definition *Next* :: *state* \Rightarrow *state* \Rightarrow *bool*

where

$$\begin{aligned} \text{Next } s \ s' = & (\exists p. \\ & \quad \text{StartBallot } s \ s' \ p \\ & \quad \vee (\exists d. \ \text{Phase0Read } s \ s' \ p \ d \\ & \quad \quad \vee \text{Phase1or2Write } s \ s' \ p \ d \\ & \quad \quad \vee (\exists q. \ q \neq p \ \wedge \ \text{Phase1or2Read } s \ s' \ p \ d \ q)) \\ & \quad \vee \text{EndPhase1or2 } s \ s' \ p \\ & \quad \vee \text{Fail } s \ s' \ p \\ & \quad \vee \text{EndPhase0 } s \ s' \ p) \end{aligned}$$

In the following, for each action or state *name* we name *Hname* the corresponding action that includes the history part of the HNext action or state predicate that includes history variables.

definition *HInit* :: *state* \Rightarrow *bool*

where

$$\begin{aligned} \text{HInit } s = & \\ & (\text{Init } s \\ & \ \& \ \text{chosen } s = \text{NotAnInput} \\ & \ \& \ \text{allInput } s = \text{range } (\text{inpt } s)) \end{aligned}$$

HNextPart is the part of the Next action that is concerned with history variables.

definition $HNextPart :: state \Rightarrow state \Rightarrow bool$

where

$$\begin{aligned} HNextPart\ s\ s' = & \\ & (chosen\ s' = \\ & \quad (if\ chosen\ s \neq NotAnInput \vee (\forall p. outpt\ s'\ p = NotAnInput) \\ & \quad \quad then\ chosen\ s \\ & \quad \quad else\ outpt\ s'\ (SOME\ p. outpt\ s'\ p \neq NotAnInput)) \\ & \wedge\ allInput\ s' = allInput\ s \cup (range\ (inpt\ s')) \end{aligned}$$

definition $HNext :: state \Rightarrow state \Rightarrow bool$

where

$$\begin{aligned} HNext\ s\ s' = & \\ & (Next\ s\ s' \\ & \wedge\ HNextPart\ s\ s') \end{aligned}$$

We add HNextPart to every action (rather than proving that Next maintains the HInv invariant) to make proofs easier.

definition

$$\begin{aligned} HPhase1or2ReadThen :: state \Rightarrow state \Rightarrow Proc \Rightarrow Disk \Rightarrow Proc \Rightarrow bool \textbf{ where} \\ HPhase1or2ReadThen\ s\ s'\ p\ d\ q = (Phase1or2ReadThen\ s\ s'\ p\ d\ q \wedge HNextPart\ s\ s') \end{aligned}$$

definition

$$\begin{aligned} HEndPhase1 :: state \Rightarrow state \Rightarrow Proc \Rightarrow bool \textbf{ where} \\ HEndPhase1\ s\ s'\ p = (EndPhase1\ s\ s'\ p \wedge HNextPart\ s\ s') \end{aligned}$$

definition

$$\begin{aligned} HStartBallot :: state \Rightarrow state \Rightarrow Proc \Rightarrow bool \textbf{ where} \\ HStartBallot\ s\ s'\ p = (StartBallot\ s\ s'\ p \wedge HNextPart\ s\ s') \end{aligned}$$

definition

$$\begin{aligned} HPhase1or2Write :: state \Rightarrow state \Rightarrow Proc \Rightarrow Disk \Rightarrow bool \textbf{ where} \\ HPhase1or2Write\ s\ s'\ p\ d = (Phase1or2Write\ s\ s'\ p\ d \wedge HNextPart\ s\ s') \end{aligned}$$

definition

$$\begin{aligned} HPhase1or2ReadElse :: state \Rightarrow state \Rightarrow Proc \Rightarrow Disk \Rightarrow Proc \Rightarrow bool \textbf{ where} \\ HPhase1or2ReadElse\ s\ s'\ p\ d\ q = (Phase1or2ReadElse\ s\ s'\ p\ d\ q \wedge HNextPart\ s\ s') \end{aligned}$$

definition

$$\begin{aligned} HEndPhase2 :: state \Rightarrow state \Rightarrow Proc \Rightarrow bool \textbf{ where} \\ HEndPhase2\ s\ s'\ p = (EndPhase2\ s\ s'\ p \wedge HNextPart\ s\ s') \end{aligned}$$

definition

$$\begin{aligned} HFail :: state \Rightarrow state \Rightarrow Proc \Rightarrow bool \textbf{ where} \\ HFail\ s\ s'\ p = (Fail\ s\ s'\ p \wedge HNextPart\ s\ s') \end{aligned}$$

definition

$HPhase0Read :: state \Rightarrow state \Rightarrow Proc \Rightarrow Disk \Rightarrow bool$ **where**
 $HPhase0Read\ s\ s'\ p\ d = (Phase0Read\ s\ s'\ p\ d \wedge HNextPart\ s\ s')$

definition

$HEndPhase0 :: state \Rightarrow state \Rightarrow Proc \Rightarrow bool$ **where**
 $HEndPhase0\ s\ s'\ p = (EndPhase0\ s\ s'\ p \wedge HNextPart\ s\ s')$

Since these definitions are the conjunction of two other definitions declaring them as simplification rules should be harmless.

declare $HPhase1or2ReadThen-def$ [*simp*]
declare $HPhase1or2ReadElse-def$ [*simp*]
declare $HEndPhase1-def$ [*simp*]
declare $HStartBallot-def$ [*simp*]
declare $HPhase1or2Write-def$ [*simp*]
declare $HEndPhase2-def$ [*simp*]
declare $HFail-def$ [*simp*]
declare $HPhase0Read-def$ [*simp*]
declare $HEndPhase0-def$ [*simp*]

end

C Proof of Disk Paxos' Invariant

theory $DiskPaxos-Inv1$ **imports** $DiskPaxos-Model$ **begin**

C.1 Invariant 1

This is just a type Invariant.

definition $Inv1 :: state \Rightarrow bool$

where

$Inv1\ s = (\forall p.$
 $\quad inpt\ s\ p \in Inputs$
 $\quad \wedge\ phase\ s\ p \leq 3$
 $\quad \wedge\ finite\ (allRdBlks\ s\ p))$

definition $HInv1 :: state \Rightarrow bool$

where

$HInv1\ s =$
 $\quad (Inv1\ s$
 $\quad \wedge\ allInput\ s \subseteq Inputs)$

declare $HInv1-def$ [*simp*]

We added the assertion that the set $allRdBlksp$ is finite for every process p ; one may therefore choose a block with a maximum ballot number in action $EndPhase1$.

With the following the lemma, it will be enough to prove $\text{Inv1 } s'$ for every action, without taking the history variables in account.

lemma *HNextPart-Inv1*: $\llbracket \text{HInv1 } s; \text{HNextPart } s \ s'; \text{Inv1 } s' \rrbracket \implies \text{HInv1 } s'$
 by(*auto simp add: HNextPart-def Inv1-def*)

theorem *HInit-HInv1*: $\text{HInit } s \longrightarrow \text{HInv1 } s$
 by(*auto simp add: HInit-def Inv1-def Init-def allRdBlks-def*)

lemma *allRdBlks-finite*:
 assumes *inv*: $\text{HInv1 } s$
 and *asm*: $\forall p. \text{allRdBlks } s' \ p \subseteq \text{insert } bk \ (\text{allRdBlks } s \ p)$
 shows $\forall p. \text{finite } (\text{allRdBlks } s' \ p)$

proof
 fix *pp*
 from *inv*
 have $\forall p. \text{finite } (\text{allRdBlks } s \ p)$
 by(*simp add: Inv1-def*)
 hence $\text{finite } (\text{allRdBlks } s \ pp)$
 by *blast*
 with *asm*
 show $\text{finite } (\text{allRdBlks } s' \ pp)$
 by (*auto intro: finite-subset*)

qed

theorem *HPhase1or2ReadThen-HInv1*:
 assumes *inv1*: $\text{HInv1 } s$
 and *act*: $\text{HPhase1or2ReadThen } s \ s' \ p \ d \ q$
 shows $\text{HInv1 } s'$

proof –
 – we focus on the last conjunct of Inv1
 from *act*
 have $\forall p. \text{allRdBlks } s' \ p \subseteq \text{allRdBlks } s \ p \cup \{\text{block} = \text{disk } s \ d \ q, \text{proc} = q\}$
 by(*auto simp add: Phase1or2ReadThen-def allRdBlks-def*
 split: if-split-asm)
 with *inv1*
 have $\forall p. \text{finite } (\text{allRdBlks } s' \ p)$
 by(*blast dest: allRdBlks-finite*)
 – the others conjuncts are trivial
 with *inv1 act*
 show *?thesis*
 by(*auto simp add: Inv1-def Phase1or2ReadThen-def HNextPart-def*)

qed

theorem *HEndPhase1-HInv1*:
 assumes *inv1*: $\text{HInv1 } s$
 and *act*: $\text{HEndPhase1 } s \ s' \ p$
 shows $\text{HInv1 } s'$

proof –
 from *inv1 act*

have $Inv1\ s'$
by(*auto simp add: Inv1-def EndPhase1-def InitializePhase-def allRdBlks-def*)
with $inv1\ act$
show $?thesis$
by(*auto simp del: HInv1-def dest: HNextPart-Inv1*)
qed

theorem *HStartBallot-HInv1*:
assumes $inv1: HInv1\ s$
and $act: HStartBallot\ s\ s'\ p$
shows $HInv1\ s'$
proof –
from $inv1\ act$
have $Inv1\ s'$
by(*auto simp add: Inv1-def StartBallot-def InitializePhase-def allRdBlks-def*)
with $inv1\ act$
show $?thesis$
by(*auto simp del: HInv1-def elim: HNextPart-Inv1*)
qed

theorem *HPhase1or2Write-HInv1*:
assumes $inv1: HInv1\ s$
and $act: HPhase1or2Write\ s\ s'\ p\ d$
shows $HInv1\ s'$
proof –
from $inv1\ act$
have $Inv1\ s'$
by(*auto simp add: Inv1-def Phase1or2Write-def allRdBlks-def*)
with $inv1\ act$
show $?thesis$
by(*auto simp del: HInv1-def elim: HNextPart-Inv1*)
qed

theorem *HPhase1or2ReadElse-HInv1*:
assumes $act: HPhase1or2ReadElse\ s\ s'\ p\ d\ q$
and $inv1: HInv1\ s$
shows $HInv1\ s'$
using *HStartBallot-HInv1[OF inv1] act*
by(*auto simp add: Phase1or2ReadElse-def*)

theorem *HEndPhase2-HInv1*:
assumes $inv1: HInv1\ s$
and $act: HEndPhase2\ s\ s'\ p$
shows $HInv1\ s'$
proof –
from $inv1\ act$
have $Inv1\ s'$
by(*auto simp add: Inv1-def EndPhase2-def InitializePhase-def allRdBlks-def*)
with $inv1\ act$

show *?thesis*
by(*auto simp del: HInv1-def elim: HNextPart-Inv1*)
qed

theorem *HFail-HInv1*:
assumes *inv1: HInv1 s*
and *act: HFail s s' p*
shows *HInv1 s'*
proof –
from *inv1 act*
have *Inv1 s'*
by(*auto simp add: Inv1-def Fail-def InitializePhase-def allRdBlks-def*)
with *inv1 act* **show** *?thesis*
by(*auto simp del: HInv1-def elim: HNextPart-Inv1*)
qed

theorem *HPhase0Read-HInv1*:
assumes *inv1: HInv1 s*
and *act: HPhase0Read s s' p d*
shows *HInv1 s'*
proof –
— we focus on the last conjunct of *Inv1*
from *act*
have $\forall pp. \text{allRdBlks } s' pp \subseteq \text{allRdBlks } s pp \cup \{(block = \text{disk } s \ d \ p, \text{proc} = p)\}$
by(*auto simp add: Phase0Read-def allRdBlks-def*
split: if-split-asm)
with *inv1*
have $\forall p. \text{finite } (\text{allRdBlks } s' p)$
by(*blast dest: allRdBlks-finite*)
— the others conjuncts are trivial
with *inv1 act*
have *Inv1 s'*
by(*auto simp add: Inv1-def Phase0Read-def*)
with *inv1 act*
show *?thesis*
by(*auto simp del: HInv1-def elim: HNextPart-Inv1*)
qed

theorem *HEndPhase0-HInv1*:
assumes *inv1: HInv1 s*
and *act: HEndPhase0 s s' p*
shows *HInv1 s'*
proof –
from *inv1 act*
have *Inv1 s'*
by(*auto simp add: Inv1-def EndPhase0-def allRdBlks-def InitializePhase-def*)
with *inv1 act*
show *?thesis*
by(*auto simp del: HInv1-def elim: HNextPart-Inv1*)

qed

declare *HInv1-def* [*simp del*]

HInv1 is an invariant of *HNext*

lemma *I2a*:

assumes *next*: *HNext s s'*
and *inv*: *HInv1 s*
shows *HInv1 s'*
using *assms*
by(*auto*
 simp add: *HNext-def Next-def*,
 auto intro: *HStartBallot-HInv1*,
 auto intro: *HPhase0Read-HInv1*,
 auto intro: *HPhase1or2Write-HInv1*,
 auto simp add: *Phase1or2Read-def*
 intro: *HPhase1or2ReadThen-HInv1*
 HPhase1or2ReadElse-HInv1,
 auto simp add: *EndPhase1or2-def*
 intro: *HEndPhase1-HInv1*
 HEndPhase2-HInv1,
 auto intro: *HFail-HInv1*,
 auto intro: *HEndPhase0-HInv1*)

end

theory *DiskPaxos-Inv2* imports *DiskPaxos-Inv1* begin

C.2 Invariant 2

The second invariant is split into three main conjuncts called *Inv2a*, *Inv2b*, and *Inv2c*. The main difficulty is in proving the preservation of the first conjunct.

definition *rdBy* :: *state* \Rightarrow *Proc* \Rightarrow *Proc* \Rightarrow *Disk* \Rightarrow *BlockProc set*

where

rdBy s p q d =
 {*br* . *br* \in *blocksRead s q d* \wedge *proc br* = *p*}

definition *blocksOf* :: *state* \Rightarrow *Proc* \Rightarrow *DiskBlock set*

where

blocksOf s p =
 {*dblock s p*}
 \cup {*disk s d p* | *d* . *d* \in *UNIV*}
 \cup {*block br* | *br* . *br* \in (*UN q d* . *rdBy s p q d*) }

definition *allBlocks* :: *state* \Rightarrow *DiskBlock set*

where $allBlocks\ s = (UN\ p.\ blocksOf\ s\ p)$

definition $Inv2a\text{-innermost} :: state \Rightarrow Proc \Rightarrow DiskBlock \Rightarrow bool$

where

$$\begin{aligned} Inv2a\text{-innermost}\ s\ p\ bk = & \\ & (mbal\ bk \in (Ballot\ p) \cup \{0\}) \\ & \wedge\ bal\ bk \in (Ballot\ p) \cup \{0\} \\ & \wedge\ (bal\ bk = 0) = (inp\ bk = NotAnInput) \\ & \wedge\ bal\ bk \leq\ mbal\ bk \\ & \wedge\ inp\ bk \in (allInput\ s) \cup \{NotAnInput\} \end{aligned}$$

definition $Inv2a\text{-inner} :: state \Rightarrow Proc \Rightarrow bool$

where $Inv2a\text{-inner}\ s\ p = (\forall\ bk \in\ blocksOf\ s\ p.\ Inv2a\text{-innermost}\ s\ p\ bk)$

definition $Inv2a :: state \Rightarrow bool$

where $Inv2a\ s = (\forall\ p.\ Inv2a\text{-inner}\ s\ p)$

definition $Inv2b\text{-inner} :: state \Rightarrow Proc \Rightarrow Disk \Rightarrow bool$

where

$$\begin{aligned} Inv2b\text{-inner}\ s\ p\ d = & \\ & ((d \in\ disksWritten\ s\ p \longrightarrow \\ & \quad (phase\ s\ p \in \{1,2\} \wedge\ disk\ s\ d\ p =\ dblock\ s\ p)) \\ \wedge\ (phase\ s\ p \in \{1,2\} \longrightarrow & \\ & \quad ((blocksRead\ s\ p\ d \neq \{\} \longrightarrow d \in\ disksWritten\ s\ p) \\ & \quad \wedge\ \neg\ hasRead\ s\ p\ d\ p))) \end{aligned}$$

definition $Inv2b :: state \Rightarrow bool$

where $Inv2b\ s = (\forall\ p\ d.\ Inv2b\text{-inner}\ s\ p\ d)$

definition $Inv2c\text{-inner} :: state \Rightarrow Proc \Rightarrow bool$

where

$$\begin{aligned} Inv2c\text{-inner}\ s\ p = & \\ & ((phase\ s\ p = 0 \longrightarrow \\ & \quad (dblock\ s\ p =\ InitDB \\ & \quad \wedge\ disksWritten\ s\ p = \{\} \\ & \quad \wedge\ (\forall\ d.\ \forall\ br \in\ blocksRead\ s\ p\ d. \\ & \quad \quad proc\ br = p \wedge\ block\ br = disk\ s\ d\ p))) \\ \wedge\ (phase\ s\ p \neq 0 \longrightarrow & \\ & \quad (mbal(dblock\ s\ p) \in\ Ballot\ p \\ & \quad \wedge\ bal(dblock\ s\ p) \in\ Ballot\ p \cup \{0\} \\ & \quad \wedge\ (\forall\ d.\ \forall\ br \in\ blocksRead\ s\ p\ d. \\ & \quad \quad mbal(block\ br) <\ mbal(dblock\ s\ p)))) \\ \wedge\ (phase\ s\ p \in \{2,3\} \longrightarrow & bal(dblock\ s\ p) =\ mbal(dblock\ s\ p)) \\ \wedge\ outpt\ s\ p = (if\ phase\ s\ p = 3\ then\ inp(dblock\ s\ p) & \text{ else } NotAnInput) \\ \wedge\ chosen\ s \in\ allInput\ s \cup \{NotAnInput\} & \\ \wedge\ (\forall\ p.\ inpt\ s\ p \in\ allInput\ s & \\ & \quad \wedge\ (chosen\ s = NotAnInput \longrightarrow outpt\ s\ p = NotAnInput))) \end{aligned}$$

definition $Inv2c :: state \Rightarrow bool$

where $Inv2c\ s = (\forall p. Inv2c\text{-inner}\ s\ p)$

definition $HInv2 :: state \Rightarrow bool$

where $HInv2\ s = (Inv2a\ s \wedge Inv2b\ s \wedge Inv2c\ s)$

C.2.1 Proofs of Invariant 2 a

theorem $HInit\text{-}Inv2a: HInit\ s \longrightarrow Inv2a\ s$

by (auto simp add: $HInit\text{-}def\ Init\text{-}def\ Inv2a\text{-}def\ Inv2a\text{-}inner\text{-}def$
 $Inv2a\text{-}innermost\text{-}def\ rdBy\text{-}def\ blocksOf\text{-}def$
 $InitDB\text{-}def$)

For every action we define a *action-blocksOf* lemma. We have two cases: either the new *blocksOf* is included in the old *blocksOf*, or the new *blocksOf* is included in the old *blocksOf* union the new *dblock*. In the former case the assumption *inv* will imply the thesis. In the latter, we just have to prove the innermost predicate for the particular case of the new *dblock*. This particular case is proved in lemma *action-Inv2a-dblock*.

lemma $HPhase1or2ReadThen\text{-}blocksOf:$

$\llbracket HPhase1or2ReadThen\ s\ s'\ p\ d\ q \rrbracket \Longrightarrow blocksOf\ s'\ r \subseteq blocksOf\ s\ r$
 by (auto simp add: $Phase1or2ReadThen\text{-}def\ blocksOf\text{-}def\ rdBy\text{-}def$)

theorem $HPhase1or2ReadThen\text{-}Inv2a:$

assumes $inv: Inv2a\ s$

and $act: HPhase1or2ReadThen\ s\ s'\ p\ d\ q$

shows $Inv2a\ s'$

proof (clarsimp simp add: $Inv2a\text{-}def\ Inv2a\text{-}inner\text{-}def$)

fix $pp\ bk$

assume $bk: bk \in blocksOf\ s'\ pp$

with $inv\ HPhase1or2ReadThen\text{-}blocksOf[OF\ act]$

have $Inv2a\text{-}innermost\ s\ pp\ bk$

by (auto simp add: $Inv2a\text{-}def\ Inv2a\text{-}inner\text{-}def$)

with act

show $Inv2a\text{-}innermost\ s'\ pp\ bk$

by (auto simp add: $Inv2a\text{-}innermost\text{-}def\ HNextPart\text{-}def$)

qed

lemma $InitializePhase\text{-}rdBy:$

$InitializePhase\ s\ s'\ p \Longrightarrow rdBy\ s'\ pp\ qq\ dd \subseteq rdBy\ s\ pp\ qq\ dd$

by (auto simp add: $InitializePhase\text{-}def\ rdBy\text{-}def$)

lemma $HStartBallot\text{-}blocksOf:$

$HStartBallot\ s\ s'\ p \Longrightarrow blocksOf\ s'\ q \subseteq blocksOf\ s\ q \cup \{dblock\ s'\ q\}$

by (auto simp add: $StartBallot\text{-}def\ blocksOf\text{-}def$
 $dest: subsetD[OF\ InitializePhase\text{-}rdBy]$)

lemma $HStartBallot\text{-}Inv2a\text{-}dblock:$

assumes $act: HStartBallot\ s\ s'\ p$

and $inv2a: Inv2a\text{-}innermost\ s\ p\ (dblock\ s\ p)$

```

  shows Inv2a-innermost s' p (dblock s' p)
proof -
  from act
  have mbal': mbal (dblock s' p) ∈ Ballot p
    by(auto simp add: StartBallot-def)
  from act
  have bal': bal (dblock s' p) = bal (dblock s p)
    by(auto simp add: StartBallot-def)
  with act
  have inp': inp (dblock s' p) = inp (dblock s p)
    by(auto simp add: StartBallot-def)
  from act
  have mbal (dblock s p) ≤ mbal (dblock s' p)
    by(auto simp add: StartBallot-def)
  with bal' inv2a
  have bal-mbal: bal (dblock s' p) ≤ mbal (dblock s' p)
    by(auto simp add: Inv2a-innermost-def)
  from act
  have allInput s ⊆ allInput s'
    by(auto simp add: HNextPart-def)
  with mbal' bal' inp' bal-mbal act inv2a
  show ?thesis
    by(auto simp add: Inv2a-innermost-def)
qed

lemma HStartBallot-Inv2a-dblock-q:
  assumes act: HStartBallot s s' p
  and inv2a: Inv2a-innermost s q (dblock s q)
  shows Inv2a-innermost s' q (dblock s' q)
proof(cases p=q)
  case True
  with act inv2a
  show ?thesis
    by(blast dest: HStartBallot-Inv2a-dblock)
next
  case False
  with act inv2a
  show ?thesis
    by(clarsimp simp add: StartBallot-def HNextPart-def
      InitializePhase-def Inv2a-innermost-def)
qed

theorem HStartBallot-Inv2a:
  assumes inv: Inv2a s
  and act: HStartBallot s s' p
  shows Inv2a s'
proof (clarsimp simp add: Inv2a-def Inv2a-inner-def)
  fix q bk
  assume bk: bk ∈ blocksOf s' q

```

```

with inv
have oldBlks:  $bk \in \text{blocksOf } s \ q \longrightarrow \text{Inv2a-innermost } s \ q \ bk$ 
  by(auto simp add: Inv2a-def Inv2a-inner-def)
from bk HStartBallot-blocksOf[OF act]
have  $bk \in \{\text{dblock } s' \ q\} \cup \text{blocksOf } s \ q$ 
  by blast
thus Inv2a-innermost s' q bk
proof
  assume bk-dblock:  $bk \in \{\text{dblock } s' \ q\}$ 
  from inv
  have inv-q-dblock: Inv2a-innermost s q (dblock s q)
  by(auto simp add: Inv2a-def Inv2a-inner-def Inv2a-innermost-def blocksOf-def)
  with act inv bk-dblock
  show ?thesis
  by(blast dest: HStartBallot-Inv2a-dblock-q)
next
  assume bk-in-blocks:  $bk \in \text{blocksOf } s \ q$ 
  with oldBlks
  have Inv2a-innermost s q bk ..
  with act
  show ?thesis
  by(auto simp add: StartBallot-def HNextPart-def
      InitializePhase-def Inv2a-innermost-def)
qed
qed

```

lemma *HPhase1or2Write-blocksOf*:
 $\llbracket \text{HPhase1or2Write } s \ s' \ p \ d \rrbracket \implies \text{blocksOf } s' \ r \subseteq \text{blocksOf } s \ r$
by(*auto simp add: Phase1or2Write-def blocksOf-def rdBy-def*)

theorem *HPhase1or2Write-Inv2a*:
assumes *inv: Inv2a s*
and *act: HPhase1or2Write s s' p d*
shows *Inv2a s'*
proof(*clarsimp simp add: Inv2a-def Inv2a-inner-def*)
fix *q bk*
assume *bk*: $bk \in \text{blocksOf } s' \ q$
from *inv bk HPhase1or2Write-blocksOf[OF act]*
have *inp-q-bk*: *Inv2a-innermost s q bk*
by(*auto simp add: Inv2a-def Inv2a-inner-def*)
with *act*
show *Inv2a-innermost s' q bk*
by(*auto simp add: Inv2a-innermost-def HNextPart-def*)
qed

theorem *HPhase1or2ReadElse-Inv2a*:
assumes *inv: Inv2a s*
and *act: HPhase1or2ReadElse s s' p d q*
shows *Inv2a s'*

proof –
from *act*
have *HStartBallot s s' p*
by(*simp add: Phase1or2ReadElse-def*)
with *inv*
show *?thesis*
by(*auto elim: HStartBallot-Inv2a*)
qed

lemma *HEndPhase2-blocksOf*:
 $\llbracket \text{HEndPhase2 } s \ s' \ p \rrbracket \implies \text{blocksOf } s' \ q \subseteq \text{blocksOf } s \ q$
by(*auto simp add: EndPhase2-def blocksOf-def*
dest: subsetD[OF InitializePhase-rdBy])

theorem *HEndPhase2-Inv2a*:
assumes *inv: Inv2a s*
and *act: HEndPhase2 s s' p*
shows *Inv2a s'*
proof(*clarsimp simp add: Inv2a-def Inv2a-inner-def*)
fix *q bk*
assume *bk: bk ∈ blocksOf s' q*
from *inv bk HEndPhase2-blocksOf[OF act]*
have *inp-q-bk: Inv2a-innermost s q bk*
by(*auto simp add: Inv2a-def Inv2a-inner-def*)
with *act*
show *Inv2a-innermost s' q bk*
by(*auto simp add: Inv2a-innermost-def HNextPart-def*)
qed

lemma *HFail-blocksOf*:
 $\text{HFail } s \ s' \ p \implies \text{blocksOf } s' \ q \subseteq \text{blocksOf } s \ q \cup \{\text{dblock } s' \ q\}$
by(*auto simp add: Fail-def blocksOf-def*
dest: subsetD[OF InitializePhase-rdBy])

lemma *HFail-Inv2a-dblock-q*:
assumes *act: HFail s s' p*
and *inv: Inv2a-innermost s q (dblock s q)*
shows *Inv2a-innermost s' q (dblock s' q)*
proof(*cases p=q*)
case *True*
with *act*
have *dblock s' q = InitDB*
by (*simp add: Fail-def*)
with *True*
show *?thesis*
by(*auto simp add: InitDB-def Inv2a-innermost-def*)
next
case *False*
with *inv act*

```

show ?thesis
  by(auto simp add: Fail-def HNextPart-def
      InitializePhase-def Inv2a-innermost-def)
qed

theorem HFail-Inv2a:
assumes inv: Inv2a s
and act: HFail s s' p
shows Inv2a s'
proof(clarsimp simp add: Inv2a-def Inv2a-inner-def)
  fix q bk
  assume bk: bk ∈ blocksOf s' q
  with HFail-blocksOf[OF act]
  have dblock-blocks: bk ∈ {dblock s' q} ∪ blocksOf s q
    by blast
  thus Inv2a-innermost s' q bk
  proof
    assume bk-dblock: bk ∈ {dblock s' q}
    from inv
    have inv-q-dblock: Inv2a-innermost s q (dblock s q)
      by(auto simp add: Inv2a-def Inv2a-inner-def Inv2a-innermost-def blocksOf-def)
    with act bk-dblock
    show ?thesis
      by(blast dest: HFail-Inv2a-dblock-q)
  next
    assume bk-in-blocks: bk ∈ blocksOf s q
    with inv
    have Inv2a-innermost s q bk
      by (auto simp add: Inv2a-def Inv2a-inner-def)
    with act
    show ?thesis
      by(auto simp add: Fail-def HNextPart-def
          InitializePhase-def Inv2a-innermost-def)
  qed
qed

```

```

lemma HPhase0Read-blocksOf:
  HPhase0Read s s' p d ⇒ blocksOf s' q ⊆ blocksOf s q
  by(auto simp add: Phase0Read-def InitializePhase-def
      blocksOf-def rdBy-def)

```

```

theorem HPhase0Read-Inv2a:
assumes inv: Inv2a s
and act: HPhase0Read s s' p d
shows Inv2a s'
proof(clarsimp simp add: Inv2a-def Inv2a-inner-def)
  fix q bk
  assume bk: bk ∈ blocksOf s' q
  from inv bk HPhase0Read-blocksOf[OF act]

```

have *inp-q-bk*: *Inv2a-innermost s q bk*
by(*auto simp add: Inv2a-def Inv2a-inner-def*)
with *act*
show *Inv2a-innermost s' q bk*
by(*auto simp add: Inv2a-innermost-def HNextPart-def*)
qed

lemma *HEndPhase0-blocksOf*:
 $HEndPhase0\ s\ s'\ p \implies blocksOf\ s'\ q \subseteq blocksOf\ s\ q \cup \{dblock\ s'\ q\}$
by(*auto simp add: EndPhase0-def blocksOf-def*)
dest: subsetD[OF InitializePhase-rdBy]

lemma *HEndPhase0-blocksRead*:
assumes *act: HEndPhase0 s s' p*
shows $\exists d. blocksRead\ s\ p\ d \neq \{\}$
proof –
from *act*
have *IsMajority*($\{d. hasRead\ s\ p\ d\ p\}$) **by**(*simp add: EndPhase0-def*)
hence $\{d. hasRead\ s\ p\ d\ p\} \neq \{\}$ **by** (*rule majority-nonempty*)
thus *?thesis*
by(*auto simp add: hasRead-def*)
qed

EndPhase0 has the additional difficulty of having a choose expression. We prove that there exists an x such that the predicate of the choose expression holds, and then apply *someI*: $?P\ ?x \implies ?P\ (Eps\ ?P)$.

lemma *HEndPhase0-some*:
assumes *act: HEndPhase0 s s' p*
and *inv1: Inv1 s*
shows $(SOME\ b. \quad b \in allBlocksRead\ s\ p$
 $\quad \wedge (\forall t \in allBlocksRead\ s\ p. bal\ t \leq bal\ b)$
 $\quad) \in allBlocksRead\ s\ p$
 $\wedge (\forall t \in allBlocksRead\ s\ p.$
 $\quad bal\ t \leq bal\ (SOME\ b. \quad b \in allBlocksRead\ s\ p$
 $\quad \wedge (\forall t \in allBlocksRead\ s\ p. bal\ t \leq bal\ b)))$

proof –
from *inv1* **have** *finite* ($bal\ `allBlocksRead\ s\ p$) (**is** *finite ?S*)
by(*simp add: Inv1-def allBlocksRead-def*)
moreover
from *HEndPhase0-blocksRead[OF act]*
have $?S \neq \{\}$
by(*auto simp add: allBlocksRead-def allRdBlks-def*)
ultimately
have $Max\ ?S \in ?S$ **and** $\forall t \in ?S. t \leq Max\ ?S$ **by** *auto*
hence $\exists r \in ?S. \forall t \in ?S. t \leq r$..
then obtain *mblk*
where $mblk \in allBlocksRead\ s\ p$
 $\wedge (\forall t \in allBlocksRead\ s\ p. bal\ t \leq bal\ mblk)$ (**is** $?P\ mblk$)

by *auto*
 thus *?thesis*
 by (*rule someI*)
 qed

lemma *HEndPhase0-dblock-allBlocksRead*:
 assumes *act*: *HEndPhase0 s s' p*
 and *inv1*: *Inv1 s*
 shows $\text{dblock } s' p \in (\lambda x. x \text{ (mbal:= mbal(dblock } s' p))}$) ‘ *allBlocksRead s p*
using *act HEndPhase0-some[OF act inv1]*
 by(*auto simp add: EndPhase0-def*)

lemma *HNextPart-allInput-or-NotAnInput*:
 assumes *act*: *HNextPart s s'*
 and *inv2a*: *Inv2a-innermost s p (dblock s' p)*
 shows $\text{inp (dblock } s' p) \in \text{allInput } s' \cup \{\text{NotAnInput}\}$
proof –
 from *act*
 have $\text{allInput } s' = \text{allInput } s \cup (\text{range (inpt } s'))$
 by(*simp add: HNextPart-def*)
 moreover
 from *inv2a*
 have $\text{inp (dblock } s' p) \in \text{allInput } s \cup \{\text{NotAnInput}\}$
 by(*simp add: Inv2a-innermost-def*)
 ultimately show *?thesis*
 by *blast*
 qed

lemma *HEndPhase0-Inv2a-allBlocksRead*:
 assumes *act*: *HEndPhase0 s s' p*
 and *inv2a*: *Inv2a-inner s p*
 and *inv2c*: *Inv2c-inner s p*
 shows $\forall t \in (\lambda x. x \text{ (mbal:= mbal (dblock } s' p))}$) ‘ *allBlocksRead s p*.
 Inv2a-innermost s p t
proof –
 from *act*
 have $\text{mbal}' : \text{mbal (dblock } s' p) \in \text{Ballot } p$
 by(*auto simp add: EndPhase0-def*)
 from *inv2c act*
 have $\text{allproc-}p : \forall d. \forall br \in \text{blocksRead } s p d. \text{proc } br = p$
 by(*simp add: Inv2c-inner-def EndPhase0-def*)
 with *inv2a*
 have $\text{allBlocks-inv2a} : \forall t \in \text{allBlocksRead } s p. \text{Inv2a-innermost } s p t$
proof(*auto simp add: Inv2a-inner-def allBlocksRead-def*
 allRdBlks-def blocksOf-def rdBy-def)
 fix *d bk*
 assume *bk-in-blocksRead*: $bk \in \text{blocksRead } s p d$
 and *inv2a-bk*: $\forall x \in \{u. \exists d. u = \text{disk } s d p\}$
 $\cup \{\text{block } br \mid br. (\exists q d. br \in \text{blocksRead } s q d)\}$

$\wedge \text{proc } br = p\}. \text{Inv2a-innermost } s \ p \ x$

with *allproc-p* **have** *proc bk = p* **by** *auto*
with *bk-in-blocksRead inv2a-bk*
show *Inv2a-innermost s p (block bk)* **by** *blast*
qed
from *act*
have *mbal'-gt: $\forall bk \in \text{allBlocksRead } s \ p. \text{mbal } bk \leq \text{mbal } (\text{dblock } s' \ p)$*
by(*auto simp add: EndPhase0-def*)
with *mbal' allBlocks-inv2a*
show *?thesis*
proof (*auto simp add: Inv2a-innermost-def*)
fix *t*
assume *t-blocksRead: $t \in \text{allBlocksRead } s \ p$*
with *allBlocks-inv2a*
have *bal t \leq mbal t* **by** (*auto simp add: Inv2a-innermost-def*)
moreover
from *t-blocksRead mbal'-gt*
have *mbal t \leq mbal (dblock s' p)* **by** *blast*
ultimately show *bal t \leq mbal (dblock s' p)*
by *auto*
qed
qed

lemma *HEndPhase0-Inv2a-dblock:*
assumes *act: HEndPhase0 s s' p*
and *inv1: Inv1 s*
and *inv2a: Inv2a-inner s p*
and *inv2c: Inv2c-inner s p*
shows *Inv2a-innermost s' p (dblock s' p)*
proof –
from *act inv2a inv2c*
have *t1: $\forall t \in (\lambda x. x (\text{mbal} := \text{mbal } (\text{dblock } s' \ p))) \text{ 'allBlocksRead } s \ p.$*
Inv2a-innermost s p t
by(*blast dest: HEndPhase0-Inv2a-allBlocksRead*)
from *act inv1*
have *dblock s' p \in ($\lambda x. x (\text{mbal} := \text{mbal } (\text{dblock } s' \ p))) \text{ 'allBlocksRead } s \ p$*
by(*simp, blast dest: HEndPhase0-dblock-allBlocksRead*)
with *t1*
have *inv2-dblock: Inv2a-innermost s p (dblock s' p)* **by** *auto*
with *act*
have *inp (dblock s' p) \in allInput s' \cup {NotAnInput}*
by(*auto dest: HNextPart-allInput-or-NotAnInput*)
with *inv2-dblock*
show *?thesis*
by(*auto simp add: Inv2a-innermost-def*)
qed

lemma *HEndPhase0-Inv2a-dblock-q:*
assumes *act: HEndPhase0 s s' p*


```

and inv1: Inv1 s
and inv2a: Inv2a-inner s q
and inv2c: Inv2c-inner s p
shows Inv2a-innermost s' q (dblock s' q)
proof(cases p=q)
  case True
    with act inv2a inv2c inv1
    show ?thesis
      by(blast dest: HEndPhase0-Inv2a-dblock)
  next
    case False
    from inv2a
    have inv-q-dblock: Inv2a-innermost s q (dblock s q)
      by(auto simp add: Inv2a-inner-def blocksOf-def)
    with False act
    show ?thesis
      by(clarsimp simp add: EndPhase0-def HNextPart-def
        InitializePhase-def Inv2a-innermost-def)
qed

```

```

theorem HEndPhase0-Inv2a:
  assumes inv: Inv2a s
  and act: HEndPhase0 s s' p
  and inv1: Inv1 s
  and inv2c: Inv2c-inner s p
  shows Inv2a s'
proof(clarsimp simp add: Inv2a-def Inv2a-inner-def)
  fix q bk
  assume bk: bk ∈ blocksOf s' q
  with HEndPhase0-blocksOf[OF act]
  have dblock-blocks: bk ∈ {dblock s' q} ∪ blocksOf s q
    by blast
  thus Inv2a-innermost s' q bk
  proof
    from inv
    have inv-q: Inv2a-inner s q
      by(auto simp add: Inv2a-def)
    assume bk ∈ {dblock s' q}
    with act inv1 inv2c inv-q
    show ?thesis
      by(blast dest:HEndPhase0-Inv2a-dblock-q)
  next
    assume bk-in-blocks: bk ∈ blocksOf s q
    with inv
    have Inv2a-innermost s q bk
      by(auto simp add: Inv2a-def Inv2a-inner-def)
    with act show ?thesis
      by(auto simp add: EndPhase0-def HNextPart-def
        InitializePhase-def Inv2a-innermost-def)

```

qed
qed

lemma *HEndPhase1-blocksOf*:

$H\text{EndPhase1 } s \ s' \ p \implies \text{blocksOf } s' \ q \subseteq \text{blocksOf } s \ q \cup \{\text{dblock } s' \ q\}$
by (*auto simp add: EndPhase1-def blocksOf-def*
dest: subsetD[OF InitializePhase-rdBy])

lemma *maxBlk-in-nonInitBlks*:

assumes $b: b \in \text{nonInitBlks } s \ p$
and *inv1: Inv1 s*
shows $\text{maxBlk } s \ p \in \text{nonInitBlks } s \ p$
 $\wedge (\forall c \in \text{nonInitBlks } s \ p. \text{bal } c \leq \text{bal } (\text{maxBlk } s \ p))$

proof –

have *nibals-finite*: $\text{finite } (\text{bal } ` (\text{nonInitBlks } s \ p))$ (**is** *finite ?S*)

proof (*rule finite-imageI*)

from *inv1*

have *finite* (*allRdBlks s p*)

by (*auto simp add: Inv1-def*)

hence *finite* (*allBlocksRead s p*)

by (*auto simp add: allBlocksRead-def*)

hence *finite* (*blocksSeen s p*)

by (*simp add: blocksSeen-def*)

thus *finite* (*nonInitBlks s p*)

by (*auto simp add: nonInitBlks-def intro: finite-subset*)

qed

from b **have** $\text{bal } ` (\text{nonInitBlks } s \ p) \neq \{\}$

by *auto*

with *nibals-finite*

have $\text{Max } ?S \in ?S$ **and** $\forall bb \in ?S. bb \leq \text{Max } ?S$ **by** *auto*

hence $\exists mb \in ?S. \forall bb \in ?S. bb \leq mb$..

then obtain *mblk*

where $mblk \in \text{nonInitBlks } s \ p$

$\wedge (\forall c \in \text{nonInitBlks } s \ p. \text{bal } c \leq \text{bal } mblk)$

(**is** *?P mblk*)

by *auto*

hence *?P* (*SOME b. ?P b*)

by (*rule someI*)

thus *?thesis*

by (*simp add: maxBlk-def*)

qed

lemma *blocksOf-nonInitBlks*:

$(\forall p \ bk. bk \in \text{blocksOf } s \ p \implies P \ bk)$

$\implies bk \in \text{nonInitBlks } s \ p \implies P \ bk$

by (*auto simp add: allRdBlks-def blocksOf-def nonInitBlks-def*
blocksSeen-def allBlocksRead-def rdBy-def,

blast)

lemma *maxBlk-allInput*:
assumes *inv*: *Inv2a s*
and *mblk*: *maxBlk s p* \in *nonInitBlks s p*
shows *inp* (*maxBlk s p*) \in *allInput s*
proof –
from *inv*
have *blocks*: $\forall p$ *bk*. *bk* \in *blocksOf s p*
 \longrightarrow *inp bk* \in (*allInput s*) \cup {*NotAnInput*}
by(*auto simp add: Inv2a-def Inv2a-inner-def Inv2a-innermost-def*)
from *mblk NotAnInput*
have *inp* (*maxBlk s p*) \neq *NotAnInput*
by(*auto simp add: nonInitBlks-def*)
with *mblk blocksOf-nonInitBlks[OF blocks]*
show *?thesis*
by *auto*
qed

lemma *HEndPhase1-dblock-allInput*:
assumes *act*: *HEndPhase1 s s' p*
and *inv1*: *HInv1 s*
and *inv2*: *Inv2a s*
shows *inp'*: *inp* (*dblock s' p*) \in *allInput s'*
proof –
from *act*
have *inpt*: *inpt s p* \in *allInput s'*
by(*auto simp add: HNextPart-def EndPhase1-def*)
have *nonInitBlks s p* \neq {} \longrightarrow *inp* (*maxBlk s p*) \in *allInput s*
proof
assume *ni*: *nonInitBlks s p* \neq {}
with *inv1*
have *maxBlk s p* \in *nonInitBlks s p*
by (*auto simp add: HInv1-def maxBlk-in-nonInitBlks*)
with *inv2*
show *inp* (*maxBlk s p*) \in *allInput s*
by(*blast dest: maxBlk-allInput*)
qed
with *act inpt*
show *?thesis*
by(*auto simp add: EndPhase1-def HNextPart-def*)
qed

lemma *HEndPhase1-Inv2a-dblock*:
assumes *act*: *HEndPhase1 s s' p*
and *inv1*: *HInv1 s*
and *inv2*: *Inv2a s*
and *inv2c*: *Inv2c-inner s p*
shows *Inv2a-innermost s' p* (*dblock s' p*)
proof –
from *inv1 act* **have** *inv1'*: *HInv1 s'*

```

    by(blast dest: HEndPhase1-HInv1)
  from inv2
  have inv2a: Inv2a-innermost s p (dblock s p)
    by(auto simp add: Inv2a-def Inv2a-inner-def blocksOf-def)
  from act inv2c
  have mbal': mbal (dblock s' p) ∈ Ballot p
    by (auto simp add: EndPhase1-def Inv2c-def Inv2c-inner-def)
  moreover
  from act
  have bal': bal (dblock s' p) = mbal (dblock s p)
    by (auto simp add: EndPhase1-def)
  moreover
  from act inv1 inv2
  have inp': inp (dblock s' p) ∈ allInput s'
    by(blast dest: HEndPhase1-dblock-allInput)
  moreover
  with inv1' NotAnInput
  have inp (dblock s' p) ≠ NotAnInput
    by(auto simp add: HInv1-def)
  ultimately show ?thesis
    using act inv2a
    by(auto simp add: Inv2a-innermost-def EndPhase1-def)
qed

```

```

lemma HEndPhase1-Inv2a-dblock-q:
  assumes act: HEndPhase1 s s' p
  and inv1: HInv1 s
  and inv: Inv2a s
  and inv2c: Inv2c-inner s p
  shows Inv2a-innermost s' q (dblock s' q)
proof(cases p=q)
  case True
  with act inv inv2c inv1
  show ?thesis
    by(blast dest: HEndPhase1-Inv2a-dblock)
next
  case False
  from inv
  have inv-q-dblock: Inv2a-innermost s q (dblock s q)
    by(auto simp add: Inv2a-def Inv2a-inner-def blocksOf-def)
  with False act
  show ?thesis
    by(clarsimp simp add: EndPhase1-def HNextPart-def
      InitializePhase-def Inv2a-innermost-def)
qed

```

```

theorem HEndPhase1-Inv2a:
  assumes act: HEndPhase1 s s' p
  and inv1: HInv1 s

```

```

and inv: Inv2a s
and inv2c: Inv2c-inner s p
shows Inv2a s'
proof (clarsimp simp add: Inv2a-def Inv2a-inner-def)
  fix q bk
  assume bk-in-bks: bk ∈ blocksOf s' q
  with HEndPhase1-blocksOf[OF act]
  have dblock-blocks: bk ∈ {dblock s' q} ∪ blocksOf s q
    by blast
  thus Inv2a-innermost s' q bk
  proof
    assume bk ∈ {dblock s' q}
    with act inv1 inv2c inv
    show ?thesis
    by(blast dest: HEndPhase1-Inv2a-dblock-q)
  next
  assume bk-in-blocks: bk ∈ blocksOf s q
  with inv
  have Inv2a-innermost s q bk
    by(auto simp add: Inv2a-def Inv2a-inner-def)
  with act show ?thesis
    by(auto simp add: EndPhase1-def HNextPart-def
      InitializePhase-def Inv2a-innermost-def)
  qed
qed

```

C.2.2 Proofs of Invariant 2 b

Invariant 2b is proved automatically, given that we expand the definitions involved.

theorem *HInit-Inv2b*: *HInit s → Inv2b s*
by (*auto simp add: HInit-def Init-def Inv2b-def*
Inv2b-inner-def InitDB-def)

theorem *HPhase1or2ReadThen-Inv2b*:
 [*Inv2b s; HPhase1or2ReadThen s s' p d q*]
 \implies *Inv2b s'*
by (*auto simp add: Phase1or2ReadThen-def Inv2b-def*
Inv2b-inner-def hasRead-def)

theorem *HStartBallot-Inv2b*:
 [*Inv2b s; HStartBallot s s' p*]
 \implies *Inv2b s'*
by(*auto simp add: StartBallot-def InitializePhase-def*
Inv2b-def Inv2b-inner-def hasRead-def)

theorem *HPhase1or2Write-Inv2b*:
 [*Inv2b s; HPhase1or2Write s s' p d*]
 \implies *Inv2b s'*

by (*auto simp add: Phase1or2Write-def Inv2b-def
Inv2b-inner-def hasRead-def*)

theorem *HPhase1or2ReadElse-Inv2b:*

$\llbracket \text{Inv2b } s; \text{HPhase1or2ReadElse } s' \text{ } p \text{ } d \text{ } q \rrbracket$
 $\implies \text{Inv2b } s'$

by (*auto simp add: Phase1or2ReadElse-def StartBallot-def hasRead-def
InitializePhase-def Inv2b-def Inv2b-inner-def*)

theorem *HEndPhase1-Inv2b:*

$\llbracket \text{Inv2b } s; \text{HEndPhase1 } s' \text{ } p \rrbracket \implies \text{Inv2b } s'$

by (*auto simp add: EndPhase1-def InitializePhase-def
Inv2b-def Inv2b-inner-def hasRead-def*)

theorem *HFail-Inv2b:*

$\llbracket \text{Inv2b } s; \text{HFail } s' \text{ } p \rrbracket$
 $\implies \text{Inv2b } s'$

by (*auto simp add: Fail-def InitializePhase-def
Inv2b-def Inv2b-inner-def hasRead-def*)

theorem *HEndPhase2-Inv2b:*

$\llbracket \text{Inv2b } s; \text{HEndPhase2 } s' \text{ } p \rrbracket \implies \text{Inv2b } s'$

by (*auto simp add: EndPhase2-def InitializePhase-def
Inv2b-def Inv2b-inner-def hasRead-def*)

theorem *HPhase0Read-Inv2b:*

$\llbracket \text{Inv2b } s; \text{HPhase0Read } s' \text{ } p \text{ } d \rrbracket \implies \text{Inv2b } s'$

by (*auto simp add: Phase0Read-def Inv2b-def
Inv2b-inner-def hasRead-def*)

theorem *HEndPhase0-Inv2b:*

$\llbracket \text{Inv2b } s; \text{HEndPhase0 } s' \text{ } p \rrbracket \implies \text{Inv2b } s'$

by (*auto simp add: EndPhase0-def InitializePhase-def
Inv2b-def Inv2b-inner-def hasRead-def*)

C.2.3 Proofs of Invariant 2 c

theorem *HInit-Inv2c: HInit s \longrightarrow Inv2c s*

by (*auto simp add: HInit-def Init-def Inv2c-def Inv2c-inner-def*)

lemma *HNextPart-Inv2c-chosen:*

assumes *hnp: HNextPart s s'*

and *inv2c: Inv2c s*

and *outpt': $\forall p. \text{outpt } s' \text{ } p = (\text{if phase } s' \text{ } p = 3$
 $\text{then } \text{inp}(\text{dblock } s' \text{ } p)$
 $\text{else } \text{NotAnInput})$*

and *inp-dblk: $\forall p. \text{inp}(\text{dblock } s' \text{ } p) \in \text{allInput } s' \cup \{\text{NotAnInput}\}$*

shows *chosen s' $\in \text{allInput } s' \cup \{\text{NotAnInput}\}$*

```

using hnp outpt' inp-dblk inv2c
proof(auto simp add: HNextPart-def Inv2c-def Inv2c-inner-def
      split: if-split-asm)
qed

lemma HNextPart-chosen:
  assumes hnp: HNextPart s s'
  shows chosen s' = NotAnInput  $\longrightarrow$  ( $\forall p. \text{outpt } s' p = \text{NotAnInput}$ )
using hnp
proof(auto simp add: HNextPart-def split: if-split-asm)
  fix p pa
  assume o1: outpt s' p  $\neq$  NotAnInput
  and o2: outpt s' (SOME p. outpt s' p  $\neq$  NotAnInput) = NotAnInput
  from o1
  have  $\exists p. \text{outpt } s' p \neq \text{NotAnInput}$ 
    by auto
  hence outpt s' (SOME p. outpt s' p  $\neq$  NotAnInput)  $\neq$  NotAnInput
    by(rule someI-ex)
  with o2
  show outpt s' pa = NotAnInput
    by simp
qed

lemma HNextPart-allInput:
  [HNextPart s s'; Inv2c s]  $\implies$   $\forall p. \text{inpt } s' p \in \text{allInput } s'$ 
  by(auto simp add: HNextPart-def Inv2c-def Inv2c-inner-def)

theorem HPhase1or2ReadThen-Inv2c:
  assumes inv: Inv2c s
  and act: HPhase1or2ReadThen s s' p d q
  and inv2a: Inv2a s
  shows Inv2c s'
proof -
  from inv2a act
  have inv2a': Inv2a s'
    by(blast dest: HPhase1or2ReadThen-Inv2a)
  from act inv
  have outpt':  $\forall p. \text{outpt } s' p = (\text{if phase } s' p = 3$ 
    then inp(dblock s' p)
    else NotAnInput)
    by(auto simp add: Phase1or2ReadThen-def Inv2c-def Inv2c-inner-def)
  from inv2a'
  have dblk:  $\forall p. \text{inp } (\text{dblock } s' p) \in \text{allInput } s' \cup \{\text{NotAnInput}\}$ 
    by(auto simp add: Inv2a-def Inv2a-inner-def
      Inv2a-innermost-def blocksOf-def)
  with act inv outpt'
  have chosen': chosen s'  $\in$  allInput s'  $\cup$  {NotAnInput}
    by(auto dest: HNextPart-Inv2c-chosen)
  from act inv

```

have $\forall p. \text{ inpt } s' p \in \text{allInput } s'$
 $\wedge (\text{chosen } s' = \text{NotAnInput} \longrightarrow \text{outpt } s' p = \text{NotAnInput})$
by(*auto dest: HNextPart-chosen HNextPart-allInput*)
with *outpt' chosen' act inv*
show *?thesis*
by(*auto simp add: Phase1or2ReadThen-def Inv2c-def Inv2c-inner-def*)
qed

theorem *HStartBallot-Inv2c:*

assumes *inv: Inv2c s*
and *act: HStartBallot s s' p*
and *inv2a: Inv2a s*
shows *Inv2c s'*

proof –

from *act*
have *phase': phase s' p = 1*
by(*simp add: StartBallot-def*)
from *act*
have *phase: phase s p \in {1,2}*
by(*simp add: StartBallot-def*)
from *act inv*
have *mbal': mbal(dblock s' p) \in Ballot p*
by(*auto simp add: StartBallot-def Inv2c-def Inv2c-inner-def*)
from *inv phase*
have *bal(dblock s p) \in Ballot p \cup {0}*
by(*auto simp add: Inv2c-def Inv2c-inner-def*)
with *act*
have *bal': bal(dblock s' p) \in Ballot p \cup {0}*
by(*auto simp add: StartBallot-def*)
from *act inv phase phase'*
have *blks': ($\forall d. \forall br \in \text{blocksRead } s' p d.$
 $\text{mbal}(\text{block } br) < \text{mbal}(\text{dblock } s' p)$)*
by(*auto simp add: StartBallot-def InitializePhase-def*
Inv2c-def Inv2c-inner-def)
from *inv2a act*
have *inv2a': Inv2a s'*
by(*blast dest: HStartBallot-Inv2a*)
from *act inv*
have *outpt': $\forall p. \text{outpt } s' p = (\text{if } \text{phase } s' p = 3$
 $\text{then } \text{inp}(\text{dblock } s' p)$
 $\text{else } \text{NotAnInput})$*
by(*auto simp add: StartBallot-def Inv2c-def Inv2c-inner-def*)
from *inv2a'*
have *dblk: $\forall p. \text{inp } (\text{dblock } s' p) \in \text{allInput } s' \cup \{\text{NotAnInput}\}$*
by(*auto simp add: Inv2a-def Inv2a-inner-def*
Inv2a-innermost-def blocksOf-def)
with *act inv outpt'*
have *chosen': chosen s' \in allInput s' \cup {NotAnInput}*
by(*auto dest: HNextPart-Inv2c-chosen*)

from *act inv*
have *allinp*: $\forall p. \text{ inpt } s' p \in \text{allInput } s' \wedge (\text{chosen } s' = \text{NotAnInput} \longrightarrow \text{outpt } s' p = \text{NotAnInput})$
by(*auto dest: HNextPart-chosen HNextPart-allInput*)
with *phase' mbal' bal' outpt' chosen' act inv blks'*
show *?thesis*
by(*auto simp add: StartBallot-def InitializePhase-def Inv2c-def Inv2c-inner-def*)
qed

theorem *HPhase1or2Write-Inv2c*:
assumes *inv: Inv2c s*
and *act: HPhase1or2Write s s' p d*
and *inv2a: Inv2a s*
shows *Inv2c s'*
proof –
from *inv2a act*
have *inv2a': Inv2a s'*
by(*blast dest: HPhase1or2Write-Inv2a*)
from *act inv*
have *outpt'*: $\forall p. \text{ outpt } s' p = (\text{if } \text{phase } s' p = 3 \text{ then } \text{inp}(\text{dblock } s' p) \text{ else } \text{NotAnInput})$
by(*auto simp add: Phase1or2Write-def Inv2c-def Inv2c-inner-def*)
from *inv2a'*
have *dblk*: $\forall p. \text{ inp } (\text{dblock } s' p) \in \text{allInput } s' \cup \{\text{NotAnInput}\}$
by(*auto simp add: Inv2a-def Inv2a-inner-def Inv2a-innermost-def blocksOf-def*)
with *act inv outpt'*
have *chosen'*: $\text{chosen } s' \in \text{allInput } s' \cup \{\text{NotAnInput}\}$
by(*auto dest: HNextPart-Inv2c-chosen*)
from *act inv*
have *allinp*: $\forall p. \text{ inpt } s' p \in \text{allInput } s' \wedge (\text{chosen } s' = \text{NotAnInput} \longrightarrow \text{outpt } s' p = \text{NotAnInput})$
by(*auto dest: HNextPart-chosen HNextPart-allInput*)
with *outpt' chosen' act inv*
show *?thesis*
by(*auto simp add: Phase1or2Write-def Inv2c-def Inv2c-inner-def*)
qed

theorem *HPhase1or2ReadElse-Inv2c*:
 $\llbracket \text{Inv2c } s; \text{HPhase1or2ReadElse } s s' p d q; \text{Inv2a } s \rrbracket \Longrightarrow \text{Inv2c } s'$
by(*auto simp add: Phase1or2ReadElse-def dest: HStartBallot-Inv2c*)

theorem *HEndPhase1-Inv2c*:
assumes *inv: Inv2c s*
and *act: HEndPhase1 s s' p*
and *inv2a: Inv2a s*

and $inv1: HInv1\ s$
shows $Inv2c\ s'$
proof –
from inv
have $Inv2c\text{-inner}\ s\ p$ **by** (*auto simp add: Inv2c-def*)
with $inv2a\ act\ inv1$
have $inv2a': Inv2a\ s'$
by(*blast dest: HEndPhase1-Inv2a*)
from $act\ inv$
have $mbal': mbal(dblock\ s'\ p) \in Ballot\ p$
by(*auto simp add: EndPhase1-def Inv2c-def Inv2c-inner-def*)
from act
have $bal': bal(dblock\ s'\ p) = mbal\ (dblock\ s'\ p)$
by(*auto simp add: EndPhase1-def*)
from $act\ inv$
have $blks': (\forall d. \forall br \in blocksRead\ s'\ p\ d.$
 $\quad mbal(block\ br) < mbal(dblock\ s'\ p))$
by(*auto simp add: EndPhase1-def InitializePhase-def*
 $Inv2c-def\ Inv2c-inner-def$)
from $act\ inv$
have $outpt': \forall p. outpt\ s'\ p = (if\ phase\ s'\ p = 3$
 $\quad then\ inp(dblock\ s'\ p)$
 $\quad else\ NotAnInput)$
by(*auto simp add: EndPhase1-def Inv2c-def Inv2c-inner-def*)
from $inv2a'$
have $dblk: \forall p. inp\ (dblock\ s'\ p) \in allInput\ s' \cup \{NotAnInput\}$
by(*auto simp add: Inv2a-def Inv2a-inner-def*
 $Inv2a-innermost-def\ blocksOf-def$)
with $act\ inv\ outpt'$
have $chosen': chosen\ s' \in allInput\ s' \cup \{NotAnInput\}$
by(*auto dest: HNextPart-Inv2c-chosen*)
from $act\ inv$
have $allinp: \forall p. \quad inpt\ s'\ p \in allInput\ s'$
 $\quad \wedge\ (chosen\ s' = NotAnInput$
 $\quad \quad \longrightarrow\ outpt\ s'\ p = NotAnInput)$
by(*auto dest: HNextPart-chosen HNextPart-allInput*)
with $mbal'\ bal'\ blks'\ outpt'\ chosen'\ act\ inv$
show *?thesis*
by(*auto simp add: EndPhase1-def InitializePhase-def*
 $Inv2c-def\ Inv2c-inner-def$)
qed

theorem $HEndPhase2-Inv2c:$
assumes $inv: Inv2c\ s$
and $act: HEndPhase2\ s\ s'\ p$
and $inv2a: Inv2a\ s$
shows $Inv2c\ s'$
proof –
from $inv2a\ act$

have $inv2a'$: $Inv2a\ s'$
by(blast dest: $HEndPhase2-Inv2a$)
from $act\ inv$
have $outpt'$: $\forall p. outpt\ s'\ p = (if\ phase\ s'\ p = 3$
 $then\ inp(dblock\ s'\ p)$
 $else\ NotAnInput)$
by(auto simp add: $EndPhase2-def\ Inv2c-def\ Inv2c-inner-def$)
from $inv2a'$
have $dblck$: $\forall p. inp\ (dblock\ s'\ p) \in allInput\ s' \cup \{NotAnInput\}$
by(auto simp add: $Inv2a-def\ Inv2a-inner-def$
 $Inv2a-innermost-def\ blocksOf-def$)
with $act\ inv\ outpt'$
have $chosen'$: $chosen\ s' \in allInput\ s' \cup \{NotAnInput\}$
by(auto dest: $HNextPart-Inv2c-chosen$)
from $act\ inv$
have $allinp$: $\forall p. inpt\ s'\ p \in allInput\ s'$
 $\wedge (chosen\ s' = NotAnInput$
 $\longrightarrow outpt\ s'\ p = NotAnInput)$
by(auto dest: $HNextPart-chosen\ HNextPart-allInput$)
with $outpt'\ chosen'\ act\ inv$
show $?thesis$
by(auto simp add: $EndPhase2-def\ InitializePhase-def$
 $Inv2c-def\ Inv2c-inner-def$)

qed

theorem $HFail-Inv2c$:

assumes inv : $Inv2c\ s$
and act : $HFail\ s\ s'\ p$
and $inv2a$: $Inv2a\ s$
shows $Inv2c\ s'$

proof –

from $inv2a\ act$
have $inv2a'$: $Inv2a\ s'$
by(blast dest: $HFail-Inv2a$)
from $act\ inv$
have $outpt'$: $\forall p. outpt\ s'\ p = (if\ phase\ s'\ p = 3$
 $then\ inp(dblock\ s'\ p)$
 $else\ NotAnInput)$
by(auto simp add: $Fail-def\ Inv2c-def\ Inv2c-inner-def$)
from $inv2a'$
have $dblck$: $\forall p. inp\ (dblock\ s'\ p) \in allInput\ s' \cup \{NotAnInput\}$
by(auto simp add: $Inv2a-def\ Inv2a-inner-def$
 $Inv2a-innermost-def\ blocksOf-def$)
with $act\ inv\ outpt'$
have $chosen'$: $chosen\ s' \in allInput\ s' \cup \{NotAnInput\}$
by(auto dest: $HNextPart-Inv2c-chosen$)
from $act\ inv$
have $allinp$: $\forall p. inpt\ s'\ p \in allInput\ s' \wedge (chosen\ s' = NotAnInput$
 $\longrightarrow outpt\ s'\ p = NotAnInput)$

```

    by(auto dest: HNextPart-chosen HNextPart-allInput)
  with outpt' chosen' act inv
  show ?thesis
    by(auto simp add: Fail-def InitializePhase-def
                  Inv2c-def Inv2c-inner-def)

```

qed

theorem *HPhase0Read-Inv2c*:

```

  assumes inv: Inv2c s
  and act: HPhase0Read s s' p d
  and inv2a: Inv2a s
  shows Inv2c s'
  proof -
    from inv2a act
    have inv2a': Inv2a s'
      by(blast dest: HPhase0Read-Inv2a)
    from act inv
    have outpt':  $\forall p. \text{outpt } s' p = (\text{if phase } s' p = 3$ 
                                      $\text{then inp}(\text{dblock } s' p)$ 
                                      $\text{else NotAnInput})$ 
      by(auto simp add: Phase0Read-def Inv2c-def Inv2c-inner-def)
    from inv2a'
    have dblk:  $\forall p. \text{inp } (\text{dblock } s' p) \in \text{allInput } s' \cup \{\text{NotAnInput}\}$ 
      by(auto simp add: Inv2a-def Inv2a-inner-def
                    Inv2a-innermost-def blocksOf-def)
    with act inv outpt'
    have chosen':  $\text{chosen } s' \in \text{allInput } s' \cup \{\text{NotAnInput}\}$ 
      by(auto dest: HNextPart-Inv2c-chosen)
    from act inv
    have allinp:  $\forall p. \text{inpt } s' p \in \text{allInput } s'$ 
       $\wedge (\text{chosen } s' = \text{NotAnInput}$ 
             $\longrightarrow \text{outpt } s' p = \text{NotAnInput})$ 
      by(auto dest: HNextPart-chosen HNextPart-allInput)
    with outpt' chosen' act inv
    show ?thesis
      by(auto simp add: Phase0Read-def
                    Inv2c-def Inv2c-inner-def)

```

qed

theorem *HEndPhase0-Inv2c*:

```

  assumes inv: Inv2c s
  and act: HEndPhase0 s s' p
  and inv2a: Inv2a s
  and inv1: Inv1 s
  shows Inv2c s'
  proof -
    from inv
    have Inv2c-inner s p by (auto simp add: Inv2c-def)
    with inv2a act inv1

```

```

have  $inv2a'$ :  $Inv2a\ s'$ 
  by( $blast\ dest: HEndPhase0-Inv2a$ )
hence  $bal'$ :  $bal(dblock\ s'\ p) \in Ballot\ p \cup \{0\}$ 
  by( $auto\ simp\ add: Inv2a-def\ Inv2a-inner-def$ 
       $Inv2a-innermost-def\ blocksOf-def$ )
from  $act\ inv$ 
have  $mbal'$ :  $mbal(dblock\ s'\ p) \in Ballot\ p$ 
  by( $auto\ simp\ add: EndPhase0-def\ Inv2c-def\ Inv2c-inner-def$ )
from  $act\ inv$ 
have  $blks'$ :  $(\forall d. \forall br \in blocksRead\ s'\ p\ d.$ 
       $mbal(block\ br) < mbal(dblock\ s'\ p))$ 
  by( $auto\ simp\ add: EndPhase0-def\ InitializePhase-def$ 
       $Inv2c-def\ Inv2c-inner-def$ )
from  $act\ inv$ 
have  $outpt'$ :  $\forall p. outpt\ s'\ p = (if\ phase\ s'\ p = 3$ 
       $then\ inp(dblock\ s'\ p)$ 
       $else\ NotAnInput)$ 
  by( $auto\ simp\ add: EndPhase0-def\ Inv2c-def\ Inv2c-inner-def$ )
from  $inv2a'$ 
have  $dblck'$ :  $\forall p. inp\ (dblock\ s'\ p) \in allInput\ s' \cup \{NotAnInput\}$ 
  by( $auto\ simp\ add: Inv2a-def\ Inv2a-inner-def$ 
       $Inv2a-innermost-def\ blocksOf-def$ )
with  $act\ inv\ outpt'$ 
have  $chosen'$ :  $chosen\ s' \in allInput\ s' \cup \{NotAnInput\}$ 
  by( $auto\ dest: HNextPart-Inv2c-chosen$ )
from  $act\ inv$ 
have  $allinp'$ :  $\forall p. inpt\ s'\ p \in allInput\ s' \wedge (chosen\ s' = NotAnInput$ 
       $\longrightarrow outpt\ s'\ p = NotAnInput)$ 
  by( $auto\ dest: HNextPart-chosen\ HNextPart-allInput$ )
with  $mbal'\ bal'\ blks'\ outpt'\ chosen'\ act\ inv$ 
show  $?thesis$ 
  by( $auto\ simp\ add: EndPhase0-def\ InitializePhase-def$ 
       $Inv2c-def\ Inv2c-inner-def$ )

```

qed

theorem $HInit-HInv2$:

$HInit\ s \implies HInv2\ s$

using $HInit-Inv2a\ HInit-Inv2b\ HInit-Inv2c$

by($auto\ simp\ add: HInv2-def$)

$HInv1 \wedge HInv2$ is an invariant of $HNext$.

lemma $I2b$:

assumes nxt : $HNext\ s\ s'$

and inv : $HInv1\ s \wedge HInv2\ s$

shows $HInv2\ s'$

proof($auto\ simp\ add: HInv2-def$)

show $Inv2a\ s'$ **using** $assms$

by ($auto\ simp\ add: HInv2-def\ HNext-def\ Next-def,$
 $auto\ intro: HStartBallot-Inv2a,$

```

    auto intro: HPhase1or2Write-Inv2a,
    auto simp add: Phase1or2Read-def
      intro: HPhase1or2ReadThen-Inv2a
           HPhase1or2ReadElse-Inv2a,
    auto intro: HPhase0Read-Inv2a,
    auto simp add: EndPhase1or2-def Inv2c-def
      intro: HEndPhase1-Inv2a
           HEndPhase2-Inv2a,
    auto intro: HFail-Inv2a,
    auto simp add: HInv1-def
      intro: HEndPhase0-Inv2a)
show Inv2b s' using assms
  by(auto simp add: HInv2-def HNext-def Next-def,
    auto intro: HStartBallot-Inv2b,
    auto intro: HPhase0Read-Inv2b,
    auto intro: HPhase1or2Write-Inv2b,
    auto simp add: Phase1or2Read-def
      intro: HPhase1or2ReadThen-Inv2b
           HPhase1or2ReadElse-Inv2b,
    auto simp add: EndPhase1or2-def
      intro: HEndPhase1-Inv2b HEndPhase2-Inv2b,
    auto intro: HFail-Inv2b HEndPhase0-Inv2b)
show Inv2c s' using assms
  by(auto simp add: HInv2-def HNext-def Next-def,
    auto intro: HStartBallot-Inv2c,
    auto intro: HPhase0Read-Inv2c,
    auto intro: HPhase1or2Write-Inv2c,
    auto simp add: Phase1or2Read-def
      intro: HPhase1or2ReadThen-Inv2c
           HPhase1or2ReadElse-Inv2c,
    auto simp add: EndPhase1or2-def
      intro: HEndPhase1-Inv2c
           HEndPhase2-Inv2c,
    auto intro: HFail-Inv2c,
    auto simp add: HInv1-def intro: HEndPhase0-Inv2c)
qed

end

```

theory *DiskPaxos-Inv3* **imports** *DiskPaxos-Inv2* **begin**

C.3 Invariant 3

This invariant says that if two processes have read each other's block from disk d during their current phases, then at least one of them has read the other's current block.

definition $HInv3-L :: state \Rightarrow Proc \Rightarrow Proc \Rightarrow Disk \Rightarrow bool$
where

$$\begin{aligned}
HInv3-L \ s \ p \ q \ d = & (phase \ s \ p \in \{1,2\} \\
& \wedge \ phase \ s \ q \in \{1,2\} \\
& \wedge \ hasRead \ s \ p \ d \ q \\
& \wedge \ hasRead \ s \ q \ d \ p)
\end{aligned}$$

definition $HInv3-R :: state \Rightarrow Proc \Rightarrow Proc \Rightarrow Disk \Rightarrow bool$
where

$$\begin{aligned}
HInv3-R \ s \ p \ q \ d = & ((block = dblock \ s \ q, \ proc = q) \in \text{blocksRead} \ s \ p \ d \\
& \vee (block = dblock \ s \ p, \ proc = p) \in \text{blocksRead} \ s \ q \ d)
\end{aligned}$$

definition $HInv3-inner :: state \Rightarrow Proc \Rightarrow Proc \Rightarrow Disk \Rightarrow bool$

where $HInv3-inner \ s \ p \ q \ d = (HInv3-L \ s \ p \ q \ d \longrightarrow HInv3-R \ s \ p \ q \ d)$

definition $HInv3 :: state \Rightarrow bool$

where $HInv3 \ s = (\forall p \ q \ d. HInv3-inner \ s \ p \ q \ d)$

C.3.1 Proofs of Invariant 3

theorem $HInit-HInv3: HInit \ s \Longrightarrow HInv3 \ s$

by(*simp add: HInit-def Init-def HInv3-def*
HInv3-inner-def HInv3-L-def HInv3-R-def)

lemma $InitPhase-HInv3-p:$

$\llbracket InitializePhase \ s \ s' \ p; HInv3-L \ s' \ p \ q \ d \rrbracket \Longrightarrow HInv3-R \ s' \ p \ q \ d$
by(*auto simp add: InitializePhase-def HInv3-inner-def*
hasRead-def HInv3-L-def HInv3-R-def)

lemma $InitPhase-HInv3-q:$

$\llbracket InitializePhase \ s \ s' \ q; HInv3-L \ s' \ p \ q \ d \rrbracket \Longrightarrow HInv3-R \ s' \ p \ q \ d$
by(*auto simp add: InitializePhase-def HInv3-inner-def*
hasRead-def HInv3-L-def HInv3-R-def)

lemma $HInv3-L-sym: HInv3-L \ s \ p \ q \ d \Longrightarrow HInv3-L \ s \ q \ p \ d$

by(*auto simp add: HInv3-L-def*)

lemma $HInv3-R-sym: HInv3-R \ s \ p \ q \ d \Longrightarrow HInv3-R \ s \ q \ p \ d$

by(*auto simp add: HInv3-R-def*)

lemma $Phase1or2ReadThen-HInv3-pq:$

assumes *act: Phase1or2ReadThen \ s \ s' \ p \ d \ q*
and *inv-L': HInv3-L \ s' \ p \ q \ d*
and *pq: p \neq q*
and *inv2b: Inv2b \ s*
shows $HInv3-R \ s' \ p \ q \ d$

proof –

from *inv-L' act pq*
have $phase \ s \ q \in \{1,2\} \wedge hasRead \ s \ q \ d \ p$
by(*auto simp add: Phase1or2ReadThen-def HInv3-L-def*
hasRead-def split: if-split-asm)

```

with inv2b
have disk s d q = dblock s q
  by(auto simp add: Inv2b-def Inv2b-inner-def
      hasRead-def)
with act
show ?thesis
  by(auto simp add: Phase1or2ReadThen-def HInv3-def
      HInv3-inner-def HInv3-R-def)
qed

```

```

lemma Phase1or2ReadThen-HInv3-hasRead:
  [[  $\neg$ hasRead s pp dd qq;
     Phase1or2ReadThen s s' p d q;
      $pp \neq p \vee qq \neq q \vee dd \neq d$  ]]
   $\implies \neg$ hasRead s' pp dd qq
  by(auto simp add: hasRead-def Phase1or2ReadThen-def)

```

```

theorem HPhase1or2ReadThen-HInv3:
  assumes act: HPhase1or2ReadThen s s' p d q
  and inv: HInv3 s
  and pq: p  $\neq$  q
  and inv2b: Inv2b s
  shows HInv3 s'
proof(clarsimp simp add: HInv3-def HInv3-inner-def)
  fix pp qq dd
  assume h3l': HInv3-L s' pp qq dd
  show HInv3-R s' pp qq dd
  proof(cases HInv3-L s pp qq dd)
    case True
    with inv
    have HInv3-R s pp qq dd
    by(auto simp add: HInv3-def HInv3-inner-def)
    with act h3l'
    show ?thesis
    by(auto simp add: HInv3-R-def HInv3-L-def
        Phase1or2ReadThen-def)

```

```

next
  case False
  assume nh3l:  $\neg$  HInv3-L s pp qq dd
  show HInv3-R s' pp qq dd
  proof(cases ((pp=p  $\wedge$  qq=q)  $\vee$  (pp=q  $\wedge$  qq=p))  $\wedge$  dd=d)
    case True
    with act pq inv2b h3l' HInv3-L-sym[OF h3l']
    show ?thesis
    by(auto dest: Phase1or2ReadThen-HInv3-pq HInv3-R-sym)
  next
  case False
  from nh3l h3l' act
  have ( $\neg$ hasRead s pp dd qq  $\vee$   $\neg$ hasRead s qq dd pp)

```


$\wedge \text{hasRead } s' \text{ pp dd qq} \wedge \text{hasRead } s' \text{ qq dd pp}$
by(*auto simp add: HInv3-L-def Phase1or2ReadThen-def*)
with *act False*
show *?thesis*
by(*auto dest: Phase1or2ReadThen-HInv3-hasRead*)
qed
qed
qed

lemma *StartBallot-HInv3-p:*
 $\llbracket \text{StartBallot } s \text{ s}' \text{ p}; \text{HInv3-L } s' \text{ p } q \text{ d} \rrbracket$
 $\implies \text{HInv3-R } s' \text{ p } q \text{ d}$
by(*auto simp add: StartBallot-def dest: InitPhase-HInv3-p*)

lemma *StartBallot-HInv3-q:*
 $\llbracket \text{StartBallot } s \text{ s}' \text{ q}; \text{HInv3-L } s' \text{ p } q \text{ d} \rrbracket$
 $\implies \text{HInv3-R } s' \text{ p } q \text{ d}$
by(*auto simp add: StartBallot-def dest: InitPhase-HInv3-q*)

lemma *StartBallot-HInv3-nL:*
 $\llbracket \text{StartBallot } s \text{ s}' \text{ t}; \neg \text{HInv3-L } s \text{ p } q \text{ d}; t \neq p; t \neq q \rrbracket$
 $\implies \neg \text{HInv3-L } s' \text{ p } q \text{ d}$
by(*auto simp add: StartBallot-def InitializePhase-def*
HInv3-L-def hasRead-def)

lemma *StartBallot-HInv3-R:*
 $\llbracket \text{StartBallot } s \text{ s}' \text{ t}; \text{HInv3-R } s \text{ p } q \text{ d}; t \neq p; t \neq q \rrbracket$
 $\implies \text{HInv3-R } s' \text{ p } q \text{ d}$
by(*auto simp add: StartBallot-def InitializePhase-def*
HInv3-R-def hasRead-def)

lemma *StartBallot-HInv3-t:*
 $\llbracket \text{StartBallot } s \text{ s}' \text{ t}; \text{HInv3-inner } s \text{ p } q \text{ d}; t \neq p; t \neq q \rrbracket$
 $\implies \text{HInv3-inner } s' \text{ p } q \text{ d}$
by(*auto simp add: HInv3-inner-def*
dest: StartBallot-HInv3-nL StartBallot-HInv3-R)

lemma *StartBallot-HInv3:*
assumes *act: StartBallot s s' t*
and *inv: HInv3-inner s p q d*
shows $\text{HInv3-inner } s' \text{ p } q \text{ d}$
proof(*cases t=p \vee t=q*)
case *True*
with *act inv*
show *?thesis*
by(*auto simp add: HInv3-inner-def*
dest: StartBallot-HInv3-p StartBallot-HInv3-q)
next
case *False*

with *inv act*
show *?thesis*
by(*auto simp add: HInv3-inner-def dest: StartBallot-HInv3-t*)
qed

theorem *HStartBallot-HInv3*:
 $\llbracket \text{HStartBallot } s \ s' \ p; \text{HInv3 } s \rrbracket \implies \text{HInv3 } s'$
by(*auto simp add: HInv3-def dest: StartBallot-HInv3*)

theorem *HPhase1or2ReadElse-HInv3*:
 $\llbracket \text{HPhase1or2ReadElse } s \ s' \ p \ d \ q; \text{HInv3 } s \rrbracket \implies \text{HInv3 } s'$
by(*auto simp add: Phase1or2ReadElse-def HInv3-def dest: StartBallot-HInv3*)

theorem *HPhase1or2Write-HInv3*:
assumes *act: HPhase1or2Write s s' p d*
and *inv: HInv3 s*
shows *HInv3 s'*
proof(*auto simp add: HInv3-def*)
fix *pp qq dd*
show *HInv3-inner s' pp qq dd*
proof(*cases HInv3-L s pp qq dd*)
case *True*
with *inv*
have *HInv3-R s pp qq dd*
by(*simp add: HInv3-def HInv3-inner-def*)
with *act*
show *?thesis*
by(*auto simp add: HInv3-inner-def HInv3-R-def Phase1or2Write-def*)
next
case *False*
with *act*
have $\neg \text{HInv3-L } s' \ pp \ qq \ dd$
by(*auto simp add: HInv3-L-def hasRead-def Phase1or2Write-def*)
thus *?thesis*
by(*simp add: HInv3-inner-def*)
qed
qed

lemma *EndPhase1-HInv3-p*:
 $\llbracket \text{EndPhase1 } s \ s' \ p; \text{HInv3-L } s' \ p \ q \ d \rrbracket \implies \text{HInv3-R } s' \ p \ q \ d$
by(*auto simp add: EndPhase1-def dest: InitPhase-HInv3-p*)

lemma *EndPhase1-HInv3-q*:
 $\llbracket \text{EndPhase1 } s \ s' \ q; \text{HInv3-L } s' \ p \ q \ d \rrbracket \implies \text{HInv3-R } s' \ p \ q \ d$
by(*auto simp add: EndPhase1-def dest: InitPhase-HInv3-q*)

lemma *EndPhase1-HInv3-nL*:

$$\llbracket \text{EndPhase1 } s \ s' \ t; \neg \text{HInv3-L } s \ p \ q \ d; \ t \neq p; \ t \neq q \rrbracket$$

$$\implies \neg \text{HInv3-L } s' \ p \ q \ d$$
by(*auto simp add: EndPhase1-def InitializePhase-def HInv3-L-def hasRead-def*)

lemma *EndPhase1-HInv3-R*:

$$\llbracket \text{EndPhase1 } s \ s' \ t; \text{HInv3-R } s \ p \ q \ d; \ t \neq p; \ t \neq q \rrbracket$$

$$\implies \text{HInv3-R } s' \ p \ q \ d$$
by(*auto simp add: EndPhase1-def InitializePhase-def HInv3-R-def hasRead-def*)

lemma *EndPhase1-HInv3-t*:

$$\llbracket \text{EndPhase1 } s \ s' \ t; \text{HInv3-inner } s \ p \ q \ d; \ t \neq p; \ t \neq q \rrbracket$$

$$\implies \text{HInv3-inner } s' \ p \ q \ d$$
by(*auto simp add: HInv3-inner-def dest: EndPhase1-HInv3-nL EndPhase1-HInv3-R*)

lemma *EndPhase1-HInv3*:

assumes *act: EndPhase1 s s' t*

and *inv: HInv3-inner s p q d*

shows *HInv3-inner s' p q d*

proof(*cases t=p ∨ t=q*)

case *True*

with *act inv*

show *?thesis*

by(*auto simp add: HInv3-inner-def dest: EndPhase1-HInv3-p EndPhase1-HInv3-q*)

next

case *False*

with *inv act*

show *?thesis*

by(*auto simp add: HInv3-inner-def dest: EndPhase1-HInv3-t*)

qed

theorem *HEndPhase1-HInv3*:

$$\llbracket \text{HEndPhase1 } s \ s' \ p; \text{HInv3 } s \rrbracket \implies \text{HInv3 } s'$$
by(*auto simp add: HInv3-def dest: EndPhase1-HInv3*)

lemma *EndPhase2-HInv3-p*:

$$\llbracket \text{EndPhase2 } s \ s' \ p; \text{HInv3-L } s' \ p \ q \ d \rrbracket \implies \text{HInv3-R } s' \ p \ q \ d$$
by(*auto simp add: EndPhase2-def dest: InitPhase-HInv3-p*)

lemma *EndPhase2-HInv3-q*:

$$\llbracket \text{EndPhase2 } s \ s' \ q; \text{HInv3-L } s' \ p \ q \ d \rrbracket \implies \text{HInv3-R } s' \ p \ q \ d$$
by(*auto simp add: EndPhase2-def dest: InitPhase-HInv3-q*)

lemma *EndPhase2-HInv3-nL*:

$$\llbracket \text{EndPhase2 } s \ s' \ t; \neg \text{HInv3-L } s \ p \ q \ d; \ t \neq p; \ t \neq q \rrbracket$$

$$\implies \neg \text{HInv3-L } s' \ p \ q \ d$$

by(*auto simp add: EndPhase2-def InitializePhase-def
HInv3-L-def hasRead-def*)

lemma *EndPhase2-HInv3-R:*

$\llbracket \text{EndPhase2 } s \ s' \ t; \text{HInv3-R } s \ p \ q \ d; \ t \neq p; \ t \neq q \rrbracket$
 $\implies \text{HInv3-R } s' \ p \ q \ d$

by(*auto simp add: EndPhase2-def InitializePhase-def
HInv3-R-def hasRead-def*)

lemma *EndPhase2-HInv3-t:*

$\llbracket \text{EndPhase2 } s \ s' \ t; \text{HInv3-inner } s \ p \ q \ d; \ t \neq p; \ t \neq q \rrbracket$
 $\implies \text{HInv3-inner } s' \ p \ q \ d$

by(*auto simp add: HInv3-inner-def
dest: EndPhase2-HInv3-nL EndPhase2-HInv3-R*)

lemma *EndPhase2-HInv3:*

assumes *act: EndPhase2 s s' t*

and *inv: HInv3-inner s p q d*

shows *HInv3-inner s' p q d*

proof(*cases t=p \vee t=q*)

case *True*

with *act inv*

show *?thesis*

by(*auto simp add: HInv3-inner-def*

dest: EndPhase2-HInv3-p EndPhase2-HInv3-q)

next

case *False*

with *inv act*

show *?thesis*

by(*auto simp add: HInv3-inner-def dest: EndPhase2-HInv3-t*)

qed

theorem *HEndPhase2-HInv3:*

$\llbracket \text{HEndPhase2 } s \ s' \ p; \text{HInv3 } s \rrbracket \implies \text{HInv3 } s'$

by(*auto simp add: HInv3-def dest: EndPhase2-HInv3*)

lemma *Fail-HInv3-p:*

$\llbracket \text{Fail } s \ s' \ p; \text{HInv3-L } s' \ p \ q \ d \rrbracket \implies \text{HInv3-R } s' \ p \ q \ d$

by(*auto simp add: Fail-def dest: InitPhase-HInv3-p*)

lemma *Fail-HInv3-q:*

$\llbracket \text{Fail } s \ s' \ q; \text{HInv3-L } s' \ p \ q \ d \rrbracket \implies \text{HInv3-R } s' \ p \ q \ d$

by(*auto simp add: Fail-def dest: InitPhase-HInv3-q*)

lemma *Fail-HInv3-nL:*

$\llbracket \text{Fail } s \ s' \ t; \neg \text{HInv3-L } s \ p \ q \ d; \ t \neq p; \ t \neq q \rrbracket$

$\implies \neg \text{HInv3-L } s' \ p \ q \ d$

by(*auto simp add: Fail-def InitializePhase-def
HInv3-L-def hasRead-def*)

lemma *Fail-HInv3-R*:
 $\llbracket \text{Fail } s \ s' \ t; \text{HInv3-R } s \ p \ q \ d; \ t \neq p; \ t \neq q \rrbracket$
 $\implies \text{HInv3-R } s' \ p \ q \ d$
by(*auto simp add: Fail-def InitializePhase-def*
HInv3-R-def hasRead-def)

lemma *Fail-HInv3-t*:
 $\llbracket \text{Fail } s \ s' \ t; \text{HInv3-inner } s \ p \ q \ d; \ t \neq p; \ t \neq q \rrbracket$
 $\implies \text{HInv3-inner } s' \ p \ q \ d$
by(*auto simp add: HInv3-inner-def*
dest: Fail-HInv3-nL Fail-HInv3-R)

lemma *Fail-HInv3*:
assumes *act: Fail s s' t*
and *inv: HInv3-inner s p q d*
shows *HInv3-inner s' p q d*
proof(*cases t=p \vee t=q*)
case *True*
with *act inv*
show *?thesis*
by(*auto simp add: HInv3-inner-def*
dest: Fail-HInv3-p Fail-HInv3-q)
next
case *False*
with *inv act*
show *?thesis*
by(*auto simp add: HInv3-inner-def dest: Fail-HInv3-t*)
qed

theorem *HFail-HInv3*:
 $\llbracket \text{HFail } s \ s' \ p; \text{HInv3 } s \rrbracket \implies \text{HInv3 } s'$
by(*auto simp add: HInv3-def dest: Fail-HInv3*)

theorem *HPhase0Read-HInv3*:
assumes *act: HPhase0Read s s' p d*
and *inv: HInv3 s*
shows *HInv3 s'*
proof(*auto simp add: HInv3-def*)
fix *pp qq dd*
show *HInv3-inner s' pp qq dd*
proof(*cases HInv3-L s pp qq dd*)
case *True*
with *inv*
have *HInv3-R s pp qq dd*
by(*simp add: HInv3-def HInv3-inner-def*)
with *act*
show *?thesis*
by(*auto simp add: HInv3-inner-def HInv3-R-def Phase0Read-def*)

```

next
  case False
  with act
  have  $\neg HInv3-L\ s'\ pp\ qq\ dd$ 
    by(auto simp add: HInv3-L-def hasRead-def Phase0Read-def)
  thus ?thesis
    by(simp add: HInv3-inner-def)
qed
qed

```

```

lemma EndPhase0-HInv3-p:
  [[ EndPhase0 s s' p; HInv3-L s' p q d ]
    $\implies HInv3-R\ s'\ p\ q\ d$  ]
by(auto simp add: EndPhase0-def dest: InitPhase-HInv3-p)

```

```

lemma EndPhase0-HInv3-q:
  [[ EndPhase0 s s' q; HInv3-L s' p q d ]
    $\implies HInv3-R\ s'\ p\ q\ d$  ]
by(auto simp add: EndPhase0-def dest: InitPhase-HInv3-q)

```

```

lemma EndPhase0-HInv3-nL:
  [[ EndPhase0 s s' t;  $\neg HInv3-L\ s\ p\ q\ d$ ;  $t \neq p$ ;  $t \neq q$  ]
    $\implies \neg HInv3-L\ s'\ p\ q\ d$  ]
by(auto simp add: EndPhase0-def InitializePhase-def
  HInv3-L-def hasRead-def)

```

```

lemma EndPhase0-HInv3-R:
  [[ EndPhase0 s s' t; HInv3-R s p q d;  $t \neq p$ ;  $t \neq q$  ]
    $\implies HInv3-R\ s'\ p\ q\ d$  ]
by(auto simp add: EndPhase0-def InitializePhase-def
  HInv3-R-def hasRead-def)

```

```

lemma EndPhase0-HInv3-t:
  [[ EndPhase0 s s' t; HInv3-inner s p q d;  $t \neq p$ ;  $t \neq q$  ]
    $\implies HInv3-inner\ s'\ p\ q\ d$  ]
by(auto simp add: HInv3-inner-def
  dest: EndPhase0-HInv3-nL EndPhase0-HInv3-R)

```

```

lemma EndPhase0-HInv3:
  assumes act: EndPhase0 s s' t
  and inv: HInv3-inner s p q d
  shows HInv3-inner s' p q d
proof(cases t=p  $\vee$  t=q)
  case True
  with act inv
  show ?thesis
    by(auto simp add: HInv3-inner-def
  dest: EndPhase0-HInv3-p EndPhase0-HInv3-q)

```

```

next

```

```

case False
with inv act
show ?thesis
  by(auto simp add: HInv3-inner-def dest: EndPhase0-HInv3-t)
qed

```

```

theorem HEndPhase0-HInv3:
   $\llbracket \text{HEndPhase0 } s \ s' \ p; \text{HInv3 } s \rrbracket \implies \text{HInv3 } s'$ 
  by(auto simp add: HInv3-def dest: EndPhase0-HInv3)

```

HInv1 \wedge *HInv2* \wedge *HInv3* is an invariant of *HNext*.

```

lemma I2c:
  assumes next: HNext s s'
  and inv: HInv1 s  $\wedge$  HInv2 s  $\wedge$  HInv3 s
  shows HInv3 s' using assms
  by(auto simp add: HNext-def Next-def,
    auto intro: HStartBallot-HInv3,
    auto intro: HPhase0Read-HInv3,
    auto intro: HPhase1or2Write-HInv3,
    auto simp add: Phase1or2Read-def HInv2-def
    intro: HPhase1or2ReadThen-HInv3
    HPhase1or2ReadElse-HInv3,
    auto simp add: EndPhase1or2-def
    intro: HEndPhase1-HInv3
    HEndPhase2-HInv3,
    auto intro: HFail-HInv3,
    auto intro: HEndPhase0-HInv3)

```

end

```

theory DiskPaxos-Inv4 imports DiskPaxos-Inv2 begin

```

C.4 Invariant 4

This invariant expresses relations among *mbal* and *bal* values of a processor and of its disk blocks. *HInv4a* asserts that, when *p* is not recovering from a failure, its *mbal* value is at least as large as the *bal* field of any of its blocks, and at least as large as the *mbal* field of its block on some disk in any majority set. *HInv4b* conjunct asserts that, in phase 1, its *mbal* value is actually greater than the *bal* field of any of its blocks. *HInv4c* asserts that, in phase 2, its *bal* value is the *mbal* field of all its blocks on some majority set of disks. *HInv4d* asserts that the *bal* field of any of its blocks is at most as large as the *mbal* field of all its disk blocks on some majority set of disks.

```

definition MajoritySet :: Disk set set
  where MajoritySet = {D. IsMajority(D) }

```

```

definition HInv4a1 :: state  $\Rightarrow$  Proc  $\Rightarrow$  bool

```

where $HInv4a1\ s\ p = (\forall bk \in blocksOf\ s\ p. bal\ bk \leq mbal\ (dblock\ s\ p))$

definition $HInv4a2 :: state \Rightarrow Proc \Rightarrow bool$

where

$HInv4a2\ s\ p = (\forall D \in MajoritySet. (\exists d \in D. mbal(disk\ s\ d\ p) \leq mbal(dblock\ s\ p))$
 $\wedge bal(disk\ s\ d\ p) \leq bal(dblock\ s\ p)))$

definition $HInv4a :: state \Rightarrow Proc \Rightarrow bool$

where $HInv4a\ s\ p = (phase\ s\ p \neq 0 \longrightarrow HInv4a1\ s\ p \wedge HInv4a2\ s\ p)$

definition $HInv4b :: state \Rightarrow Proc \Rightarrow bool$

where $HInv4b\ s\ p = (phase\ s\ p = 1 \longrightarrow (\forall bk \in blocksOf\ s\ p. bal\ bk < mbal(dblock\ s\ p)))$

definition $HInv4c :: state \Rightarrow Proc \Rightarrow bool$

where $HInv4c\ s\ p = (phase\ s\ p \in \{2,3\} \longrightarrow (\exists D \in MajoritySet. \forall d \in D. mbal(disk\ s\ d\ p) = bal(dblock\ s\ p)))$

definition $HInv4d :: state \Rightarrow Proc \Rightarrow bool$

where $HInv4d\ s\ p = (\forall bk \in blocksOf\ s\ p. \exists D \in MajoritySet. \forall d \in D. bal\ bk \leq mbal(disk\ s\ d\ p))$

definition $HInv4 :: state \Rightarrow bool$

where $HInv4\ s = (\forall p. HInv4a\ s\ p \wedge HInv4b\ s\ p \wedge HInv4c\ s\ p \wedge HInv4d\ s\ p)$

The initial state implies Invariant 4.

theorem $HInit-HInv4: HInit\ s \Longrightarrow HInv4\ s$

using *Disk-isMajority*

by(*auto simp add: HInit-def Init-def HInv4-def HInv4a-def HInv4a1-def*
HInv4a2-def HInv4b-def HInv4c-def HInv4d-def
MajoritySet-def blocksOf-def InitDB-def rdBy-def)

To prove that the actions preserve $HInv4$, we do it for one conjunct at a time.

For each action $actionss'q$ and conjunct $x \in a, b, c, d$ of $HInv4xs'p$, we prove two lemmas. The first lemma $action-HInv4x-p$ proves the case of $p = q$, while lemma $action-HInv4x-q$ proves the other case.

C.4.1 Proofs of Invariant 4a

lemma $HStartBallot-HInv4a1:$

assumes $act: HStartBallot\ s\ s'\ p$

and $inv: HInv4a1\ s\ p$

and $inv2a: Inv2a-inner\ s'\ p$

shows $HInv4a1\ s'\ p$

proof(*auto simp add: HInv4a1-def*)

fix bk


```

assume  $bk \in \text{blocksOf } s' p$ 
with  $H\text{StartBallot-blocksOf}[OF \text{ act}]$ 
have  $bk \in \{\text{dblock } s' p\} \cup \text{blocksOf } s p$ 
  by  $\text{blast}$ 
thus  $\text{bal } bk \leq \text{mbal } (\text{dblock } s' p)$ 
proof
  assume  $bk \in \{\text{dblock } s' p\}$ 
  with  $\text{inv2a}$ 
  show  $?thesis$ 
  by( $\text{auto simp add: Inv2a-innermost-def Inv2a-inner-def blocksOf-def}$ )
next
  assume  $bk \in \text{blocksOf } s p$ 
  with  $\text{inv act}$ 
  show  $?thesis$ 
  by( $\text{auto simp add: StartBallot-def HInv4a1-def}$ )
qed
qed

```

```

lemma  $H\text{StartBallot-HInv4a2}$ :
  assumes  $\text{act: } H\text{StartBallot } s s' p$ 
  and  $\text{inv: } H\text{Inv4a2 } s p$ 
  shows  $H\text{Inv4a2 } s' p$ 
proof( $\text{auto simp add: HInv4a2-def}$ )
  fix  $D$ 
  assume  $D\text{maj: } D \in \text{MajoritySet}$ 
  from  $\text{inv } D\text{maj}$ 
  have  $\exists d \in D. \text{mbal } (\text{disk } s d p) \leq \text{mbal } (\text{dblock } s p)$ 
     $\wedge \text{bal } (\text{disk } s d p) \leq \text{bal } (\text{dblock } s p)$ 
  by( $\text{auto simp add: HInv4a2-def}$ )
  then obtain  $d$ 
  where  $d \in D$ 
     $\wedge \text{mbal } (\text{disk } s d p) \leq \text{mbal } (\text{dblock } s p)$ 
     $\wedge \text{bal } (\text{disk } s d p) \leq \text{bal } (\text{dblock } s p)$ 
  by  $\text{auto}$ 
  with  $\text{act}$ 
  have  $d \in D$ 
     $\wedge \text{mbal } (\text{disk } s' d p) \leq \text{mbal } (\text{dblock } s' p)$ 
     $\wedge \text{bal } (\text{disk } s' d p) \leq \text{bal } (\text{dblock } s' p)$ 
  by( $\text{auto simp add: StartBallot-def}$ )
  with  $D\text{maj}$ 
  show  $\exists d \in D. \text{mbal } (\text{disk } s' d p) \leq \text{mbal } (\text{dblock } s' p)$ 
     $\wedge \text{bal } (\text{disk } s' d p) \leq \text{bal } (\text{dblock } s' p)$ 
  by  $\text{auto}$ 
qed

```

```

lemma  $H\text{StartBallot-HInv4a-p}$ :
  assumes  $\text{act: } H\text{StartBallot } s s' p$ 
  and  $\text{inv: } H\text{Inv4a } s p$ 
  and  $\text{inv2a: } \text{Inv2a-inner } s' p$ 

```

```

  shows  $HInv4a\ s'\ p$ 
using  $act\ inv\ inv2a$ 
proof -
  from  $act$ 
  have  $phase: 0 < phase\ s\ p$ 
    by( $auto\ simp\ add: StartBallot-def$ )
  from  $act\ inv\ inv2a$ 
  show  $?thesis$ 
    by( $auto\ simp\ del: HStartBallot-def\ simp\ add: HInv4a-def\ phase$ 
       $elim: HStartBallot-HInv4a1\ HStartBallot-HInv4a2$ )
qed

```

```

lemma  $HStartBallot-HInv4a-q$ :
  assumes  $act: HStartBallot\ s\ s'\ p$ 
  and  $inv: HInv4a\ s\ q$ 
  and  $pnq: p \neq q$ 
  shows  $HInv4a\ s'\ q$ 
proof -
  from  $act\ pnq$ 
  have  $blocksOf\ s'\ q \subseteq blocksOf\ s\ q$ 
    by( $auto\ simp\ add: StartBallot-def\ InitializePhase-def$ 
       $blocksOf-def\ rdBy-def$ )
  with  $act\ inv\ pnq$ 
  show  $?thesis$ 
    by( $auto\ simp\ add: StartBallot-def\ HInv4a-def$ 
       $HInv4a1-def\ HInv4a2-def$ )
qed

```

```

theorem  $HStartBallot-HInv4a$ :
  assumes  $act: HStartBallot\ s\ s'\ p$ 
  and  $inv: HInv4a\ s\ q$ 
  and  $inv2a: Inv2a\ s'$ 
  shows  $HInv4a\ s'\ q$ 
proof( $cases\ p=q$ )
  case  $True$ 
  from  $inv2a$ 
  have  $Inv2a-inner\ s'\ p$ 
    by( $auto\ simp\ add: Inv2a-def$ )
  with  $act\ inv\ True$ 
  show  $?thesis$ 
    by( $blast\ dest: HStartBallot-HInv4a-p$ )
  next
  case  $False$ 
  with  $act\ inv$ 
  show  $?thesis$ 
    by( $blast\ dest: HStartBallot-HInv4a-q$ )
qed

```

```

lemma  $Phase1or2Write-HInv4a1$ :

```

$\llbracket \text{Phase1or2Write } s \ s' \ p \ d; \text{HInv4a1 } s \ q \rrbracket \implies \text{HInv4a1 } s' \ q$
by(*auto simp add: Phase1or2Write-def HInv4a1-def*
blocksOf-def rdBy-def)

lemma *Phase1or2Write-HInv4a2:*

$\llbracket \text{Phase1or2Write } s \ s' \ p \ d; \text{HInv4a2 } s \ q \rrbracket \implies \text{HInv4a2 } s' \ q$
by(*auto simp add: Phase1or2Write-def HInv4a2-def*)

theorem *HPhase1or2Write-HInv4a:*

assumes *act: HPhase1or2Write s s' p d*

and *inv: HInv4a s q*

shows *HInv4a s' q*

proof –

from *act*

have *phase': phase s = phase s'*

by(*simp add: Phase1or2Write-def*)

show *?thesis*

proof(*cases phase s q = 0*)

case *True*

with *phase' act*

show *?thesis*

by(*auto simp add: HInv4a-def*)

next

case *False*

with *phase' act inv*

show *?thesis*

by(*auto simp add: HInv4a-def*

dest: Phase1or2Write-HInv4a1 Phase1or2Write-HInv4a2)

qed

qed

lemma *HPhase1or2ReadThen-HInv4a1-p:*

assumes *act: HPhase1or2ReadThen s s' p d q*

and *inv: HInv4a1 s p*

shows *HInv4a1 s' p*

proof(*auto simp: HInv4a1-def*)

fix *bk*

assume *bk: bk ∈ blocksOf s' p*

with *HPhase1or2ReadThen-blocksOf[OF act]*

have *bk ∈ blocksOf s p* **by** *auto*

with *inv act*

show *bal bk ≤ mbal (dblock s' p)*

by(*auto simp add: HInv4a1-def Phase1or2ReadThen-def*)

qed

lemma *HPhase1or2ReadThen-HInv4a2:*

$\llbracket \text{HPhase1or2ReadThen } s \ s' \ p \ d \ r; \text{HInv4a2 } s \ q \rrbracket \implies \text{HInv4a2 } s' \ q$

by(*auto simp add: Phase1or2ReadThen-def HInv4a2-def*)

lemma *HPhase1or2ReadThen-HInv4a-p*:
assumes *act: HPhase1or2ReadThen s s' p d r*
and *inv: HInv4a s p*
and *inv2b: Inv2b s*
shows *HInv4a s' p*
proof –
from *act inv2b*
have *phase s p ∈ {1,2}*
by(*auto simp add: Phase1or2ReadThen-def Inv2b-def Inv2b-inner-def*)
with *act inv*
show *?thesis*
by(*auto simp del: HPhase1or2ReadThen-def simp add: HInv4a-def*
elim: HPhase1or2ReadThen-HInv4a1-p HPhase1or2ReadThen-HInv4a2)
qed

lemma *HPhase1or2ReadThen-HInv4a-q*:
assumes *act: HPhase1or2ReadThen s s' p d r*
and *inv: HInv4a s q*
and *pnq: p ≠ q*
shows *HInv4a s' q*
proof –
from *act pnq*
have *blocksOf s' q ⊆ blocksOf s q*
by(*auto simp add: Phase1or2ReadThen-def InitializePhase-def*
blocksOf-def rdBy-def)
with *act inv pnq*
show *?thesis*
by(*auto simp add: Phase1or2ReadThen-def HInv4a-def*
HInv4a1-def HInv4a2-def)
qed

theorem *HPhase1or2ReadThen-HInv4a*:
 $\llbracket \text{HPhase1or2ReadThen } s \text{ } s' \text{ } p \text{ } d \text{ } r; \text{HInv4a } s \text{ } q; \text{Inv2b } s \rrbracket \implies \text{HInv4a } s' \text{ } q$
by(*blast dest: HPhase1or2ReadThen-HInv4a-p HPhase1or2ReadThen-HInv4a-q*)

theorem *HPhase1or2ReadElse-HInv4a*:
assumes *act: HPhase1or2ReadElse s s' p d r*
and *inv: HInv4a s q and inv2a: Inv2a s'*
shows *HInv4a s' q*
proof –
from *act* **have** *HStartBallot s s' p*
by(*simp add: Phase1or2ReadElse-def*)
with *inv inv2a* **show** *?thesis*
by(*blast dest: dest: HStartBallot-HInv4a*)
qed

lemma *HEndPhase1-HInv4a1*:
assumes *act: HEndPhase1 s s' p*
and *inv: HInv4a1 s p*

shows $HInv4a1\ s'\ p$
proof(*auto simp add: HInv4a1-def*)
fix bk
assume $bk: bk \in \text{blocksOf } s'\ p$
from $bk\ H\text{EndPhase1-blocksOf}[OF\ act]$
have $bk \in \{\text{dblock } s'\ p\} \cup \text{blocksOf } s\ p$
by *blast*
with $act\ inv$
show $bal\ bk \leq mbal\ (\text{dblock } s'\ p)$
by(*auto simp add: HInv4a-def HInv4a1-def EndPhase1-def*)
qed

lemma $H\text{EndPhase1-HInv4a2}$:
assumes $act: H\text{EndPhase1 } s\ s'\ p$
and $inv: HInv4a2\ s\ p$
and $inv2a: Inv2a\ s$
shows $HInv4a2\ s'\ p$
proof(*auto simp add: HInv4a2-def*)
fix D
assume $Dmaj: D \in \text{MajoritySet}$
from $inv\ Dmaj$
have $\exists d \in D. mbal\ (\text{disk } s\ d\ p) \leq mbal\ (\text{dblock } s\ p)$
 $\wedge bal\ (\text{disk } s\ d\ p) \leq bal\ (\text{dblock } s\ p)$
by(*auto simp add: HInv4a2-def*)
then obtain d
where $d\text{-cond}: d \in D$
 $\wedge mbal\ (\text{disk } s\ d\ p) \leq mbal\ (\text{dblock } s\ p)$
 $\wedge bal\ (\text{disk } s\ d\ p) \leq bal\ (\text{dblock } s\ p)$
by *auto*
have $\text{disk } s\ d\ p \in \text{blocksOf } s\ p$
by(*auto simp add: blocksOf-def*)
with $inv2a$
have $bal(\text{disk } s\ d\ p) \leq mbal\ (\text{disk } s\ d\ p)$
by(*auto simp add: Inv2a-def Inv2a-inner-def Inv2a-innermost-def*)
with $act\ d\text{-cond}$
have $d \in D$
 $\wedge mbal\ (\text{disk } s'\ d\ p) \leq mbal\ (\text{dblock } s'\ p)$
 $\wedge bal\ (\text{disk } s'\ d\ p) \leq bal\ (\text{dblock } s'\ p)$
by(*auto simp add: EndPhase1-def*)
with $Dmaj$
show $\exists d \in D. mbal\ (\text{disk } s'\ d\ p) \leq mbal\ (\text{dblock } s'\ p)$
 $\wedge bal\ (\text{disk } s'\ d\ p) \leq bal\ (\text{dblock } s'\ p)$
by *auto*
qed

lemma $H\text{EndPhase1-HInv4a-p}$:
assumes $act: H\text{EndPhase1 } s\ s'\ p$
and $inv: HInv4a\ s\ p$
and $inv2a: Inv2a\ s$

shows $HInv4a\ s'\ p$
proof –
from act
have $phase: 0 < phase\ s\ p$
by($auto\ simp\ add: EndPhase1-def$)
with $act\ inv\ inv2a$
show $?thesis$
by($auto\ simp\ del: HEndPhase1-def\ simp\ add: HInv4a-def$
 $elim: HEndPhase1-HInv4a1\ HEndPhase1-HInv4a2$)
qed

lemma $HEndPhase1-HInv4a-q$:
assumes $act: HEndPhase1\ s\ s'\ p$
and $inv: HInv4a\ s\ q$
and $pnq: p \neq q$
shows $HInv4a\ s'\ q$
proof –
from $act\ pnq$
have $dblock\ s'\ q = dblock\ s\ q \wedge disk\ s' = disk\ s$
by($auto\ simp\ add: EndPhase1-def$)
moreover
from $act\ pnq$
have $\forall p\ d. rdBy\ s'\ q\ p\ d \subseteq rdBy\ s\ q\ p\ d$
by($auto\ simp\ add: EndPhase1-def\ InitializePhase-def\ rdBy-def$)
hence $(UN\ p\ d. rdBy\ s'\ q\ p\ d) \subseteq (UN\ p\ d. rdBy\ s\ q\ p\ d)$
by($auto, blast$)
ultimately
have $blocksOf\ s'\ q \subseteq blocksOf\ s\ q$
by($auto\ simp\ add: blocksOf-def, blast$)
with $act\ inv\ pnq$
show $?thesis$
by($auto\ simp\ add: EndPhase1-def\ HInv4a-def\ HInv4a1-def\ HInv4a2-def$)
qed

theorem $HEndPhase1-HInv4a$:
 $\llbracket HEndPhase1\ s\ s'\ p; HInv4a\ s\ q; Inv2a\ s \rrbracket \implies HInv4a\ s'\ q$
by($blast\ dest: HEndPhase1-HInv4a-p\ HEndPhase1-HInv4a-q$)

theorem $HFail-HInv4a$:
 $\llbracket HFail\ s\ s'\ p; HInv4a\ s\ q \rrbracket \implies HInv4a\ s'\ q$
by($auto\ simp\ add: Fail-def\ HInv4a-def\ HInv4a1-def$
 $HInv4a2-def\ InitializePhase-def$
 $blocksOf-def\ rdBy-def$)

theorem $HPhase0Read-HInv4a$:
 $\llbracket HPhase0Read\ s\ s'\ p\ d; HInv4a\ s\ q \rrbracket \implies HInv4a\ s'\ q$
by($auto\ simp\ add: Phase0Read-def\ HInv4a-def\ HInv4a1-def$
 $HInv4a2-def\ InitializePhase-def$
 $blocksOf-def\ rdBy-def$)

theorem *HEndPhase2-HInv4a*:
 $\llbracket \text{HEndPhase2 } s \ s' \ p; \text{HInv4a } s \ q \rrbracket \implies \text{HInv4a } s' \ q$
by(*auto simp add: EndPhase2-def HInv4a-def HInv4a1-def HInv4a2-def InitializePhase-def blocksOf-def rdBy-def*)

lemma *allSet*:
assumes *aPQ*: $\forall a. \forall r \in P. a. Q \ r$ **and** *rb*: $rb \in P \ d$
shows $Q \ rb$
proof –
from *aPQ* **have** $\forall r \in P. d. Q \ r$ **by** *auto*
with *rb*
show *?thesis* **by** *auto*
qed

lemma *EndPhase0-44*:
assumes *act*: *EndPhase0* $s \ s' \ p$
and *bk*: $bk \in \text{blocksOf } s \ p$
and *inv4d*: *HInv4d* $s \ p$
and *inv2c*: *Inv2c-inner* $s \ p$
shows $\exists d. \exists rb \in \text{blocksRead } s \ p \ d. \text{bal } bk \leq \text{mbal}(\text{block } rb)$
proof –
from *bk inv4d*
have $\exists D1 \in \text{MajoritySet}. \forall d \in D1. \text{bal } bk \leq \text{mbal}(\text{disk } s \ d \ p)$ — 4.2
by(*auto simp add: HInv4d-def*)
with *majorities-intersect*
have *p43*: $\forall D \in \text{MajoritySet}. \exists d \in D. \text{bal } bk \leq \text{mbal}(\text{disk } s \ d \ p)$
by(*simp add: MajoritySet-def, blast*)
from *act*
have *phase* $s \ p = 0$ **by**(*simp add: EndPhase0-def*)
with *inv2c*
have $\forall d. \forall rb \in \text{blocksRead } s \ p \ d. \text{block } rb = \text{disk } s \ d \ p$ — 5.1
by(*simp add: Inv2c-inner-def*)
hence $\forall d. \text{hasRead } s \ p \ d \ p$
 $\longrightarrow (\exists rb \in \text{blocksRead } s \ p \ d. \text{block } rb = \text{disk } s \ d \ p)$ — 5.2
(is $\forall d. ?H \ d \longrightarrow ?P \ d$)
by(*auto simp add: hasRead-def*)
with *act*
have *p53*: $\exists D \in \text{MajoritySet}. \forall d \in D. ?P \ d$
by(*auto simp add: MajoritySet-def EndPhase0-def*)
show *?thesis*
proof –
from *p43 p53*
have $\exists D \in \text{MajoritySet}. (\exists d \in D. \text{bal } bk \leq \text{mbal}(\text{disk } s \ d \ p))$
 $\wedge (\forall d \in D. ?P \ d)$
by *auto*
thus *?thesis*
by *force*
qed

qed

lemma *HEndPhase0-HInv4a1-p*:
 assumes *act: HEndPhase0 s s' p*
 and *inv2a': Inv2a s'*
 and *inv2c: Inv2c-inner s p*
 and *inv4d: HInv4d s p*
 shows *HInv4a1 s' p*
proof(*auto simp add: HInv4a1-def*)
 fix *bk*
 assume *bk ∈ blocksOf s' p*
 with *HEndPhase0-blocksOf[OF act]*
 have *bk ∈ {dblock s' p} ∪ blocksOf s p* **by** *auto*
 thus *bal bk ≤ mbal (dblock s' p)*
 proof
 assume *bk: bk ∈ {dblock s' p}*
 with *inv2a'*
 have *Inv2a-innermost s' p bk*
 by(*auto simp add: Inv2a-def Inv2a-inner-def blocksOf-def*)
 with *bk* **show** *?thesis*
 by(*auto simp add: Inv2a-innermost-def*)
 next
 assume *bk: bk ∈ blocksOf s p*
 from *act*
 have *f1: ∀ r ∈ allBlocksRead s p. mbal r < mbal (dblock s' p)*
 by(*auto simp add: EndPhase0-def*)
 with *act inv4d inv2c bk*
 have $\exists d. \exists rb \in \text{blocksRead } s \text{ } p \text{ } d. \text{bal } bk \leq \text{mbal}(\text{block } rb)$
 by(*auto dest: EndPhase0-44*)
 with *f1*
 show *?thesis*
 by(*auto simp add: EndPhase0-def allBlocksRead-def*
 allRdBlks-def dest: allSet)

qed

qed

lemma *hasRead-allBlks*:
 assumes *inv2c: Inv2c-inner s p*
 and *phase: phase s p = 0*
 shows $(\forall d \in \{d. \text{hasRead } s \text{ } p \text{ } d \text{ } p\}. \text{disk } s \text{ } d \text{ } p \in \text{allBlocksRead } s \text{ } p)$
proof
 fix *d*
 assume *d: d ∈ {d. hasRead s p d p}* (**is** *d ∈ ?D*)
 hence *br-ne: blocksRead s p d ≠ {}*
 by (*auto simp add: hasRead-def*)
 from *inv2c phase*
 have $\forall br \in \text{blocksRead } s \text{ } p \text{ } d. \text{block } br = \text{disk } s \text{ } d \text{ } p$
 by(*auto simp add: Inv2c-inner-def*)
 with *br-ne*

have $disk\ s\ d\ p \in block\ 'blocksRead\ s\ p\ d$
by *force*
thus $disk\ s\ d\ p \in allBlocksRead\ s\ p$
by(*auto simp add: allBlocksRead-def allRdBlks-def*)
qed

lemma *HEndPhase0-41*:
assumes *act: HEndPhase0 s s' p*
and *inv1: Inv1 s*
and *inv2c: Inv2c-inner s p*
shows $\exists D \in MajoritySet. \forall d \in D. mbal(disk\ s\ d\ p) \leq mbal(dblock\ s'\ p)$
 $\wedge bal(disk\ s\ d\ p) \leq bal(dblock\ s'\ p)$

proof –
from *act HEndPhase0-some[OF act inv1]*
have $p51: \forall br \in allBlocksRead\ s\ p. mbal\ br < mbal(dblock\ s'\ p)$
 $\wedge bal\ br \leq bal(dblock\ s'\ p)$
and *a: IsMajority({d. hasRead s p d p})*
and *phase: phase s p = 0*
by(*auto simp add: EndPhase0-def*)
from *inv2c phase*
have $(\forall d \in \{d. hasRead\ s\ p\ d\ p\}. disk\ s\ d\ p \in allBlocksRead\ s\ p)$
by(*auto dest: hasRead-allBlks*)
with *p51*
have $(\forall d \in \{d. hasRead\ s\ p\ d\ p\}. mbal(disk\ s\ d\ p) \leq mbal(dblock\ s'\ p))$
 $\wedge bal(disk\ s\ d\ p) \leq bal(dblock\ s'\ p)$
by *force*
with *a show ?thesis*
by(*auto simp add: MajoritySet-def*)
qed

lemma *Majority-exQ*:
assumes *asm1: $\exists D \in MajoritySet. \forall d \in D. P\ d$*
shows $\forall D \in MajoritySet. \exists d \in D. P\ d$
using *asm1*
proof(*auto simp add: MajoritySet-def*)
fix *D1 D2*
assume *D1: IsMajority D1 and D2: IsMajority D2*
and *Px: $\forall x \in D1. P\ x$*
from *D1 D2 majorities-intersect*
have $\exists d \in D1. d \in D2$ **by** *auto*
with *Px*
show $\exists x \in D2. P\ x$
by *auto*
qed

lemma *HEndPhase0-HInv4a2-p*:
assumes *act: HEndPhase0 s s' p*
and *inv1: Inv1 s*

and $inv2c: Inv2c\text{-inner } s \ p$
shows $HInv4a2 \ s' \ p$
proof(*simp add: HInv4a2-def*)
from act
have $disk'$: $disk \ s' = disk \ s$
by(*simp add: EndPhase0-def*)
from $act \ inv1 \ inv2c$
have $\exists D \in MajoritySet. \forall d \in D. \ mbal(disk \ s \ d \ p) \leq mbal(dblock \ s' \ p)$
 $\wedge \ bal(disk \ s \ d \ p) \leq bal(dblock \ s' \ p)$
by(*blast dest: HEndPhase0-41*)
from $Majority\text{-exQ}[OF \ this]$
have $\forall D \in MajoritySet. \exists d \in D. \ mbal(disk \ s \ d \ p) \leq mbal(dblock \ s' \ p)$
 $\wedge \ bal(disk \ s \ d \ p) \leq bal(dblock \ s' \ p)$
(is $?P \ (disk \ s)$ **) .**
from $ssubst[OF \ disk', \ of \ ?P, \ OF \ this]$
show $\forall D \in MajoritySet. \exists d \in D. \ mbal \ (disk \ s' \ d \ p) \leq mbal \ (dblock \ s' \ p)$
 $\wedge \ bal \ (disk \ s' \ d \ p) \leq bal \ (dblock \ s' \ p) .$
qed

lemma $HEndPhase0\text{-}HInv4a\text{-}p$:
assumes $act: HEndPhase0 \ s \ s' \ p$
and $inv2a: Inv2a \ s$
and $inv2: Inv2c \ s$
and $inv4d: HInv4d \ s \ p$
and $inv1: Inv1 \ s$
and $inv: HInv4a \ s \ p$
shows $HInv4a \ s' \ p$
proof –
from $inv2$
have $inv2c: Inv2c\text{-inner } s \ p$
by(*auto simp add: Inv2c-def*)
with $inv1 \ inv2a \ act$
have $inv2a'$: $Inv2a \ s'$
by(*blast dest: HEndPhase0-Inv2a*)
from act
have $phase \ s' \ p = 1$
by(*auto simp add: EndPhase0-def*)
with $act \ inv \ inv2c \ inv4d \ inv2a' \ inv1$
show $?thesis$
by(*auto simp add: HInv4a-def simp del: HEndPhase0-def*
 $elim: HEndPhase0\text{-}HInv4a1\text{-}p \ HEndPhase0\text{-}HInv4a2\text{-}p$)
qed

lemma $HEndPhase0\text{-}HInv4a\text{-}q$:
assumes $act: HEndPhase0 \ s \ s' \ p$
and $inv: HInv4a \ s \ q$
and $pnq: p \neq q$
shows $HInv4a \ s' \ q$
proof –

from $act\ pnq$
have $dblock\ s'\ q = dblock\ s\ q \wedge disk\ s' = disk\ s$
by($auto\ simp\ add: EndPhase0-def$)
moreover
from $act\ pnq$
have $\forall p\ d. rdBy\ s'\ q\ p\ d \subseteq rdBy\ s\ q\ p\ d$
by($auto\ simp\ add: EndPhase0-def\ InitializePhase-def\ rdBy-def$)
hence $(UN\ p\ d. rdBy\ s'\ q\ p\ d) \subseteq (UN\ p\ d. rdBy\ s\ q\ p\ d)$
by($auto, blast$)
ultimately
have $blocksOf\ s'\ q \subseteq blocksOf\ s\ q$
by($auto\ simp\ add: blocksOf-def, blast$)
with $act\ inv\ pnq$
show $?thesis$
by($auto\ simp\ add: EndPhase0-def\ HInv4a-def\ HInv4a1-def\ HInv4a2-def$)
qed

theorem $HEndPhase0-HInv4a$:
 $\llbracket HEndPhase0\ s\ s'\ p; HInv4a\ s\ q; HInv4d\ s\ p;$
 $Inv2a\ s; Inv1\ s; Inv2a\ s; Inv2c\ s \rrbracket$
 $\implies HInv4a\ s'\ q$
by($blast\ dest: HEndPhase0-HInv4a-p\ HEndPhase0-HInv4a-q$)

C.4.2 Proofs of Invariant 4b

lemma $blocksRead-allBlocksRead$:
 $rb \in blocksRead\ s\ p\ d \implies block\ rb \in allBlocksRead\ s\ p$
by($auto\ simp\ add: allBlocksRead-def\ allRdBlks-def$)

lemma $HEndPhase0-dblock-mbal$:
 $\llbracket HEndPhase0\ s\ s'\ p \rrbracket$
 $\implies \forall br \in allBlocksRead\ s\ p. mbal\ br < mbal(dblock\ s'\ p)$
by($auto\ simp\ add: EndPhase0-def$)

lemma $HEndPhase0-HInv4b-p-dblock$:
assumes $act: HEndPhase0\ s\ s'\ p$
and $inv1: Inv1\ s$
and $inv2a: Inv2a\ s$
and $inv2c: Inv2c-inner\ s\ p$
shows $bal(dblock\ s'\ p) < mbal(dblock\ s'\ p)$

proof –

from act **have** $phase\ s\ p = 0$ **by**($auto\ simp\ add: EndPhase0-def$)
with $inv2c$
have $\forall d. \forall br \in blocksRead\ s\ p\ d. proc\ br = p \wedge block\ br = disk\ s\ d\ p$
by($auto\ simp\ add: Inv2c-inner-def$)
hence $allBlks-in-blocksOf: allBlocksRead\ s\ p \subseteq blocksOf\ s\ p$
by($auto\ simp\ add: allBlocksRead-def\ allRdBlks-def\ blocksOf-def$)
from act $HEndPhase0-some[OF\ act\ inv1]$

have $p53$: $\exists br \in allBlocksRead\ s\ p. bal(dblock\ s'\ p) = bal\ br$
by (*auto simp add: EndPhase0-def*)
from $inv2a$
have $i2$: $\forall p. \forall bk \in blocksOf\ s\ p. bal\ bk \leq mbal\ bk$
by (*auto simp add: Inv2a-def Inv2a-inner-def Inv2a-innermost-def*)
with $allBlks-in-blocksOf$
have $\forall bk \in allBlocksRead\ s\ p. bal\ bk \leq mbal\ bk$
by *auto*
with $p53$
have $\exists br \in allBlocksRead\ s\ p. bal(dblock\ s'\ p) \leq mbal\ br$
by *force*
with $HEndPhase0-dblock-mbal[OF\ act]$
show $?thesis$
by *auto*
qed

lemma $HEndPhase0-HInv4b-p-blocksOf$:

assumes act : $HEndPhase0\ s\ s'\ p$
and $inv4d$: $HInv4d\ s\ p$
and $inv2c$: $Inv2c-inner\ s\ p$
and bk : $bk \in blocksOf\ s\ p$
shows $bal\ bk < mbal(dblock\ s'\ p)$
proof –
from $inv4d$ $majorities-intersect\ bk$
have $p43$: $\forall D \in MajoritySet. \exists d \in D. bal\ bk \leq mbal(disk\ s\ d\ p)$
by (*auto simp add: HInv4d-def MajoritySet-def Majority-exQ*)
have $\exists br \in allBlocksRead\ s\ p. bal\ bk \leq mbal\ br$
proof –
from act
have maj : $IsMajority(\{d. hasRead\ s\ p\ d\ p\})$ (**is** $IsMajority(?D)$)
and $phase$: $phase\ s\ p = 0$
by (*simp add: EndPhase0-def*)
have $br-ne$: $\forall d \in ?D. blocksRead\ s\ p\ d \neq \{\}$
by (*auto simp add: hasRead-def*)
from $phase\ inv2c$
have $\forall d \in ?D. \forall br \in blocksRead\ s\ p\ d. block\ br = disk\ s\ d\ p$
by (*auto simp add: Inv2c-inner-def*)
with $br-ne$
have $\forall d \in ?D. \exists br \in allBlocksRead\ s\ p. br = disk\ s\ d\ p$
by (*blast dest: blocksRead-allBlocksRead*)
with $p43\ maj$
show $?thesis$
by (*auto simp add: MajoritySet-def*)
qed
with $HEndPhase0-dblock-mbal[OF\ act]$
show $?thesis$
by *auto*
qed

```

lemma HEndPhase0-HInv4b-p:
  assumes act: HEndPhase0 s s' p
  and inv4d: HInv4d s p
  and inv1: Inv1 s
  and inv2a: Inv2a s
  and inv2c: Inv2c-inner s p
  shows HInv4b s' p
proof(clarsimp simp add: HInv4b-def)
  from act
  have phase: phase s p = 0
    by(auto simp add: EndPhase0-def)
  fix bk
  assume bk: bk ∈ blocksOf s' p
  with HEndPhase0-blocksOf[OF act]
  have bk ∈ {dblock s' p} ∨ bk ∈ blocksOf s p
    by blast
  thus bal bk < mbal (dblock s' p)
  proof
    assume bk: bk ∈ {dblock s' p}
    with act inv1 inv2a inv2c
    show ?thesis
      by(auto simp del: HEndPhase0-def
        dest: HEndPhase0-HInv4b-p-dblock )
  next
    assume bk: bk ∈ blocksOf s p
    with act inv2c inv4d
    show ?thesis
      by(blast dest: HEndPhase0-HInv4b-p-blocksOf)
  qed
qed

```

```

lemma HEndPhase0-HInv4b-q:
  assumes act: HEndPhase0 s s' p
  and pnq: p ≠ q
  and inv: HInv4b s q
  shows HInv4b s' q
proof –
  from act pnq
  have disk': disk s' = disk s
  and dblock': dblock s' q = dblock s q
  and phase': phase s' q = phase s q
    by(auto simp add: EndPhase0-def)
  from act pnq
  have blocksRead':  $\forall q. \text{allRdBlks } s' q \subseteq \text{allRdBlks } s q$ 
    by(auto simp add: EndPhase0-def InitializePhase-def allRdBlks-def)
  with disk' dblock'
  have blocksOf s' q  $\subseteq$  blocksOf s q
    by(auto simp add: allRdBlks-def blocksOf-def rdBy-def, blast)
  with inv phase' dblock'

```

```

show ?thesis
  by(auto simp add: HInv4b-def)
qed

theorem HEndPhase0-HInv4b:
  assumes act: HEndPhase0 s s' p
  and inv: HInv4b s q
  and inv4d: HInv4d s p
  and inv1: Inv1 s
  and inv2a: Inv2a s
  and inv2c: Inv2c-inner s p
  shows HInv4b s' q
proof(cases p=q)
  case True
    with HEndPhase0-HInv4b-p[OF act inv4d inv1 inv2a inv2c]
    show ?thesis by simp
  next
    case False
    from HEndPhase0-HInv4b-q[OF act False inv]
    show ?thesis .
qed

```

```

lemma HStartBallot-HInv4b-p:
  assumes act: HStartBallot s s' p
  and inv2a: Inv2a-innermost s p (dblock s p)
  and inv4b: HInv4b s p
  and inv4a: HInv4a s p
  shows HInv4b s' p
proof(clarsimp simp add: HInv4b-def)
  fix bk
  assume bk: bk ∈ blocksOf s' p
  from act
  have phase': phase s' p = 1
    and phase: phase s p ∈ {1,2}
    by(auto simp add: StartBallot-def)
  from act
  have p42: mbal (dblock s p) < mbal (dblock s' p)
    ∧ bal (dblock s p) = bal (dblock s' p)
    by(auto simp add: StartBallot-def)
  from HStartBallot-blocksOf[OF act] bk
  have bk ∈ {dblock s' p} ∪ blocksOf s p
    by blast
  thus bal bk < mbal (dblock s' p)
proof
  assume bk: bk ∈ {dblock s' p}
  from inv2a
  have bal (dblock s p) ≤ mbal (dblock s p)
    by(auto simp add: Inv2a-innermost-def)
  with p42 bk

```

```

  show ?thesis by auto
next
  assume bk: bk ∈ blocksOf s p
  from phase inv4a
  have p41: HInv4a1 s p
    by(auto simp add: HInv4a-def)
  with p42 bk
  show ?thesis
    by(auto simp add: HInv4a1-def)
qed
qed

```

lemma *HStartBallot-HInv4b-q*:

```

  assumes act: HStartBallot s s' p
  and pnq: p ≠ q
  and inv: HInv4b s q
  shows HInv4b s' q
proof -
  from act pnq
  have disk': disk s' = disk s
  and dblock': dblock s' q = dblock s q
  and phase': phase s' q = phase s q
  by(auto simp add: StartBallot-def)
  from act pnq
  have blocksRead': ∀ q. allRdBlks s' q ⊆ allRdBlks s q
  by(auto simp add: StartBallot-def InitializePhase-def allRdBlks-def)
  with disk' dblock'
  have blocksOf s' q ⊆ blocksOf s q
  by(auto simp add: allRdBlks-def blocksOf-def rdBy-def, blast)
  with inv phase' dblock'
  show ?thesis
  by(auto simp add: HInv4b-def)
qed

```

theorem *HStartBallot-HInv4b*:

```

  assumes act: HStartBallot s s' p
  and inv2a: Inv2a s
  and inv4b: HInv4b s q
  and inv4a: HInv4a s p
  shows HInv4b s' q
using act inv2a inv4b inv4a
proof (cases p=q)
  case True
  from inv2a
  have Inv2a-innermost s p (dblock s p)
  by(auto simp add: Inv2a-def Inv2a-inner-def blocksOf-def)
  with act True inv4b inv4a
  show ?thesis
  by(blast dest: HStartBallot-HInv4b-p)

```

next
 case *False*
 with *act inv4b*
 show *?thesis*
 by(*blast dest: HStartBallot-HInv4b-q*)
qed

theorem *HPhase1or2Write-HInv4b*:
 $\llbracket \text{HPhase1or2Write } s \ s' \ p \ d; \text{HInv4b } s \ q \rrbracket \implies \text{HInv4b } s' \ q$
 by(*auto simp add: Phase1or2Write-def HInv4b-def*
blocksOf-def rdBy-def)

lemma *HPhase1or2ReadThen-HInv4b-p*:
 assumes *act: HPhase1or2ReadThen s s' p d q*
 and *inv: HInv4b s p*
 shows *HInv4b s' p*
proof –
 from *HPhase1or2ReadThen-blocksOf[OF act] inv act*
 show *?thesis*
 by(*auto simp add: HInv4b-def Phase1or2ReadThen-def*)
qed

lemma *HPhase1or2ReadThen-HInv4b-q*:
 assumes *act: HPhase1or2ReadThen s s' p d r*
 and *inv: HInv4b s q*
 and *pnq: p ≠ q*
 shows *HInv4b s' q*
 using *assms HPhase1or2ReadThen-blocksOf[OF act]*
 by(*auto simp add: Phase1or2ReadThen-def HInv4b-def*)

theorem *HPhase1or2ReadThen-HInv4b*:
 $\llbracket \text{HPhase1or2ReadThen } s \ s' \ p \ d \ q; \text{HInv4b } s \ r \rrbracket \implies \text{HInv4b } s' \ r$
 by(*blast dest: HPhase1or2ReadThen-HInv4b-p*
HPhase1or2ReadThen-HInv4b-q)

theorem *HPhase1or2ReadElse-HInv4b*:
 $\llbracket \text{HPhase1or2ReadElse } s \ s' \ p \ d \ q; \text{HInv4b } s \ r;$
 $\text{Inv2a } s; \text{HInv4a } s \ p \rrbracket$
 $\implies \text{HInv4b } s' \ r$
 using *HStartBallot-HInv4b*
 by(*auto simp add: Phase1or2ReadElse-def*)

lemma *HEndPhase1-HInv4b-p*:
 $\text{HEndPhase1 } s \ s' \ p \implies \text{HInv4b } s' \ p$
 by(*auto simp add: EndPhase1-def HInv4b-def*)

lemma *HEndPhase1-HInv4b-q*:
 assumes *act: HEndPhase1 s s' p*
 and *pnq: p ≠ q*


```

and inv: HInv4b s q
shows HInv4b s' q
proof –
  from act p n q
  have disk': disk s' = disk s
  and dblock': dblock s' q = dblock s q
  and phase': phase s' q = phase s q
  by(auto simp add: EndPhase1-def)
  from act p n q
  have blocksRead':  $\forall q. \text{allRdBlks } s' q \subseteq \text{allRdBlks } s q$ 
  by(auto simp add: EndPhase1-def InitializePhase-def allRdBlks-def)
  with disk' dblock'
  have blocksOf s' q  $\subseteq$  blocksOf s q
  by(auto simp add: allRdBlks-def blocksOf-def rdBy-def, blast)
  with inv phase' dblock'
  show ?thesis
  by(auto simp add: HInv4b-def)
qed

```

```

theorem HEndPhase1-HInv4b:
  assumes act: HEndPhase1 s s' p
  and inv: HInv4b s q
  shows HInv4b s' q
proof(cases p=q)
  case True
  with HEndPhase1-HInv4b-p[OF act]
  show ?thesis by simp
next
  case False
  from HEndPhase1-HInv4b-q[OF act False inv]
  show ?thesis .
qed

```

```

lemma HEndPhase2-HInv4b-p:
  HEndPhase2 s s' p  $\implies$  HInv4b s' p
  by(auto simp add: EndPhase2-def HInv4b-def)

```

```

lemma HEndPhase2-HInv4b-q:
  assumes act: HEndPhase2 s s' p
  and p n q: p ≠ q
  and inv: HInv4b s q
  shows HInv4b s' q
proof –
  from act p n q
  have disk': disk s' = disk s
  and dblock': dblock s' q = dblock s q
  and phase': phase s' q = phase s q
  by(auto simp add: EndPhase2-def)
  from act p n q

```

have $blocksRead'$: $\forall q. allRdBlks\ s'\ q \subseteq allRdBlks\ s\ q$
by(*auto simp add: EndPhase2-def InitializePhase-def allRdBlks-def*)
with $disk'\ dblock'$
have $blocksOf\ s'\ q \subseteq blocksOf\ s\ q$
by(*auto simp add: allRdBlks-def blocksOf-def rdBy-def, blast*)
with $inv\ phase'\ dblock'$
show $?thesis$
by(*auto simp add: HInv4b-def*)
qed

theorem *HEndPhase2-HInv4b*:
assumes $act: HEndPhase2\ s\ s'\ p$
and $inv: HInv4b\ s\ q$
shows $HInv4b\ s'\ q$
proof(*cases p=q*)
case *True*
with $HEndPhase2-HInv4b-p[OF\ act]$
show $?thesis$ **by** *simp*
next
case *False*
from $HEndPhase2-HInv4b-q[OF\ act\ False\ inv]$
show $?thesis$.
qed

lemma *HFail-HInv4b-p*:
 $HFail\ s\ s'\ p \implies HInv4b\ s'\ q$
by(*auto simp add: Fail-def HInv4b-def*)

lemma *HFail-HInv4b-q*:
assumes $act: HFail\ s\ s'\ p$
and $pnq: p \neq q$
and $inv: HInv4b\ s\ q$
shows $HInv4b\ s'\ q$
proof –
from $act\ pnq$
have $disk': disk\ s' = disk\ s$
and $dblock': dblock\ s'\ q = dblock\ s\ q$
and $phase': phase\ s'\ q = phase\ s\ q$
by(*auto simp add: Fail-def*)
from $act\ pnq$
have $blocksRead': \forall q. allRdBlks\ s'\ q \subseteq allRdBlks\ s\ q$
by(*auto simp add: Fail-def InitializePhase-def allRdBlks-def*)
with $disk'\ dblock'$
have $blocksOf\ s'\ q \subseteq blocksOf\ s\ q$
by(*auto simp add: allRdBlks-def blocksOf-def rdBy-def, blast*)
with $inv\ phase'\ dblock'$
show $?thesis$
by(*auto simp add: HInv4b-def*)
qed

theorem *HFail-HInv4b*:
assumes *act*: *HFail s s' p*
and *inv*: *HInv4b s q*
shows *HInv4b s' q*
proof(*cases p=q*)
case *True*
with *HFail-HInv4b-p[OF act]*
show *?thesis* **by** *simp*
next
case *False*
from *HFail-HInv4b-q[OF act False inv]*
show *?thesis* .
qed

lemma *HPhase0Read-HInv4b-p*:
HPhase0Read s s' p d \implies HInv4b s' p
by(*auto simp add: Phase0Read-def HInv4b-def*)

lemma *HPhase0Read-HInv4b-q*:
assumes *act*: *HPhase0Read s s' p d*
and *pnq*: *p \neq q*
and *inv*: *HInv4b s q*
shows *HInv4b s' q*
proof –
from *act pnq*
have *disk'*: *disk s'=disk s*
and *dblock'*: *dblock s' q=dblock s q*
and *phase'*: *phase s' q=phase s q*
by(*auto simp add: Phase0Read-def*)
from *HPhase0Read-blocksOf[OF act] inv phase' dblock'*
show *?thesis*
by(*auto simp add: HInv4b-def*)
qed

theorem *HPhase0Read-HInv4b*:
assumes *act*: *HPhase0Read s s' p d*
and *inv*: *HInv4b s q*
shows *HInv4b s' q*
proof(*cases p=q*)
case *True*
with *HPhase0Read-HInv4b-p[OF act]*
show *?thesis* **by** *simp*
next
case *False*
from *HPhase0Read-HInv4b-q[OF act False inv]*
show *?thesis* .
qed

C.4.3 Proofs of Invariant 4c

lemma *HStartBallot-HInv4c-p*:
 $\llbracket HStartBallot\ s\ s'\ p; HInv4c\ s\ p \rrbracket \implies HInv4c\ s'\ p$
by(*auto simp add: StartBallot-def HInv4c-def*)

lemma *HStartBallot-HInv4c-q*:
assumes *act: HStartBallot s s' p*
and *inv: HInv4c s q*
and *pnq: p ≠ q*
shows *HInv4c s' q*

proof –
from *act pnq*
have *phase: phase s' q = phase s q*
and *dblock: dblock s q = dblock s' q*
and *disk: disk s' = disk s*
by(*auto simp add: StartBallot-def*)
with *inv*
show *?thesis*
by(*auto simp add: HInv4c-def*)
qed

theorem *HStartBallot-HInv4c*:
 $\llbracket HStartBallot\ s\ s'\ p; HInv4c\ s\ q \rrbracket \implies HInv4c\ s'\ q$
by(*blast dest: HStartBallot-HInv4c-p HStartBallot-HInv4c-q*)

lemma *HPhase1or2Write-HInv4c-p*:
assumes *act: HPhase1or2Write s s' p d*
and *inv: HInv4c s p*
and *inv2c: Inv2c s*
shows *HInv4c s' p*
proof(*cases phase s' p = 2*)
assume *phase': phase s' p = 2*
show *?thesis*
proof(*auto simp add: HInv4c-def phase' MajoritySet-def*)
from *act phase'*
have *bal: bal(dblock s' p)=bal(dblock s p)*
and *phase: phase s p = 2*
by(*auto simp add: Phase1or2Write-def*)
from *phase' inv2c act*
have *mbal(disk s' d p)=bal(dblock s p)*
by(*auto simp add: Phase1or2Write-def Inv2c-def Inv2c-inner-def*)
with *bal*
have *bal(dblock s' p) = mbal(disk s' d p)*
by *auto*
with *inv phase act*
show $\exists D. \text{ IsMajority } D$
 $\wedge (\forall d \in D. \text{ mbal } (disk\ s'\ d\ p) = \text{ bal } (dblock\ s'\ p))$
by(*auto simp add: HInv4c-def Phase1or2Write-def MajoritySet-def*)
qed

next
 case *False*
 with *act*
 show *?thesis*
 by(*auto simp add: HInv4c-def Phase1or2Write-def*)
qed

lemma *HPhase1or2Write-HInv4c-q*:
 assumes *act: HPhase1or2Write s s' p d*
 and *inv: HInv4c s q*
 and *pnq: p ≠ q*
 shows *HInv4c s' q*
proof –
 from *act pnq*
 have *phase: phase s' q = phase s q*
 and *dblock: dblock s q = dblock s' q*
 and *disk: ∀ d. disk s' d q = disk s d q*
 by(*auto simp add: Phase1or2Write-def*)
 with *inv*
 show *?thesis*
 by(*auto simp add: HInv4c-def*)
qed

theorem *HPhase1or2Write-HInv4c*:
 [*HPhase1or2Write s s' p d; HInv4c s q; Inv2c s*]
 ⇒ *HInv4c s' q*
 by(*blast dest: HPhase1or2Write-HInv4c-p*
HPhase1or2Write-HInv4c-q)

lemma *HPhase1or2ReadThen-HInv4c-p*:
 [*HPhase1or2ReadThen s s' p d q; HInv4c s p*] ⇒ *HInv4c s' p*
 by(*auto simp add: Phase1or2ReadThen-def HInv4c-def*)

lemma *HPhase1or2ReadThen-HInv4c-q*:
 assumes *act: HPhase1or2ReadThen s s' p d r*
 and *inv: HInv4c s q*
 and *pnq: p ≠ q*
 shows *HInv4c s' q*
proof –
 from *act pnq*
 have *phase: phase s' q = phase s q*
 and *dblock: dblock s q = dblock s' q*
 and *disk: disk s' = disk s*
 by(*auto simp add: Phase1or2ReadThen-def*)
 with *inv*
 show *?thesis*
 by(*auto simp add: HInv4c-def*)
qed

theorem *HPhase1or2ReadThen-HInv4c*:
 $\llbracket \text{HPhase1or2ReadThen } s \ s' \ p \ d \ r; \text{HInv4c } s \ q \rrbracket$
 $\implies \text{HInv4c } s' \ q$
by(*blast dest: HPhase1or2ReadThen-HInv4c-p*
HPhase1or2ReadThen-HInv4c-q)

theorem *HPhase1or2ReadElse-HInv4c*:
 $\llbracket \text{HPhase1or2ReadElse } s \ s' \ p \ d \ r; \text{HInv4c } s \ q \rrbracket \implies \text{HInv4c } s' \ q$
using *HStartBallot-HInv4c*
by(*auto simp add: Phase1or2ReadElse-def*)

lemma *HEndPhase1-HInv4c-p*:
assumes *act: HEndPhase1 s s' p*
and *inv2b: Inv2b s*
shows *HInv4c s' p*
proof –
from *act*
have *maj: IsMajority {d. d ∈ disksWritten s p*
 $\wedge (\forall q \in (\text{UNIV} - \{p\}). \text{hasRead } s \ p \ d \ q)\}$
(is *IsMajority ?M*)
by(*simp add: EndPhase1-def*)
from *inv2b*
have $\forall d \in ?M. \text{disk } s \ d \ p = \text{dblock } s \ p$
by(*auto simp add: Inv2b-def Inv2b-inner-def*)
with *act maj*
show *?thesis*
by(*auto simp add: HInv4c-def EndPhase1-def MajoritySet-def*)
qed

lemma *HEndPhase1-HInv4c-q*:
assumes *act: HEndPhase1 s s' p*
and *inv: HInv4c s q*
and *pnq: p ≠ q*
shows *HInv4c s' q*
proof –
from *act pnq*
have *phase: phase s' q = phase s q*
and *dblock: dblock s q = dblock s' q*
and *disk: disk s' = disk s*
by(*auto simp add: EndPhase1-def*)
with *inv*
show *?thesis*
by(*auto simp add: HInv4c-def*)
qed

theorem *HEndPhase1-HInv4c*:
 $\llbracket \text{HEndPhase1 } s \ s' \ p; \text{HInv4c } s \ q; \text{Inv2b } s \rrbracket \implies \text{HInv4c } s' \ q$
by(*blast dest: HEndPhase1-HInv4c-p HEndPhase1-HInv4c-q*)

lemma *HEndPhase2-HInv4c-p*:
 $\llbracket \text{HEndPhase2 } s \ s' \ p; \text{HInv4c } s \ p \rrbracket \implies \text{HInv4c } s' \ p$
by(*auto simp add: EndPhase2-def HInv4c-def*)

lemma *HEndPhase2-HInv4c-q*:
assumes *act: HEndPhase2 s s' p*
and *inv: HInv4c s q*
and *pnq: p ≠ q*
shows *HInv4c s' q*

proof –
from *act pnq*
have *phase: phase s' q = phase s q*
and *dblock: dblock s q = dblock s' q*
and *disk: disk s' = disk s*
by(*auto simp add: EndPhase2-def*)
with *inv*
show *?thesis*
by(*auto simp add: HInv4c-def*)
qed

theorem *HEndPhase2-HInv4c*:
 $\llbracket \text{HEndPhase2 } s \ s' \ p; \text{HInv4c } s \ q \rrbracket \implies \text{HInv4c } s' \ q$
by(*blast dest: HEndPhase2-HInv4c-p HEndPhase2-HInv4c-q*)

lemma *HFail-HInv4c-p*:
 $\llbracket \text{HFail } s \ s' \ p; \text{HInv4c } s \ p \rrbracket \implies \text{HInv4c } s' \ p$
by(*auto simp add: Fail-def HInv4c-def*)

lemma *HFail-HInv4c-q*:
assumes *act: HFail s s' p*
and *inv: HInv4c s q*
and *pnq: p ≠ q*
shows *HInv4c s' q*

proof –
from *act pnq*
have *phase: phase s' q = phase s q*
and *dblock: dblock s q = dblock s' q*
and *disk: disk s' = disk s*
by(*auto simp add: Fail-def*)
with *inv*
show *?thesis*
by(*auto simp add: HInv4c-def*)
qed

theorem *HFail-HInv4c*:
 $\llbracket \text{HFail } s \ s' \ p; \text{HInv4c } s \ q \rrbracket \implies \text{HInv4c } s' \ q$
by(*blast dest: HFail-HInv4c-p HFail-HInv4c-q*)

lemma *HPhase0Read-HInv4c-p*:

$\llbracket \text{HPhase0Read } s \ s' \ p \ d; \text{HInv4c } s \ p \rrbracket \implies \text{HInv4c } s' \ p$
by(*auto simp add: Phase0Read-def HInv4c-def*)

lemma *HPhase0Read-HInv4c-q*:
assumes *act: HPhase0Read s s' p d*
and *inv: HInv4c s q*
and *pnq: p ≠ q*
shows *HInv4c s' q*
proof –
from *act pnq*
have *phase: phase s' q = phase s q*
and *dblock: dblock s q = dblock s' q*
and *disk: disk s' = disk s*
by(*auto simp add: Phase0Read-def*)
with *inv*
show *?thesis*
by(*auto simp add: HInv4c-def*)
qed

theorem *HPhase0Read-HInv4c*:
 $\llbracket \text{HPhase0Read } s \ s' \ p \ d; \text{HInv4c } s \ q \rrbracket \implies \text{HInv4c } s' \ q$
by(*blast dest: HPhase0Read-HInv4c-p HPhase0Read-HInv4c-q*)

lemma *HEndPhase0-HInv4c-p*:
 $\llbracket \text{HEndPhase0 } s \ s' \ p; \text{HInv4c } s \ p \rrbracket \implies \text{HInv4c } s' \ p$
by(*auto simp add: EndPhase0-def HInv4c-def*)

lemma *HEndPhase0-HInv4c-q*:
assumes *act: HEndPhase0 s s' p*
and *inv: HInv4c s q*
and *pnq: p ≠ q*
shows *HInv4c s' q*
proof –
from *act pnq*
have *phase: phase s' q = phase s q*
and *dblock: dblock s q = dblock s' q*
and *disk: disk s' = disk s*
by(*auto simp add: EndPhase0-def*)
with *inv*
show *?thesis*
by(*auto simp add: HInv4c-def*)
qed

theorem *HEndPhase0-HInv4c*:
 $\llbracket \text{HEndPhase0 } s \ s' \ p; \text{HInv4c } s \ q \rrbracket \implies \text{HInv4c } s' \ q$
by(*blast dest: HEndPhase0-HInv4c-p HEndPhase0-HInv4c-q*)

C.4.4 Proofs of Invariant 4d

lemma *HStartBallot-HInv4d-p*:
assumes *act*: *HStartBallot s s' p*
and *inv*: *HInv4d s p*
shows *HInv4d s' p*
proof(*clarsimp simp add: HInv4d-def*)
fix *bk*
assume *bk*: *bk ∈ blocksOf s' p*
from *act*
have *bal'*: *bal (dblock s' p) = bal (dblock s p)*
by(*auto simp add: StartBallot-def*)
from *subsetD[OF HStartBallot-blocksOf[OF act] bk]*
have $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal } (\text{disk } s \ d \ p)$
proof
assume *bk*: *bk ∈ blocksOf s p*
with *inv*
show *?thesis*
by(*auto simp add: HInv4d-def*)
next
assume *bk*: *bk ∈ {dblock s' p}*
with *bal' inv*
show *?thesis*
by(*auto simp add: HInv4d-def blocksOf-def*)
qed
with *act*
show $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal } (\text{disk } s' \ d \ p)$
by(*auto simp add: StartBallot-def*)
qed

lemma *HStartBallot-HInv4d-q*:
assumes *act*: *HStartBallot s s' p*
and *inv*: *HInv4d s q*
and *pnq*: *p ≠ q*
shows *HInv4d s' q*
proof –
from *act pnq*
have *disk'*: *disk s' = disk s*
and *dblock'*: *dblock s' q = dblock s q*
by(*auto simp add: StartBallot-def*)
from *act pnq*
have *blocksRead'*: $\forall q. \text{allRdBlks } s' \ q \subseteq \text{allRdBlks } s \ q$
by(*auto simp add: StartBallot-def InitializePhase-def allRdBlks-def*)
with *disk' dblock'*
have *blocksOf s' q* \subseteq *blocksOf s q*
by(*auto simp add: allRdBlks-def blocksOf-def rdBy-def, blast*)
from *subsetD[OF this] inv*
have $\forall bk \in \text{blocksOf } s' \ q.$
 $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal } (\text{disk } s \ d \ q)$
by(*auto simp add: HInv4d-def*)

with *disk'*
show *?thesis*
by(*auto simp add: HInv4d-def*)
qed

theorem *HStartBallot-HInv4d*:
 $\llbracket \text{HStartBallot } s \ s' \ p; \text{HInv4d } s \ q \rrbracket \implies \text{HInv4d } s' \ q$
by(*blast dest: HStartBallot-HInv4d-p HStartBallot-HInv4d-q*)

lemma *HPhase1or2Write-HInv4d-p*:
assumes *act: HPhase1or2Write s s' p d*
and *inv: HInv4d s p*
and *inv4a: HInv4a s p*
shows *HInv4d s' p*
proof(*clarsimp simp add: HInv4d-def*)
fix *bk*
assume *bk: bk ∈ blocksOf s' p*
from *act*
have *ddisk: $\forall dd. \text{disk } s' \ dd \ p = (\text{if } d = dd \text{ then } \text{dblock } s \ p \text{ else } \text{disk } s \ dd \ p)$*
and *phase: phase s p \neq 0*
by(*auto simp add: Phase1or2Write-def*)
from *inv subsetD[OF HPhase1or2Write-blocksOf[OF act] bk]*
have *asm3: $\exists D \in \text{MajoritySet}. \forall dd \in D. \text{bal } bk \leq \text{mbal } (\text{disk } s \ dd \ p)$*
by(*auto simp add: HInv4d-def*)
from *phase inv4a subsetD[OF HPhase1or2Write-blocksOf[OF act] bk] ddisk*
have *p41: $\text{bal } bk \leq \text{mbal } (\text{disk } s' \ d \ p)$*
by(*auto simp add: HInv4a-def HInv4a1-def*)
with *ddisk asm3*
show $\exists D \in \text{MajoritySet}. \forall dd \in D. \text{bal } bk \leq \text{mbal } (\text{disk } s' \ dd \ p)$
by(*auto simp add: MajoritySet-def split: if-split-asm*)
qed

lemma *HPhase1or2Write-HInv4d-q*:
assumes *act: HPhase1or2Write s s' p d*
and *inv: HInv4d s q*
and *pnq: p \neq q*
shows *HInv4d s' q*
proof –
from *act pnq*
have *disk': $\forall d. \text{disk } s' \ d \ q = \text{disk } s \ d \ q$*
by(*auto simp add: Phase1or2Write-def*)
from *act pnq*
have *blocksRead': $\forall q. \text{allRdBlks } s' \ q \subseteq \text{allRdBlks } s \ q$*
by(*auto simp add: Phase1or2Write-def InitializePhase-def allRdBlks-def*)
with *act pnq*
have *blocksOf s' q \subseteq blocksOf s q*

by(*auto simp add: Phase1or2Write-def allRdBlks-def
blocksOf-def rdBy-def*)
from *subsetD[OF this] inv*
have $\forall bk \in \text{blocksOf } s' q.$
 $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal}(\text{disk } s \ d \ q)$
by(*auto simp add: HInv4d-def*)
with *disk'*
show *?thesis*
by(*auto simp add: HInv4d-def*)
qed

theorem *HPhase1or2Write-HInv4d:*

$\llbracket \text{HPhase1or2Write } s \ s' \ p \ d; \text{HInv4d } s \ q; \text{HInv4a } s \ p \rrbracket \implies \text{HInv4d } s' \ q$
by(*blast dest: HPhase1or2Write-HInv4d-p HPhase1or2Write-HInv4d-q*)

lemma *HPhase1or2ReadThen-HInv4d-p:*

assumes *act: HPhase1or2ReadThen s s' p d q*
and *inv: HInv4d s p*
shows *HInv4d s' p*
proof(*clarsimp simp add: HInv4d-def*)
fix *bk*
assume *bk: bk ∈ blocksOf s' p*
from *act*
have *bal': bal (dblock s' p) = bal (dblock s p)*
by(*auto simp add: Phase1or2ReadThen-def*)
from *subsetD[OF HPhase1or2ReadThen-blocksOf[OF act] bk] inv*
have $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal}(\text{disk } s \ d \ p)$
by(*auto simp add: HInv4d-def*)
with *act*
show $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal}(\text{disk } s' \ d \ p)$
by(*auto simp add: Phase1or2ReadThen-def*)
qed

lemma *HPhase1or2ReadThen-HInv4d-q:*

assumes *act: HPhase1or2ReadThen s s' p d r*
and *inv: HInv4d s q*
and *pnq: p ≠ q*
shows *HInv4d s' q*
proof –
from *act pnq*
have *disk': disk s' = disk s*
by(*auto simp add: Phase1or2ReadThen-def*)
from *act pnq*
have *blocksOf s' q ⊆ blocksOf s q*
by(*auto simp add: Phase1or2ReadThen-def allRdBlks-def
blocksOf-def rdBy-def*)
from *subsetD[OF this] inv*
have $\forall bk \in \text{blocksOf } s' q.$
 $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal}(\text{disk } s \ d \ q)$

by(*auto simp add: HInv4d-def*)
with *disk'*
show *?thesis*
by(*auto simp add: HInv4d-def*)
qed

theorem *HPhase1or2ReadThen-HInv4d*:
 $\llbracket \text{HPhase1or2ReadThen } s \ s' \ p \ d \ r; \text{HInv4d } s \ q \rrbracket \implies \text{HInv4d } s' \ q$
by(*blast dest: HPhase1or2ReadThen-HInv4d-p*
HPhase1or2ReadThen-HInv4d-q)

theorem *HPhase1or2ReadElse-HInv4d*:
 $\llbracket \text{HPhase1or2ReadElse } s \ s' \ p \ d \ r; \text{HInv4d } s \ q \rrbracket \implies \text{HInv4d } s' \ q$
using *HStartBallot-HInv4d*
by(*auto simp add: Phase1or2ReadElse-def*)

lemma *HEndPhase1-HInv4d-p*:
assumes *act: HEndPhase1 s s' p*
and *inv: HInv4d s p*
and *inv2b: Inv2b s*
and *inv4c: HInv4c s p*
shows *HInv4d s' p*
proof(*clarsimp simp add: HInv4d-def*)
fix *bk*
assume *bk: bk ∈ blocksOf s' p*
from *HEndPhase1-HInv4c[OF act inv4c inv2b]*
have *HInv4c s' p* .
with *act*
have *p31: ∃ D ∈ MajoritySet.*
 $\forall d \in D. \text{mbal } (\text{disk } s' \ d \ p) = \text{bal}(\text{dblock } s' \ p)$
and *disk': disk s' = disk s*
by(*auto simp add: EndPhase1-def HInv4c-def*)
from *subsetD[OF HEndPhase1-blocksOf[OF act] bk]*
show $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal } (\text{disk } s' \ d \ p)$
proof
assume *bk: bk ∈ blocksOf s p*
with *inv disk'*
show *?thesis*
by(*auto simp add: HInv4d-def*)
next
assume *bk: bk ∈ {dblock s' p}*
with *p31*
show *?thesis*
by *force*
qed
qed

lemma *HEndPhase1-HInv4d-q*:
assumes *act: HEndPhase1 s s' p*

and $inv: HInv4d\ s\ q$
and $pnq: p \neq q$
shows $HInv4d\ s'\ q$
proof –
from $act\ pnq$
have $disk': disk\ s' = disk\ s$
and $dblock': dblock\ s'\ q = dblock\ s\ q$
by($auto\ simp\ add: EndPhase1-def$)
from $act\ pnq$
have $blocksRead': \forall q. allRdBlks\ s'\ q \subseteq allRdBlks\ s\ q$
by($auto\ simp\ add: EndPhase1-def\ InitializePhase-def$
 $allRdBlks-def$)
with $disk'\ dblock'$
have $blocksOf\ s'\ q \subseteq blocksOf\ s\ q$
by($auto\ simp\ add: allRdBlks-def\ blocksOf-def\ rdBy-def, blast$)
from $subsetD[OF\ this]\ inv$
have $\forall bk \in blocksOf\ s'\ q.$
 $\exists D \in MajoritySet. \forall d \in D. bal\ bk \leq mbal(disk\ s\ d\ q)$
by($auto\ simp\ add: HInv4d-def$)
with $disk'$
show $?thesis$
by($auto\ simp\ add: HInv4d-def$)
qed

theorem $HEndPhase1-HInv4d$:
 $[HEndPhase1\ s\ s'\ p; HInv4d\ s\ q; Inv2b\ s; HInv4c\ s\ p]$
 $\implies HInv4d\ s'\ q$
by($blast\ dest: HEndPhase1-HInv4d-p\ HEndPhase1-HInv4d-q$)

lemma $HEndPhase2-HInv4d-p$:
assumes $act: HEndPhase2\ s\ s'\ p$
and $inv: HInv4d\ s\ p$
shows $HInv4d\ s'\ p$
proof($clarsimp\ simp\ add: HInv4d-def$)
fix bk
assume $bk: bk \in blocksOf\ s'\ p$
from act
have $bal': bal\ (dblock\ s'\ p) = bal\ (dblock\ s\ p)$
by($auto\ simp\ add: EndPhase2-def$)
from $subsetD[OF\ HEndPhase2-blocksOf[OF\ act]\ bk]\ inv$
have $\exists D \in MajoritySet. \forall d \in D. bal\ bk \leq mbal(disk\ s\ d\ p)$
by($auto\ simp\ add: HInv4d-def$)
with act
show $\exists D \in MajoritySet. \forall d \in D. bal\ bk \leq mbal(disk\ s'\ d\ p)$
by($auto\ simp\ add: EndPhase2-def$)
qed

lemma $HEndPhase2-HInv4d-q$:
assumes $act: HEndPhase2\ s\ s'\ p$

```

and inv: HInv4d s q
and pnq: p ≠ q
shows HInv4d s' q
proof –
  from act pnq
  have disk': disk s' = disk s
    by(auto simp add: EndPhase2-def)
  from act pnq
  have blocksOf s' q ⊆ blocksOf s q
    by(auto simp add: EndPhase2-def InitializePhase-def
      allRdBlks-def blocksOf-def rdBy-def)
  from subsetD[OF this] inv
  have  $\forall bk \in \text{blocksOf } s' q.$ 
     $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal}(\text{disk } s \ d \ q)$ 
    by(auto simp add: HInv4d-def)
  with disk'
  show ?thesis
  by(auto simp add: HInv4d-def)
qed

```

```

theorem HEndPhase2-HInv4d:
   $\llbracket \text{HEndPhase2 } s \ s' \ p; \text{HInv4d } s \ q \rrbracket \implies \text{HInv4d } s' \ q$ 
  by(blast dest: HEndPhase2-HInv4d-p HEndPhase2-HInv4d-q)

```

```

lemma HFail-HInv4d-p:
  assumes act: HFail s s' p
  and inv: HInv4d s p
  shows HInv4d s' p
proof(clarsimp simp add: HInv4d-def)
  fix bk
  assume bk: bk ∈ blocksOf s' p
  from act
  have disk': disk s' = disk s
    by(auto simp add: Fail-def)
  from subsetD[OF HFail-blocksOf[OF act] bk]
  show  $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal}(\text{disk } s' \ d \ p)$ 
  proof
    assume bk: bk ∈ blocksOf s p
    with inv disk'
    show ?thesis
    by(auto simp add: HInv4d-def)
  next
    assume bk: bk ∈ {dblock s' p}
    with act
    have bal bk = 0
    by(auto simp add: Fail-def InitDB-def)
    with Disk-isMajority
    show ?thesis
    by(auto simp add: MajoritySet-def)

```

qed
qed

lemma *HFail-HInv4d-q*:
assumes *act*: *HFail s s' p*
and *inv*: *HInv4d s q*
and *pnq*: *p ≠ q*
shows *HInv4d s' q*
proof –
from *act pnq*
have *disk'*: *disk s' = disk s*
and *dblock'*: *dblock s' q = dblock s q*
by(*auto simp add: Fail-def*)
from *act pnq*
have *blocksRead'*: $\forall q. \text{allRdBlks } s' q \subseteq \text{allRdBlks } s q$
by(*auto simp add: Fail-def InitializePhase-def allRdBlks-def*)
with *disk' dblock'*
have *blocksOf s' q* \subseteq *blocksOf s q*
by(*auto simp add: allRdBlks-def blocksOf-def rdBy-def, blast*)
from *subsetD[OF this] inv*
have $\forall bk \in \text{blocksOf } s' q.$
 $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal}(\text{disk } s \ d \ q)$
by(*auto simp add: HInv4d-def*)
with *disk'*
show *?thesis*
by(*auto simp add: HInv4d-def*)
qed

theorem *HFail-HInv4d*:
 $\llbracket \text{HFail } s \ s' \ p; \text{HInv4d } s \ q \rrbracket \implies \text{HInv4d } s' \ q$
by(*blast dest: HFail-HInv4d-p HFail-HInv4d-q*)

lemma *HPhase0Read-HInv4d-p*:
assumes *act*: *HPhase0Read s s' p d*
and *inv*: *HInv4d s p*
shows *HInv4d s' p*
proof(*clarsimp simp add: HInv4d-def*)
fix *bk*
assume *bk*: *bk ∈ blocksOf s' p*
from *act*
have *bal'*: *bal (dblock s' p) = bal (dblock s p)*
by(*auto simp add: Phase0Read-def*)
from *subsetD[OF HPhase0Read-blocksOf[OF act] bk] inv*
have $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal}(\text{disk } s \ d \ p)$
by(*auto simp add: HInv4d-def*)
with *act*
show $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal}(\text{disk } s' \ d \ p)$
by(*auto simp add: Phase0Read-def*)
qed

lemma *HPhase0Read-HInv4d-q*:
assumes *act*: *HPhase0Read s s' p d*
and *inv*: *HInv4d s q*
and *pnq*: $p \neq q$
shows *HInv4d s' q*
proof –
from *act pnq*
have *disk'*: $disk\ s' = disk\ s$
by(*auto simp add: Phase0Read-def*)
from *act pnq*
have *blocksOf s' q* \subseteq *blocksOf s q*
by(*auto simp add: Phase0Read-def allRdBlks-def*
blocksOf-def rdBy-def)
from *subsetD[OF this] inv*
have $\forall bk \in blocksOf\ s'\ q.$
 $\exists D \in MajoritySet. \forall d \in D. bal\ bk \leq mbal(disk\ s\ d\ q)$
by(*auto simp add: HInv4d-def*)
with *disk'*
show *?thesis*
by(*auto simp add: HInv4d-def*)
qed

theorem *HPhase0Read-HInv4d*:
 $\llbracket HPhase0Read\ s\ s'\ p\ d; HInv4d\ s\ q \rrbracket \implies HInv4d\ s'\ q$
by(*blast dest: HPhase0Read-HInv4d-p HPhase0Read-HInv4d-q*)

lemma *HEndPhase0-blocksOf2*:
assumes *act*: *HEndPhase0 s s' p*
and *inv2c*: *Inv2c-inner s p*
shows *allBlocksRead s p* \subseteq *blocksOf s p*
proof –
from *act inv2c*
have $\forall d. \forall br \in blocksRead\ s\ p\ d. \quad proc\ br = p$
 $\quad \wedge\ block\ br = disk\ s\ d\ p$
by(*auto simp add: EndPhase0-def Inv2c-inner-def*)
thus *?thesis*
by(*auto simp add: allBlocksRead-def allRdBlks-def*
blocksOf-def)
qed

lemma *HEndPhase0-HInv4d-p*:
assumes *act*: *HEndPhase0 s s' p*
and *inv*: *HInv4d s p*
and *inv2c*: *Inv2c s*
and *inv1*: *Inv1 s*
shows *HInv4d s' p*
proof(*clarsimp simp add: HInv4d-def*)
fix *bk*


```

assume  $bk: bk \in \text{blocksOf } s' p$ 
from  $\text{subsetD}[OF \text{HEndPhase0-blocksOf}[OF \text{act}] bk]$ 
have  $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal } (\text{disk } s \ d \ p)$ 
proof
  assume  $bk: bk \in \text{blocksOf } s \ p$ 
  with  $\text{inv}$ 
  show  $?thesis$ 
  by( $\text{auto simp add: HInv4d-def}$ )
next
  assume  $bk: bk \in \{\text{dblock } s' \ p\}$ 
  from  $\text{inv2c}$ 
  have  $\text{inv2c-inner}: \text{Inv2c-inner } s \ p$ 
  by( $\text{auto simp add: Inv2c-def}$ )
  from  $bk \ \text{HEndPhase0-some}[OF \text{act } \text{inv1}]$ 
   $\text{HEndPhase0-blocksOf2}[OF \text{act } \text{inv2c-inner}] \ \text{act}$ 
  have  $\text{bal } bk \in \text{bal } (\text{blocksOf } s \ p)$ 
  by( $\text{auto simp add: EndPhase0-def}$ )
  with  $\text{inv}$ 
  show  $?thesis$ 
  by( $\text{auto simp add: HInv4d-def}$ )
qed
with  $\text{act}$ 
show  $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal } (\text{disk } s' \ d \ p)$ 
by( $\text{auto simp add: EndPhase0-def}$ )
qed

lemma  $\text{HEndPhase0-HInv4d-q}$ :
  assumes  $\text{act}: \text{HEndPhase0 } s \ s' \ p$ 
  and  $\text{inv}: \text{HInv4d } s \ q$ 
  and  $\text{pnq}: p \neq q$ 
  shows  $\text{HInv4d } s' \ q$ 
proof –
  from  $\text{act } \text{pnq}$ 
  have  $\text{dblock } s' \ q = \text{dblock } s \ q \wedge \text{disk } s' = \text{disk } s$ 
  by( $\text{auto simp add: EndPhase0-def}$ )
  moreover
  from  $\text{act } \text{pnq}$ 
  have  $\forall p \ d. \text{rdBy } s' \ q \ p \ d \subseteq \text{rdBy } s \ q \ p \ d$ 
  by( $\text{auto simp add: EndPhase0-def InitializePhase-def rdBy-def}$ )
  hence  $(\bigcup p \ d. \text{rdBy } s' \ q \ p \ d) \subseteq (\bigcup p \ d. \text{rdBy } s \ q \ p \ d)$ 
  by( $\text{auto, blast}$ )
  ultimately
  have  $\text{blocksOf } s' \ q \subseteq \text{blocksOf } s \ q$ 
  by( $\text{auto simp add: blocksOf-def, blast}$ )
  from  $\text{subsetD}[OF \text{this}] \ \text{inv}$ 
  have  $\forall bk \in \text{blocksOf } s' \ q.$ 
   $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal}(\text{disk } s \ d \ q)$ 
  by( $\text{auto simp add: HInv4d-def}$ )
  with  $\text{act}$ 

```

show *?thesis*
by(*auto simp add: EndPhase0-def HInv4d-def*)
qed

theorem *HEndPhase0-HInv4d*:
 $\llbracket \text{HEndPhase0 } s \ s' \ p; \text{HInv4d } s \ q; \text{Inv2c } s; \text{Inv1 } s \rrbracket \implies \text{HInv4d } s' \ q$
by(*blast dest: HEndPhase0-HInv4d-p HEndPhase0-HInv4d-q*)

Since we have already proved *HInv2* is an invariant of *HNext*, $\text{HInv1} \wedge \text{HInv2} \wedge \text{HInv4}$ is also an invariant of *HNext*.

lemma *I2d*:

assumes *next: HNext s s'*
and *inv: HInv1 s \wedge HInv2 s \wedge HInv2 s' \wedge HInv4 s*
shows *HInv4 s'*

proof(*auto simp add: HInv4-def*)

fix *p*

show *HInv4a s' p using assms*

by(*auto simp add: HInv4-def HNext-def Next-def,*
auto simp add: HInv2-def intro: HStartBallot-HInv4a,
auto intro: HPhase0Read-HInv4a,
auto intro: HPhase1or2Write-HInv4a,
auto simp add: Phase1or2Read-def
intro: HPhase1or2ReadThen-HInv4a
HPhase1or2ReadElse-HInv4a,
auto simp add: EndPhase1or2-def
intro: HEndPhase1-HInv4a
HEndPhase2-HInv4a,
auto intro: HFail-HInv4a,
auto intro: HEndPhase0-HInv4a simp add: HInv1-def)

show *HInv4b s' p using assms*

by(*auto simp add: HInv4-def HNext-def Next-def,*
auto simp add: HInv2-def
intro: HStartBallot-HInv4b,
auto intro: HPhase0Read-HInv4b,
auto intro: HPhase1or2Write-HInv4b,
auto simp add: Phase1or2Read-def
intro: HPhase1or2ReadThen-HInv4b
HPhase1or2ReadElse-HInv4b,
auto simp add: EndPhase1or2-def
intro: HEndPhase1-HInv4b
HEndPhase2-HInv4b,
auto intro: HFail-HInv4b,
auto intro: HEndPhase0-HInv4b simp add: HInv1-def Inv2c-def)

show *HInv4c s' p using assms*

by(*auto simp add: HInv4-def HNext-def Next-def,*
auto simp add: HInv2-def
intro: HStartBallot-HInv4c,
auto intro: HPhase0Read-HInv4c,

```

auto intro: HPhase1or2Write-HInv4c,
auto simp add: Phase1or2Read-def
      intro: HPhase1or2ReadThen-HInv4c
      HPhase1or2ReadElse-HInv4c,
auto simp add: EndPhase1or2-def
      intro: HEndPhase1-HInv4c
      HEndPhase2-HInv4c,
auto intro: HFail-HInv4c,
auto intro: HEndPhase0-HInv4c simp add: HInv1-def)
show HInv4d s' p using assms
by(auto simp add: HInv4-def HNext-def Next-def,
auto simp add: HInv2-def
      intro: HStartBallot-HInv4d,
auto intro: HPhase0Read-HInv4d,
auto intro: HPhase1or2Write-HInv4d,
auto simp add: Phase1or2Read-def
      intro: HPhase1or2ReadThen-HInv4d
      HPhase1or2ReadElse-HInv4d,
auto simp add: EndPhase1or2-def
      intro: HEndPhase1-HInv4d
      HEndPhase2-HInv4d,
auto intro: HFail-HInv4d,
auto intro: HEndPhase0-HInv4d simp add: HInv1-def)
qed

end

```

theory *DiskPaxos-Inv5* **imports** *DiskPaxos-Inv3* *DiskPaxos-Inv4* **begin**

C.5 Invariant 5

This invariant asserts that, if a processor p is in phase 2, then either its bal and inp values satisfy $maxBalInp$, or else p must eventually abort its current ballot. Processor p will eventually abort its ballot if there is some processor q and majority set D such that p has not read q 's block on any disk D , and all of those blocks have $mbal$ values greater than $bal(dblocksp)$.

definition $maxBalInp :: state \Rightarrow nat \Rightarrow InputsOrNi \Rightarrow bool$
where $maxBalInp\ s\ b\ v = (\forall bk \in allBlocks\ s.\ b \leq bal\ bk \longrightarrow inp\ bk = v)$

definition $HInv5\text{-inner}\text{-}R :: state \Rightarrow Proc \Rightarrow bool$
where

$$\begin{aligned}
HInv5\text{-inner}\text{-}R\ s\ p = & \\
& (maxBalInp\ s\ (bal(dblock\ s\ p))\ (inp(dblock\ s\ p))) \\
& \vee (\exists D \in MajoritySet.\ \exists q.\ (\forall d \in D.\ bal(dblock\ s\ p) < mbal(disk\ s\ d\ q)) \\
& \quad \wedge \neg hasRead\ s\ p\ d\ q))
\end{aligned}$$

definition $HInv5\text{-inner} :: state \Rightarrow Proc \Rightarrow bool$

where $HInv5\text{-inner } s \ p = (\text{phase } s \ p = 2 \longrightarrow HInv5\text{-inner-R } s \ p)$

definition $HInv5 :: \text{state} \Rightarrow \text{bool}$
 where $HInv5 \ s = (\forall p. HInv5\text{-inner } s \ p)$

C.5.1 Proof of Invariant 5

The initial state implies Invariant 5.

theorem $HInit\text{-}HInv5: HInit \ s \Longrightarrow HInv5 \ s$
using *Disk-isMajority*
by(*auto simp add: HInit-def Init-def HInv5-def HInv5-inner-def*)

We will use the notation used in the proofs of invariant 4, and prove the lemma *action-HInv5-p* and *action-HInv5-q* for each action, for the cases $p = q$ and $p \neq q$ respectively.

Also, for each action we will define an *action-allBlocks* lemma in the same way that we defined *-blocksOf* lemmas in the proofs of *HInv2*. Now we prove that for each action the new *allBlocks* are included in the old *allBlocks* or, in some cases, included in the old *allBlocks* union the new *dblock*.

lemma $HStartBallot\text{-}HInv5\text{-}p$:
assumes $act: HStartBallot \ s \ s' \ p$
and $inv: HInv5\text{-inner } s \ p$
shows $HInv5\text{-inner } s' \ p$ **using** *assms*
by(*auto simp add: StartBallot-def HInv5-inner-def*)

lemma $HStartBallot\text{-}blocksOf\text{-}q$:
assumes $act: HStartBallot \ s \ s' \ p$
and $pnq: p \neq q$
shows $blocksOf \ s' \ q \subseteq blocksOf \ s \ q$ **using** *assms*
by(*auto simp add: StartBallot-def InitializePhase-def blocksOf-def rdBy-def*)

lemma $HStartBallot\text{-}allBlocks$:
assumes $act: HStartBallot \ s \ s' \ p$
shows $allBlocks \ s' \subseteq allBlocks \ s \cup \{dblock \ s' \ p\}$
proof(*auto simp del: HStartBallot-def simp add: allBlocks-def*
dest: HStartBallot-blocksOf-q[OF act])
fix $x \ pa$
assume $x\text{-}pa: x \in blocksOf \ s' \ pa$ **and**
 $x\text{-}nblks: \forall xa. x \notin blocksOf \ s \ xa$
show $x = dblock \ s' \ p$
proof(*cases p=pa*)
case *True*
from $x\text{-}nblks$
have $x \notin blocksOf \ s \ p$
by *auto*
with $True \ subsetD[OF \ HStartBallot\text{-}blocksOf[OF \ act] \ x\text{-}pa]$

```

  show ?thesis
  by auto
next
  case False
  from x-nblks subsetD[OF HStartBallot-blocksOf-q[OF act False] x-pa]
  show ?thesis
  by auto
qed
qed

```

```

lemma HStartBallot-HInv5-q1:
  assumes act: HStartBallot s s' p
  and pnq: p ≠ q
  and inv5-1: maxBalInp s (bal(dblock s q)) (inp(dblock s q))
  shows maxBalInp s' (bal(dblock s' q)) (inp(dblock s' q))
proof(auto simp add: maxBalInp-def)
  fix bk
  assume bk: bk ∈ allBlocks s'
  and bal: bal (dblock s' q) ≤ bal bk
  from act pnq
  have dblock': dblock s' q = dblock s q by(auto simp add: StartBallot-def)
  from subsetD[OF HStartBallot-allBlocks[OF act] bk]
  show inp bk = inp (dblock s' q)
proof
  assume bk: bk ∈ allBlocks s
  with inv5-1 dblock' bal
  show ?thesis
  by(auto simp add: maxBalInp-def)
next
  assume bk: bk ∈ {dblock s' p}
  have dblock s p ∈ allBlocks s
  by(auto simp add: allBlocks-def blocksOf-def)
  with bal act bk dblock' inv5-1
  show ?thesis
  by(auto simp add: maxBalInp-def StartBallot-def)
qed
qed

```

```

lemma HStartBallot-HInv5-q2:
  assumes act: HStartBallot s s' p
  and pnq: p ≠ q
  and inv5-2: ∃ D ∈ MajoritySet. ∃ qq. (∀ d ∈ D. bal(dblock s q) < mbal(disk s d
qq)
  ∧ ¬hasRead s q d qq)
  shows ∃ D ∈ MajoritySet. ∃ qq. (∀ d ∈ D. bal(dblock s' q) < mbal(disk s' d qq)
  ∧ ¬hasRead s' q d qq)
proof –
  from act pnq
  have disk: disk s' = disk s

```

and *blocksRead*: $\forall d. \text{blocksRead } s' q d = \text{blocksRead } s q d$
and *dblock*: $\text{dblock } s' q = \text{dblock } s q$
by(*auto simp add: StartBallot-def InitializePhase-def*)
with *inv5-2*
show *?thesis*
by(*auto simp add: hasRead-def*)
qed

lemma *HStartBallot-HInv5-q*:
assumes *act: HStartBallot s s' p*
and *inv: HInv5-inner s q*
and *pnq: p ≠ q*
shows *HInv5-inner s' q*
using *assms and HStartBallot-HInv5-q1 [OF act pnq] HStartBallot-HInv5-q2 [OF act pnq]*
by(*auto simp add: HInv5-inner-def HInv5-inner-R-def StartBallot-def*)

theorem *HStartBallot-HInv5*:
 $\llbracket \text{HStartBallot } s s' p; \text{HInv5-inner } s q \rrbracket \implies \text{HInv5-inner } s' q$
by(*blast dest: HStartBallot-HInv5-q HStartBallot-HInv5-p*)

lemma *HPhase1or2Write-HInv5-1*:
assumes *act: HPhase1or2Write s s' p d*
and *inv5-1: maxBalInp s (bal(dblock s q)) (inp(dblock s q))*
shows *maxBalInp s' (bal(dblock s' q)) (inp(dblock s' q))*
using *assms and HPhase1or2Write-blocksOf [OF act]*
by(*auto simp add: Phase1or2Write-def maxBalInp-def allBlocks-def*)

lemma *HPhase1or2Write-HInv5-p2*:
assumes *act: HPhase1or2Write s s' p d*
and *inv4c: HInv4c s p*
and *phase: phase s p = 2*
and *inv5-2: $\exists D \in \text{MajoritySet}. \exists q. (\forall d \in D. \text{bal}(\text{dblock } s p) < \text{mbal}(\text{disk } s d q) \wedge \neg \text{hasRead } s p d q)$*
shows $\exists D \in \text{MajoritySet}. \exists q. (\forall d \in D. \text{bal}(\text{dblock } s' p) < \text{mbal}(\text{disk } s' d q) \wedge \neg \text{hasRead } s' p d q)$

proof –
from *inv5-2*
obtain *D q*
where *i1: IsMajority D*
and *i2: $\forall d \in D. \text{bal}(\text{dblock } s p) < \text{mbal}(\text{disk } s d q)$*
and *i3: $\forall d \in D. \neg \text{hasRead } s p d q$*
by(*auto simp add: MajoritySet-def*)
have *pnq: p ≠ q*
proof –
from *inv4c phase*
obtain *D1 where r1: IsMajority D1 $\wedge (\forall d \in D1. \text{mbal}(\text{disk } s d p) = \text{bal}(\text{dblock } s p))$*

```

    by(auto simp add: HInv4c-def MajoritySet-def)
  with i1 majorities-intersect
  have  $D \cap D1 \neq \{\}$  by auto
  then obtain dd where  $dd \in D \cap D1$ 
    by auto
  with i1 i2 r1
  have  $bal(dblock\ s\ p) < mbal(disk\ s\ dd\ q) \wedge mbal(disk\ s\ dd\ p) = bal(dblock\ s\ p)$ 
    by auto
  thus ?thesis by auto
qed
from act pnq
  — dblock and hasRead do not change
have dblock s' = dblock s
  and  $\forall d. hasRead\ s'\ p\ d\ q = hasRead\ s\ p\ d\ q$ 
  — In all disks q blocks don't change
  and  $\forall d. disk\ s'\ d\ q = disk\ s\ d\ q$ 
  by(auto simp add: Phase1or2Write-def hasRead-def)
with i2 i1 i3 majority-nonempty
have  $\forall d \in D. bal(dblock\ s'\ p) < mbal(disk\ s'\ d\ q) \wedge \neg hasRead\ s'\ p\ d\ q$ 
  by auto
with i1
show ?thesis
  by(auto simp add: MajoritySet-def)
qed

```

```

lemma HPhase1or2Write-HInv5-p:
  assumes act: HPhase1or2Write s s' p d
  and inv: HInv5-inner s p
  and inv4: HInv4c s p
  shows HInv5-inner s' p
proof(auto simp add: HInv5-inner-def HInv5-inner-R-def)
  assume phase': phase s' p = 2
  and i2:  $\forall D \in MajoritySet. \forall q. \exists d \in D. bal(dblock\ s'\ p) < mbal(disk\ s'\ d\ q) \longrightarrow$ 
  hasRead s' p d q
  with act have phase: phase s p = 2
  by(auto simp add: Phase1or2Write-def)
  show  $maxBalInp\ s'\ (bal(dblock\ s'\ p))\ (inp(dblock\ s'\ p))$ 
  proof(rule HPhase1or2Write-HInv5-1[OF act, of p])
    from HPhase1or2Write-HInv5-p2[OF act inv4 phase] inv i2 phase
    show  $maxBalInp\ s\ (bal(dblock\ s\ p))\ (inp(dblock\ s\ p))$ 
    by(auto simp add: HInv5-inner-def HInv5-inner-R-def, blast)
  qed
qed

```

```

lemma HPhase1or2Write-allBlocks:
  assumes act: HPhase1or2Write s s' p d
  shows  $allBlocks\ s' \subseteq allBlocks\ s$ 
  using HPhase1or2Write-blocksOf[OF act]
  by(auto simp add: allBlocks-def)

```

```

lemma HPhase1or2Write-HInv5-q2:
  assumes act: HPhase1or2Write s s' p d
  and pnq:  $p \neq q$ 
  and inv4a: HInv4a s p
  and inv5-2:  $\exists D \in \text{MajoritySet}. \exists qq. (\forall d \in D. \text{bal}(\text{dblock } s \ q) < \text{mbal}(\text{disk } s \ d \ qq)$ 
     $\wedge \neg \text{hasRead } s \ q \ d \ qq)$ 
  shows  $\exists D \in \text{MajoritySet}. \exists qq. (\forall d \in D. \text{bal}(\text{dblock } s' \ q) < \text{mbal}(\text{disk } s' \ d \ qq)$ 
     $\wedge \neg \text{hasRead } s' \ q \ d \ qq)$ 

proof –
  from inv5-2
  obtain D qq
  where i1: IsMajority D
  and i2:  $\forall d \in D. \text{bal}(\text{dblock } s \ q) < \text{mbal}(\text{disk } s \ d \ qq)$ 
  and i3:  $\forall d \in D. \neg \text{hasRead } s \ q \ d \ qq$ 
  by(auto simp add: MajoritySet-def)
  from act pnq
  – dblock and hasRead do not change
  have dblock':  $\text{dblock } s' = \text{dblock } s$ 
  and hasread:  $\forall d. \text{hasRead } s' \ q \ d \ qq = \text{hasRead } s \ q \ d \ qq$ 
  by(auto simp add: Phase1or2Write-def hasRead-def)
  have  $\forall d \in D. \text{bal}(\text{dblock } s' \ q) < \text{mbal}(\text{disk } s' \ d \ qq) \wedge \neg \text{hasRead } s' \ q \ d \ qq$ 
  proof(cases qq=p)
  case True
  have  $\text{bal}(\text{dblock } s \ q) < \text{mbal}(\text{dblock } s \ p)$ 
  proof –
  from inv4a act i1
  have  $\exists d \in D. \text{mbal}(\text{disk } s \ d \ p) \leq \text{mbal}(\text{dblock } s \ p)$ 
  by(auto simp add: MajoritySet-def HInv4a-def HInv4a2-def Phase1or2Write-def)
  with True i2
  show  $\text{bal}(\text{dblock } s \ q) < \text{mbal}(\text{dblock } s \ p)$ 
  by auto
  qed
  with hasread dblock' True i1 i2 i3 act
  show ?thesis
  by(auto simp add: Phase1or2Write-def)
  next
  case False
  with act i2 i3
  show ?thesis
  by(auto simp add: Phase1or2Write-def hasRead-def)
  qed
  with i1
  show ?thesis
  by(auto simp add: MajoritySet-def)
  qed

```


lemma *HPhase1or2Write-HInv5-q*:
assumes *act*: *HPhase1or2Write s s' p d*
and *inv*: *HInv5-inner s q*
and *inv4a*: *HInv4a s p*
and *pnq*: $p \neq q$
shows *HInv5-inner s' q*
proof(*auto simp add: HInv5-inner-def HInv5-inner-R-def*)
assume *phase'*: $\text{phase } s' q = 2$
and *i2*: $\forall D \in \text{MajoritySet}. \forall qa. \exists d \in D. \text{bal}(\text{dblock } s' q) < \text{mbal}(\text{disk } s' d qa)$
 $\longrightarrow \text{hasRead } s' q d qa$
from *phase' act* **have** *phase*: $\text{phase } s q = 2$
by(*auto simp add: Phase1or2Write-def*)
show $\text{maxBalInp } s' (\text{bal}(\text{dblock } s' q)) (\text{inp}(\text{dblock } s' q))$
proof(*rule HPhase1or2Write-HInv5-1[OF act, of q]*)
from *HPhase1or2Write-HInv5-q2[OF act pnq inv4a]* *inv i2 phase*
show $\text{maxBalInp } s (\text{bal}(\text{dblock } s q)) (\text{inp}(\text{dblock } s q))$
by(*auto simp add: HInv5-inner-def HInv5-inner-R-def, blast*)
qed
qed

theorem *HPhase1or2Write-HInv5*:
 $\llbracket \text{HPhase1or2Write } s s' p d; \text{HInv5-inner } s q; \text{HInv4c } s p; \text{HInv4a } s p \rrbracket \Longrightarrow \text{HInv5-inner } s' q$
by(*blast dest: HPhase1or2Write-HInv5-q HPhase1or2Write-HInv5-p*)

lemma *HPhase1or2ReadThen-HInv5-1*:
assumes *act*: *HPhase1or2ReadThen s s' p d r*
and *inv5-1*: $\text{maxBalInp } s (\text{bal}(\text{dblock } s q)) (\text{inp}(\text{dblock } s q))$
shows $\text{maxBalInp } s' (\text{bal}(\text{dblock } s' q)) (\text{inp}(\text{dblock } s' q))$
using *assms* **and** *HPhase1or2ReadThen-blocksOf[OF act]*
by(*auto simp add: Phase1or2ReadThen-def maxBalInp-def allBlocks-def*)

lemma *HPhase1or2ReadThen-HInv5-p2*:
assumes *act*: *HPhase1or2ReadThen s s' p d r*
and *inv4c*: *HInv4c s p*
and *inv2c*: *Inv2c-inner s p*
and *phase*: $\text{phase } s p = 2$
and *inv5-2*: $\exists D \in \text{MajoritySet}. \exists q. (\forall d \in D. \text{bal}(\text{dblock } s p) < \text{mbal}(\text{disk } s d q) \wedge \neg \text{hasRead } s p d q)$
shows $\exists D \in \text{MajoritySet}. \exists q. (\forall d \in D. \text{bal}(\text{dblock } s' p) < \text{mbal}(\text{disk } s' d q) \wedge \neg \text{hasRead } s' p d q)$

proof –
from *inv5-2*
obtain *D q*
where *i1*: *IsMajority D*
and *i2*: $\forall d \in D. \text{bal}(\text{dblock } s p) < \text{mbal}(\text{disk } s d q)$
and *i3*: $\forall d \in D. \neg \text{hasRead } s p d q$
by(*auto simp add: MajoritySet-def*)
from *inv2c phase*

```

have  $bal(dblock\ s\ p) = mbal(dblock\ s\ p)$ 
  by(auto simp add: Inv2c-inner-def)
moreover
from act have  $mbal(disk\ s\ d\ r) < mbal(dblock\ s\ p)$ 
  by(auto simp add: Phase1or2ReadThen-def)
moreover
from i2 have  $d \in D \longrightarrow bal(dblock\ s\ p) < mbal(disk\ s\ d\ q)$  by auto
ultimately have  $pnr: d \in D \longrightarrow q \neq r$  by auto
have  $pnq: p \neq q$ 
proof -
  from inv4c phase
  obtain D1 where  $r1: IsMajority\ D1 \wedge (\forall d \in D1. mbal(disk\ s\ d\ p) = bal(dblock\ s\ p))$ 
  by(auto simp add: HInv4c-def MajoritySet-def)
  with i1 majorities-intersect
  have  $D \cap D1 \neq \{\}$  by auto
  then obtain dd where  $dd \in D \cap D1$ 
  by auto
  with i1 i2 r1
  have  $bal(dblock\ s\ p) < mbal(disk\ s\ dd\ q) \wedge mbal(disk\ s\ dd\ p) = bal(dblock\ s\ p)$ 
  by auto
  thus ?thesis by auto
qed
from pnr act
have  $hasRead': \forall d \in D. hasRead\ s'\ p\ d\ q = hasRead\ s\ p\ d\ q$ 
  by(auto simp add: Phase1or2ReadThen-def hasRead-def)
from act pnq
  - dblock and disk do not change
have  $dblock\ s' = dblock\ s$ 
  and  $\forall d. disk\ s' = disk\ s$ 
  by(auto simp add: Phase1or2ReadThen-def)
with i2 hasRead' i3
have  $\forall d \in D. bal(dblock\ s'\ p) < mbal(disk\ s'\ d\ q) \wedge \neg hasRead\ s'\ p\ d\ q$ 
  by auto
with i1
show ?thesis
  by(auto simp add: MajoritySet-def)
qed

lemma HPhase1or2ReadThen-HInv5-p:
  assumes act: HPhase1or2ReadThen\ s'\ p\ d\ r
  and inv: HInv5-inner\ s\ p
  and inv4: HInv4c\ s\ p
  and inv2c: Inv2c\ s
  shows HInv5-inner\ s'\ p
proof(auto simp add: HInv5-inner-def HInv5-inner-R-def)
  assume phase': phase\ s'\ p = 2
  and i2: \forall D \in MajoritySet. \forall q. \exists d \in D. bal(dblock\ s'\ p) < mbal(disk\ s'\ d\ q) \longrightarrow hasRead\ s'\ p\ d\ q

```

with *act* **have** *phase: phase s p = 2*
by(*auto simp add: Phase1or2ReadThen-def*)
show *maxBalInp s' (bal (dblock s' p)) (inp (dblock s' p))*
proof(*rule HPhase1or2ReadThen-HInv5-1[OF act, of p]*)
from *inv2c*
have *Inv2c-inner s p* **by**(*auto simp add: Inv2c-def*)
from *HPhase1or2ReadThen-HInv5-p2[OF act inv4 this phase] inv i2 phase*
show *maxBalInp s (bal (dblock s p)) (inp (dblock s p))*
by(*auto simp add: HInv5-inner-def HInv5-inner-R-def, blast*)
qed
qed

lemma *HPhase1or2ReadThen-allBlocks:*
assumes *act: HPhase1or2ReadThen s s' p d r*
shows *allBlocks s' \subseteq allBlocks s*
using *HPhase1or2ReadThen-blocksOf[OF act]*
by(*auto simp add: allBlocks-def*)

lemma *HPhase1or2ReadThen-HInv5-q2:*
assumes *act: HPhase1or2ReadThen s s' p d r*
and *pnq: p \neq q*
and *inv4a: HInv4a s p*
and *inv5-2: $\exists D \in \text{MajoritySet}. \exists qq. (\forall d \in D. \text{bal}(\text{dblock } s \ q) < \text{mbal}(\text{disk } s \ d \ qq) \wedge \neg \text{hasRead } s \ q \ d \ qq)$*
shows *$\exists D \in \text{MajoritySet}. \exists qq. (\forall d \in D. \text{bal}(\text{dblock } s' \ q) < \text{mbal}(\text{disk } s' \ d \ qq) \wedge \neg \text{hasRead } s' \ q \ d \ qq)$*

proof –
from *inv5-2*
obtain *D qq*
where *i1: IsMajority D*
and *i2: $\forall d \in D. \text{bal}(\text{dblock } s \ q) < \text{mbal}(\text{disk } s \ d \ qq)$*
and *i3: $\forall d \in D. \neg \text{hasRead } s \ q \ d \ qq$*
by(*auto simp add: MajoritySet-def*)
from *act pnq*
– *dblock* and *hasRead* do not change
have *dblock': dblock s' = dblock s*
and *disk': disk s' = disk s*
and *hasread: $\forall d. \text{hasRead } s' \ q \ d \ qq = \text{hasRead } s \ q \ d \ qq$*
by(*auto simp add: Phase1or2ReadThen-def hasRead-def*)
with *i2 i3*
have *$\forall d \in D. \text{bal}(\text{dblock } s' \ q) < \text{mbal}(\text{disk } s' \ d \ qq) \wedge \neg \text{hasRead } s' \ q \ d \ qq$*
by *auto*
with *i1*
show *?thesis*
by(*auto simp add: MajoritySet-def*)
qed

lemma *HPhase1or2ReadThen-HInv5-q:*

assumes *act*: *HPhase1or2ReadThen s s' p d r*
and *inv*: *HInv5-inner s q*
and *inv4a*: *HInv4a s p*
and *pnq*: $p \neq q$
shows *HInv5-inner s' q*
proof(*auto simp add: HInv5-inner-def HInv5-inner-R-def*)
assume *phase'*: $\text{phase } s' q = 2$
and *i2*: $\forall D \in \text{MajoritySet}. \forall qa. \exists d \in D. \text{bal } (\text{dblock } s' q) < \text{mbal } (\text{disk } s' d qa)$
 \longrightarrow *hasRead s' q d qa*
from *phase' act* **have** *phase*: $\text{phase } s q = 2$
by(*auto simp add: Phase1or2ReadThen-def*)
show *maxBalInp s' (bal (dblock s' q)) (inp (dblock s' q))*
proof(*rule HPhase1or2ReadThen-HInv5-1[OF act, of q]*)
from *HPhase1or2ReadThen-HInv5-q2[OF act pnq inv4a] inv i2 phase*
show *maxBalInp s (bal (dblock s q)) (inp (dblock s q))*
by(*auto simp add: HInv5-inner-def HInv5-inner-R-def, blast*)
qed
qed

theorem *HPhase1or2ReadThen-HInv5*:
 $\llbracket \text{HPhase1or2ReadThen } s s' p d r; \text{HInv5-inner } s q; \text{Inv2c } s; \text{HInv4c } s p; \text{HInv4a } s p \rrbracket \implies \text{HInv5-inner } s' q$
by(*blast dest: HPhase1or2ReadThen-HInv5-q HPhase1or2ReadThen-HInv5-p*)

theorem *HPhase1or2ReadElse-HInv5*:
 $\llbracket \text{HPhase1or2ReadElse } s s' p d r; \text{HInv5-inner } s q \rrbracket \implies \text{HInv5-inner } s' q$
using *HStartBallot-HInv5*
by(*auto simp add: Phase1or2ReadElse-def*)

lemma *HEndPhase2-HInv5-p*:
 $\text{HEndPhase2 } s s' p \implies \text{HInv5-inner } s' p$
by(*auto simp add: EndPhase2-def HInv5-inner-def*)

lemma *HEndPhase2-allBlocks*:
assumes *act*: *HEndPhase2 s s' p*
shows *allBlocks s' \subseteq allBlocks s*
using *HEndPhase2-blocksOf[OF act]*
by(*auto simp add: allBlocks-def*)

lemma *HEndPhase2-HInv5-q1*:
assumes *act*: *HEndPhase2 s s' p*
and *pnq*: $p \neq q$
and *inv5-1*: *maxBalInp s (bal(dblock s q)) (inp(dblock s q))*
shows *maxBalInp s' (bal(dblock s' q)) (inp(dblock s' q))*
proof(*auto simp add: maxBalInp-def*)
fix *bk*
assume *bk*: $bk \in \text{allBlocks } s'$
and *bal*: $\text{bal } (\text{dblock } s' q) \leq \text{bal } bk$

from *act pnq*
have *dblock'*: *dblock s' q = dblock s q* **by**(*auto simp add: EndPhase2-def*)
from *subsetD[OF HEndPhase2-allBlocks[OF act] bk] inv5-1 dblock' bal*
show *inp bk = inp (dblock s' q)*
by(*auto simp add: maxBalInp-def*)
qed

lemma *HEndPhase2-HInv5-q2*:
assumes *act: HEndPhase2 s s' p*
and *pnq: p ≠ q*
and *inv5-2: ∃ D ∈ MajoritySet. ∃ qq. (∀ d ∈ D. bal(dblock s q) < mbal(disk s d qq) ∧ ¬hasRead s q d qq)*
shows $\exists D \in \text{MajoritySet}. \exists qq. (\forall d \in D. \text{bal}(\text{dblock } s' q) < \text{mbal}(\text{disk } s' d qq) \wedge \neg \text{hasRead } s' q d qq)$

proof –
from *act pnq*
have *disk: disk s' = disk s*
and *blocksRead: ∀ d. blocksRead s' q d = blocksRead s q d*
and *dblock: dblock s' q = dblock s q*
by(*auto simp add: EndPhase2-def InitializePhase-def*)
with *inv5-2*
show *?thesis*
by(*auto simp add: hasRead-def*)
qed

lemma *HEndPhase2-HInv5-q*:
assumes *act: HEndPhase2 s s' p*
and *inv: HInv5-inner s q*
and *pnq: p ≠ q*
shows *HInv5-inner s' q*
using *assms and HEndPhase2-HInv5-q1[OF act pnq] HEndPhase2-HInv5-q2[OF act pnq]*
by(*auto simp add: HInv5-inner-def HInv5-inner-R-def EndPhase2-def*)

theorem *HEndPhase2-HInv5*:
 $\llbracket \text{HEndPhase2 } s s' p; \text{HInv5-inner } s q \rrbracket \implies \text{HInv5-inner } s' q$
by(*blast dest: HEndPhase2-HInv5-q HEndPhase2-HInv5-p*)

lemma *HEndPhase1-HInv5-p*:
assumes *act: HEndPhase1 s s' p*
and *inv4: HInv4 s*
and *inv2a: Inv2a s*
and *inv2a': Inv2a s'*
and *inv2c: Inv2c s*
and *asm4: ¬maxBalInp s' (bal(dblock s' p)) (inp(dblock s' p))*
shows $(\exists D \in \text{MajoritySet}. \exists q. (\forall d \in D. \text{bal}(\text{dblock } s' p) < \text{mbal}(\text{disk } s' d q) \wedge \neg \text{hasRead } s' p d q))$

proof –

```

have  $\exists bk \in \text{allBlocks } s. \text{bal}(\text{dblock } s' p) \leq \text{bal } bk \wedge bk \neq \text{dblock } s' p$ 
proof –
  from asm4
  obtain bk
    where  $p31: bk \in \text{allBlocks } s' \wedge \text{bal}(\text{dblock } s' p) \leq \text{bal } bk \wedge bk \neq \text{dblock } s' p$ 
    by(auto simp add: maxBalInp-def)
  then obtain q where  $p32: bk \in \text{blocksOf } s' q$ 
    by(auto simp add: allBlocks-def)
  from act
  have  $\text{dblock}: p \neq q \implies \text{dblock } s' q = \text{dblock } s q$ 
    by(auto simp add: EndPhase1-def)
  have  $bk \in \text{blocksOf } s q$ 
  proof(cases p=q)
    case True
    with  $p32 p31 \text{ HEndPhase1-blocksOf}[OF \text{ act}]$ 
    show ?thesis
      by auto
    next
    case False
    from  $\text{dblock}[OF \text{ False}] \text{ subsetD}[OF \text{ HEndPhase1-blocksOf}[OF \text{ act}, \text{ of } q] p32]$ 
    show ?thesis
      by(auto simp add: blocksOf-def)
    qed
  with  $p31$ 
  show ?thesis
    by(auto simp add: allBlocks-def)
  qed
then obtain bk where  $p22: bk \in \text{allBlocks } s \wedge \text{bal}(\text{dblock } s' p) \leq \text{bal } bk \wedge bk \neq$ 
 $\text{dblock } s' p$  by auto
have  $\exists q \in \text{UNIV} - \{p\}. bk \in \text{blocksOf } s q$ 
proof –
  from  $p22$ 
  obtain q where  $bk: bk \in \text{blocksOf } s q$ 
    by(auto simp add: allBlocks-def)
  from act  $p22$ 
  have  $\text{mbal}(\text{dblock } s p) \leq \text{bal } bk$ 
    by(auto simp add: EndPhase1-def)
  moreover
  from act
  have  $\text{phase } s p = 1$ 
    by(auto simp add: EndPhase1-def)
  moreover
  from inv4
  have  $\text{HInv4b } s p$  by(auto simp add: HInv4-def)
  ultimately
  have  $p \neq q$ 
    using bk
    by(auto simp add: HInv4-def HInv4b-def)
  with bk

```

```

    show ?thesis
      by auto
  qed
  then obtain q where p23:  $q \in UNIV - \{p\} \wedge bk \in \text{blocksOf } s \ q$ 
    by auto
  have  $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal}(\text{dblock } s' \ p) \leq \text{mbal}(\text{disk } s \ d \ q)$ 
  proof -
    from p23 inv4
    have i4d:  $\exists D \in \text{MajoritySet}. \forall d \in D. \text{bal } bk \leq \text{mbal}(\text{disk } s \ d \ q)$ 
      by(auto simp add: HInv4-def HInv4d-def)
    from i4d p22
    show ?thesis
      by force
  qed
  then obtain D where Dmaj:  $D \in \text{MajoritySet}$  and p24:  $(\forall d \in D. \text{bal}(\text{dblock } s' \ p) \leq \text{mbal}(\text{disk } s \ d \ q))$ 
  proof -
    by auto
  have p25:  $\forall d \in D. \text{bal}(\text{dblock } s' \ p) < \text{mbal}(\text{disk } s \ d \ q)$ 
  proof -
    from inv2c
    have Inv2c-inner s p
      by(auto simp add: Inv2c-def)
    with act
    have bal-pos:  $0 < \text{bal}(\text{dblock } s' \ p)$ 
      by(auto simp add: Inv2c-inner-def EndPhase1-def)
    with inv2a'
    have  $\text{bal}(\text{dblock } s' \ p) \in \text{Ballot } p \cup \{0\}$ 
      by(auto simp add: Inv2a-def Inv2a-inner-def
        Inv2a-innermost-def blocksOf-def)
    with bal-pos have bal-in-p:  $\text{bal}(\text{dblock } s' \ p) \in \text{Ballot } p$ 
      by auto
    from inv2a have Inv2a-inner s q by(auto simp add: Inv2a-def)
    hence  $\forall d \in D. \text{mbal}(\text{disk } s \ d \ q) \in \text{Ballot } q \cup \{0\}$ 
      by(auto simp add: Inv2a-inner-def Inv2a-innermost-def
        blocksOf-def)
    with p24 bal-pos
    have  $\forall d \in D. \text{mbal}(\text{disk } s \ d \ q) \in \text{Ballot } q$ 
      by force
    with Ballot-disj p23 bal-in-p
    have  $\forall d \in D. \text{mbal}(\text{disk } s \ d \ q) \neq \text{bal}(\text{dblock } s' \ p)$ 
      by force
    with p23 p24
    show ?thesis
      by force
  qed
  with p23 act
  have  $\forall d \in D. \text{bal}(\text{dblock } s' \ p) < \text{mbal}(\text{disk } s' \ d \ q) \wedge \neg \text{hasRead } s' \ p \ d \ q$ 
    by(auto simp add: EndPhase1-def InitializePhase-def hasRead-def)
  with Dmaj

```

show *?thesis*
by *blast*
qed

lemma *union-inclusion*:
 $\llbracket A \subseteq A'; B \subseteq B' \rrbracket \implies A \cup B \subseteq A' \cup B'$
by *blast*

lemma *HEndPhase1-blocksOf-q*:
assumes *act*: *HEndPhase1 s s' p*
and *pnq*: $p \neq q$
shows $\text{blocksOf } s' \ q \subseteq \text{blocksOf } s \ q$
proof –
from *act pnq*
have *dblock*: $\{\text{dblock } s' \ q\} \subseteq \{\text{dblock } s \ q\}$
and *disk*: $\text{disk } s' = \text{disk } s$
and *blks*: $\text{blocksRead } s' \ q = \text{blocksRead } s \ q$
by(*auto simp add: EndPhase1-def InitializePhase-def*)
from *disk*
have *disk'*: $\{\text{disk } s' \ d \ q \mid d . d \in \text{UNIV}\} \subseteq \{\text{disk } s \ d \ q \mid d . d \in \text{UNIV}\}$ (**is** *?D'*
 $\subseteq ?D$)
by *auto*
from *pnq act*
have $(\text{UN } qq \ d . \text{rdBy } s' \ q \ qq \ d) \subseteq (\text{UN } qq \ d . \text{rdBy } s \ q \ qq \ d)$
by(*auto simp add: EndPhase1-def InitializePhase-def rdBy-def split: if-split-asm,*
blast)
hence $\{\text{block } br \mid br . br \in (\text{UN } qq \ d . \text{rdBy } s' \ q \ qq \ d)\} \subseteq \{\text{block } br \mid br . br \in (\text{UN } qq \ d . \text{rdBy } s \ q \ qq \ d)\}$ (**is** *?R' \subseteq ?R*)
by *auto blast*
from *union-inclusion[OF dblock union-inclusion[OF disk' this]]*
show *?thesis*
by(*auto simp add: blocksOf-def*)
qed

lemma *HEndPhase1-allBlocks*:
assumes *act*: *HEndPhase1 s s' p*
shows $\text{allBlocks } s' \subseteq \text{allBlocks } s \cup \{\text{dblock } s' \ p\}$
proof(*auto simp del: HEndPhase1-def simp add: allBlocks-def*
dest: HEndPhase1-blocksOf-q[OF act])
fix *x pa*
assume *x-pa*: $x \in \text{blocksOf } s' \ pa$ **and**
x-nblks: $\forall xa . x \notin \text{blocksOf } s \ xa$
show $x = \text{dblock } s' \ p$
proof(*cases p=pa*)
case *True*
from *x-nblks*
have $x \notin \text{blocksOf } s \ p$
by *auto*
with *True subsetD[OF HEndPhase1-blocksOf[OF act] x-pa]*


```

  show ?thesis
  by auto
next
  case False
  from  $x\text{-nblks subsetD}[OF\ HEndPhase1\text{-blocksOf-}q[OF\ act\ False]\ x\text{-pa}]$ 
  show ?thesis
  by auto
qed
qed

```

lemma $HEndPhase1\text{-HInv5-}q$:

```

  assumes  $act: HEndPhase1\ s\ s'\ p$ 
  and  $inv: HInv5\ s$ 
  and  $inv1: Inv1\ s$ 
  and  $inv2a: Inv2a\ s'$ 
  and  $inv2a\text{-}q: Inv2a\ s$ 
  and  $inv2b: Inv2b\ s$ 
  and  $inv2c: Inv2c\ s$ 
  and  $inv3: HInv3\ s$ 
  and  $phase': phase\ s'\ q = 2$ 
  and  $pnq: p \neq q$ 
  and  $asm4: \neg maxBalInp\ s'\ (bal(dblock\ s'\ q))\ (inp(dblock\ s'\ q))$ 
  shows  $(\exists D \in MajoritySet. \exists qq. (\forall d \in D. \ bal(dblock\ s'\ q) < mbal(disk\ s'\ d\ qq)$ 
     $\wedge \neg hasRead\ s'\ q\ d\ qq))$ 

```

proof –

```

  from  $act\ pnq$ 
  have  $phase\ s'\ q = phase\ s\ q$ 
  and  $phase\text{-}p: phase\ s\ p = 1$ 
  and  $disk: disk\ s' = disk\ s$ 
  and  $dblock: dblock\ s'\ q = dblock\ s\ q$ 
  and  $bal: bal(dblock\ s'\ p) = mbal(dblock\ s\ p)$ 
  by( $auto\ simp\ add: EndPhase1\text{-def}\ InitializePhase\text{-def}$ )
  with  $phase'$ 
  have  $phase: phase\ s\ q = 2$  by auto
  from  $phase\ inv2c$ 
  have  $bal\text{-}dblq: bal(dblock\ s\ q) \in Ballot\ q$ 
  by( $auto\ simp\ add: Inv2c\text{-def}\ Inv2c\text{-inner}\text{-def}$ )
  have  $\exists D \in MajoritySet. \exists qq. (\forall d \in D. \ bal(dblock\ s\ q) < mbal(disk\ s\ d\ qq)$ 
     $\wedge \neg hasRead\ s\ q\ d\ qq)$ 
  proof( $cases\ maxBalInp\ s\ (bal(dblock\ s\ q))\ (inp(dblock\ s\ q))$ )
  case True
  have  $p21: bal(dblock\ s\ q) < bal(dblock\ s'\ p) \wedge inp(dblock\ s\ q) \neq inp(dblock\ s'$ 
     $p)$ 

```

proof –

```

  from True  $asm4\ dblock\ HEndPhase1\text{-allBlocks}[OF\ act]$ 
  have  $p32: \ bal(dblock\ s\ q) \leq bal(dblock\ s'\ p)$ 
     $\wedge inp(dblock\ s\ q) \neq inp(dblock\ s'\ p)$ 
  by( $auto\ simp\ add: maxBalInp\text{-def}$ )
  from  $inv2a$ 

```

```

have  $bal(dblock\ s'\ p) \in Ballot\ p \cup \{0\}$ 
  by(auto simp add: Inv2a-def Inv2a-inner-def
      Inv2a-innermost-def blocksOf-def)
moreover
from Ballot-disj Ballot-nzero pnq
have  $Ballot\ q \cap (Ballot\ p \cup \{0\}) = \{\}$ 
  by auto
ultimately
have  $bal(dblock\ s'\ p) \neq bal(dblock\ s\ q)$ 
  using bal-dblk-q
  by auto
with p32
show ?thesis
  by auto
qed
have  $\exists D \in MajoritySet. \forall d \in D. bal(dblock\ s\ q) < mbal(disk\ s\ d\ p) \wedge hasRead\ s$ 
 $p\ d\ q$ 
proof –
  from act
have  $\exists D \in MajoritySet. \forall d \in D. d \in disksWritten\ s\ p \wedge (\forall q \in UNIV - \{p\}. hasRead$ 
 $s\ p\ d\ q)$ 
  by(auto simp add: EndPhase1-def MajoritySet-def)
then obtain  $D$ 
  where  $act1: \forall d \in D. d \in disksWritten\ s\ p \wedge (\forall q \in UNIV - \{p\}. hasRead\ s\ p\ d$ 
 $q)$ 
  and  $Dmaj: D \in MajoritySet$ 
  by auto
from inv2b
have  $\forall d. Inv2b\ inner\ s\ p\ d$  by(auto simp add: Inv2b-def)
with act1 pnq phase-p bal
have  $\forall d \in D. bal(dblock\ s'\ p) = mbal(disk\ s\ d\ p) \wedge hasRead\ s\ p\ d\ q$ 
  by(auto simp add: Inv2b-def Inv2b-inner-def)
with p21 Dmaj
have  $\forall d \in D. bal(dblock\ s\ q) < mbal(disk\ s\ d\ p) \wedge hasRead\ s\ p\ d\ q$ 
  by auto
with  $Dmaj$ 
show ?thesis
  by auto
qed
then obtain  $D$ 
  where  $p22: D \in MajoritySet \wedge (\forall d \in D. bal(dblock\ s\ q) < mbal(disk\ s\ d\ p) \wedge$ 
 $hasRead\ s\ p\ d\ q)$ 
  by auto
have  $p23: \forall d \in D. (\backslash block = dblock\ s\ q, proc = q) \notin blocksRead\ s\ p\ d$ 
proof –
  have  $dblock\ s\ q \in allBlocksRead\ s\ p \longrightarrow inp(dblock\ s'\ p) = inp(dblock\ s\ q)$ 
proof auto
  assume  $dblock\ q: dblock\ s\ q \in allBlocksRead\ s\ p$ 
  from inv2a-q

```

```

have (bal(dblock s q)=0) = (inp (dblock s q) = NotAnInput)
  by(auto simp add: Inv2a-def Inv2a-inner-def
        blocksOf-def Inv2a-innermost-def)
with bal-dblk-q Ballot-nzero dblock-q InputsOrNi
have dblock-q-nib: dblock s q ∈ nonInitBlks s p
  by(auto simp add: nonInitBlks-def blocksSeen-def)
with act
have dblock-max: inp(dblock s' p)=inp(maxBlk s p)
  by(auto simp add: EndPhase1-def)
from maxBlk-in-nonInitBlks[OF dblock-q-nib inv1]
have max-in-nib: maxBlk s p ∈ nonInitBlks s p ..
hence nonInitBlks s p ⊆ allBlocks s
  by(auto simp add: allBlocks-def nonInitBlks-def
        blocksSeen-def blocksOf-def rdBy-def
        allBlocksRead-def allRdBlks-def)
with True subsetD[OF this max-in-nib]
have bal (dblock s q) ≤ bal (maxBlk s p) → inp (maxBlk s p) = inp (dblock
s q)
  by(auto simp add: maxBalInp-def)
with maxBlk-in-nonInitBlks[OF dblock-q-nib inv1]
        dblock-q-nib dblock-max
show inp(dblock s' p) = inp(dblock s q)
  by auto
qed
with p21
have dblock s q ∉ block ‘ allRdBlks s p
  by(auto simp add: allBlocksRead-def)
hence ∀ d. dblock s q ∉ block ‘ blocksRead s p d
  by(auto simp add: allRdBlks-def)
thus ?thesis
  by force
qed
have p24: ∀ d∈D. ¬ (∃ br∈ blocksRead s q d. bal(dblock s q) ≤ mbal (block br))
proof –
  from inv2c phase
  have ∀ d. ∀ br∈blocksRead s q d. mbal(block br)<mbal(dblock s q)
    and bal(dblock s q) = mbal(dblock s q)
    by(auto simp add: Inv2c-def Inv2c-inner-def)
  thus ?thesis
    by force
qed
have p25: ∀ d∈D. ¬hasRead s q d p
proof auto
  fix d
  assume d-in-D: d ∈ D
    and hasRead-qdp: hasRead s q d p
  have p31: (block=dblock s p, proc=p)∈blocksRead s q d
proof –
  from d-in-D p22

```

```

    have hasRead-pdq: hasRead s p d q by auto
    with hasRead-qdp phase phase-p inv3
    have HInv3-R s q p d
      by(auto simp add: HInv3-def HInv3-inner-def HInv3-L-def)
    with p23 d-in-D
    show ?thesis
      by(auto simp add: HInv3-R-def)
  qed
  from p21 act
  have p32: bal(dblock s q) < mbal(dblock s p)
    by(auto simp add: EndPhase1-def)
  with p31 d-in-D hasRead-qdp p24
  show False
    by(force)
  qed
  with p22
  show ?thesis
    by auto
next
  case False
  with inv phase
  show ?thesis
    by(auto simp add: HInv5-def HInv5-inner-def HInv5-inner-R-def)
  qed
  then obtain D qq
    where D ∈ MajoritySet ∧ (∀ d ∈ D. bal(dblock s q) < mbal(disk s d qq)
      ∧ ¬hasRead s q d qq)

    by auto
  moreover
  from act pnq
  have ∀ d. hasRead s' q d qq = hasRead s q d qq
    by(auto simp add: EndPhase1-def InitializePhase-def hasRead-def)
  ultimately show ?thesis
    using disk dblock
    by auto
  qed

```

```

theorem HEndPhase1-HInv5:
  assumes act: HEndPhase1 s s' p
  and inv: HInv5 s
  and inv1: Inv1 s
  and inv2a: Inv2a s
  and inv2a': Inv2a s'
  and inv2b: Inv2b s
  and inv2c: Inv2c s
  and inv3: HInv3 s
  and inv4: HInv4 s
shows HInv5-inner s' q
  using HEndPhase1-HInv5-p[OF act inv4 inv2a inv2a' inv2c]

```

$H\text{EndPhase1-HInv5-q}[OF\ act\ inv\ inv1\ inv2a'\ inv2a\ inv2b\ inv2c\ inv3, \text{ of } q]$
by(*auto simp add: HInv5-def HInv5-inner-def HInv5-inner-R-def*)

lemma *HFail-HInv5-p*:
 $H\text{Fail } s\ s'\ p \implies H\text{Inv5-inner } s'\ p$
by(*auto simp add: Fail-def HInv5-inner-def*)

lemma *HFail-blocksOf-q*:
assumes *act: HFail s s' p*
and *pnq: p ≠ q*
shows $\text{blocksOf } s'\ q \subseteq \text{blocksOf } s\ q$
using *assms*
by(*auto simp add: Fail-def InitializePhase-def blocksOf-def rdBy-def*)

lemma *HFail-allBlocks*:
assumes *act: HFail s s' p*
shows $\text{allBlocks } s' \subseteq \text{allBlocks } s \cup \{\text{dblock } s'\ p\}$
proof(*auto simp del: HFail-def simp add: allBlocks-def*
dest: HFail-blocksOf-q[OF act])
fix *x pa*
assume *x-pa: x ∈ blocksOf s' pa and*
x-nblks: ∀ xa. x ∉ blocksOf s xa
show $x = \text{dblock } s'\ p$
proof(*cases p=pa*)
case *True*
from *x-nblks*
have $x \notin \text{blocksOf } s\ p$
by *auto*
with *True subsetD[OF HFail-blocksOf[OF act] x-pa]*
show *?thesis*
by *auto*
next
case *False*
from *x-nblks subsetD[OF HFail-blocksOf-q[OF act False] x-pa]*
show *?thesis*
by *auto*
qed
qed

lemma *HFail-HInv5-q1*:
assumes *act: HFail s s' p*
and *pnq: p ≠ q*
and *inv2a: Inv2a-inner s' q*
and *inv5-1: maxBalInp s (bal(dblock s q)) (inp(dblock s q))*
shows $\text{maxBalInp } s'\ (\text{bal}(\text{dblock } s'\ q))\ (\text{inp}(\text{dblock } s'\ q))$
proof(*auto simp add: maxBalInp-def*)
fix *bk*
assume *bk: bk ∈ allBlocks s'*
and *bal: bal (dblock s' q) ≤ bal bk*

```

from act pnq
have dblock': dblock s' q = dblock s q by(auto simp add: Fail-def)
from subsetD[OF HFail-allBlocks[OF act] bk]
show inp bk = inp (dblock s' q)
proof
  assume bk: bk ∈ allBlocks s
  with inv5-1 dblock' bal
  show ?thesis
  by(auto simp add: maxBalInp-def)
next
  assume bk: bk ∈ {dblock s' p}
  with act have bk-init: bk = InitDB
  by(auto simp add: Fail-def)
  with bal
  have bal (dblock s' q)=0
  by(auto simp add: InitDB-def)
  with inv2a
  have inp (dblock s' q)= NotAnInput
  by(auto simp add: Inv2a-inner-def Inv2a-innermost-def blocksOf-def)
  with bk-init
  show ?thesis
  by(auto simp add: InitDB-def)
qed
qed

lemma HFail-HInv5-q2:
  assumes act: HFail s s' p
  and pnq: p≠q
  and inv5-2: ∃ D∈MajoritySet. ∃ qq. (∀ d∈D. bal(dblock s q) < mbal(disk s d qq)
  
$$\wedge \neg \text{hasRead } s \ q \ d \ qq)$$

  shows  $\exists D \in \text{MajoritySet. } \exists qq. (\forall d \in D. \text{bal}(\text{dblock } s' \ q) < \text{mbal}(\text{disk } s' \ d \ qq)$ 
  
$$\wedge \neg \text{hasRead } s' \ q \ d \ qq)$$

proof –
  from act pnq
  have disk: disk s' = disk s
  and blocksRead:  $\forall d. \text{blocksRead } s' \ q \ d = \text{blocksRead } s \ q \ d$ 
  and dblock: dblock s' q = dblock s q
  by(auto simp add: Fail-def InitializePhase-def)
  with inv5-2
  show ?thesis
  by(auto simp add: hasRead-def)
qed

lemma HFail-HInv5-q:
  assumes act: HFail s s' p
  and inv: HInv5-inner s q
  and pnq: p≠q
  and inv2a: Inv2a s'

```

shows $HInv5\text{-inner } s' q$
proof(*auto simp add: HInv5-inner-def HInv5-inner-R-def*)
assume $phase'$: $phase s' q = 2$
and $nR2$: $\forall D \in MajoritySet.$
 $\forall qa. \exists d \in D. bal (dblock s' q) < mbal (disk s' d qa) \longrightarrow$
 $hasRead s' q d qa$ (**is** $?P s'$)
from $HFail\text{-}HInv5\text{-}q2[OF act pnq]$
have $\neg (?P s) \implies \neg (?P s')$
by *auto*
with $nR2$
have P : $?P s$
by *blast*
from $inv2a$
have $inv2a'$: $Inv2a\text{-inner } s' q$ **by** (*auto simp add: Inv2a-def*)
from $act pnq phase'$
have $phase s q = 2$
by(*auto simp add: Fail-def split: if-split-asm*)
with $inv HFail\text{-}HInv5\text{-}q1[OF act pnq inv2a'] P$
show $maxBalInp s' (bal (dblock s' q)) (inp (dblock s' q))$
by(*auto simp add: HInv5-inner-def HInv5-inner-R-def*)
qed

theorem $HFail\text{-}HInv5$:
 $\llbracket HFail s s' p; HInv5\text{-inner } s q; Inv2a s' \rrbracket \implies HInv5\text{-inner } s' q$
by(*blast dest: HFail-HInv5-q HFail-HInv5-p*)

lemma $HPhase0Read\text{-}HInv5\text{-}p$:
 $HPhase0Read s s' p d \implies HInv5\text{-inner } s' p$
by(*auto simp add: Phase0Read-def HInv5-inner-def*)

lemma $HPhase0Read\text{-}allBlocks$:
assumes act : $HPhase0Read s s' p d$
shows $allBlocks s' \subseteq allBlocks s$
using $HPhase0Read\text{-}blocksOf[OF act]$
by(*auto simp add: allBlocks-def*)

lemma $HPhase0Read\text{-}HInv5\text{-}1$:
assumes act : $HPhase0Read s s' p d$
and $inv5\text{-}1$: $maxBalInp s (bal(dblock s q)) (inp(dblock s q))$
shows $maxBalInp s' (bal(dblock s' q)) (inp(dblock s' q))$
using $assms$ **and** $HPhase0Read\text{-}blocksOf[OF act]$
by(*auto simp add: Phase0Read-def maxBalInp-def allBlocks-def*)

lemma $HPhase0Read\text{-}HInv5\text{-}q2$:
assumes act : $HPhase0Read s s' p d$
and pnq : $p \neq q$
and $inv5\text{-}2$: $\exists D \in MajoritySet. \exists qq. (\forall d \in D. bal(dblock s q) < mbal(disk s d qq) \wedge \neg hasRead s q d qq)$

shows $\exists D \in \text{MajoritySet}. \exists qq. (\forall d \in D. \text{bal}(\text{dblock } s' q) < \text{mbal}(\text{disk } s' d qq) \wedge \neg \text{hasRead } s' q d qq)$

proof –

from *act pnq*
have *disk*: $\text{disk } s' = \text{disk } s$
and *blocksRead*: $\forall d. \text{blocksRead } s' q d = \text{blocksRead } s q d$
and *dblock*: $\text{dblock } s' q = \text{dblock } s q$
by(*auto simp add: Phase0Read-def InitializePhase-def*)
with *inv5-2*
show *?thesis*
by(*auto simp add: hasRead-def*)

qed

lemma *HPhase0Read-HInv5-q*:

assumes *act*: *HPhase0Read s s' p d*
and *inv*: *HInv5-inner s q*
and *pnq*: $p \neq q$
shows *HInv5-inner s' q*

proof(*auto simp add: HInv5-inner-def HInv5-inner-R-def*)

assume *phase'*: $\text{phase } s' q = 2$
and *i2*: $\forall D \in \text{MajoritySet}. \forall qa. \exists d \in D. \text{bal}(\text{dblock } s' q) < \text{mbal}(\text{disk } s' d qa)$
 $\longrightarrow \text{hasRead } s' q d qa$

from *phase' act* **have** *phase*: $\text{phase } s q = 2$
by(*auto simp add: Phase0Read-def*)
show *maxBalInp s' (bal (dblock s' q)) (inp (dblock s' q))*
proof(*rule HPhase0Read-HInv5-1[OF act, of q]*)
from *HPhase0Read-HInv5-q2[OF act pnq] inv i2 phase*
show *maxBalInp s (bal (dblock s q)) (inp (dblock s q))*
by(*auto simp add: HInv5-inner-def HInv5-inner-R-def, blast*)

qed

qed

theorem *HPhase0Read-HInv5*:

$\llbracket \text{HPhase0Read } s s' p d; \text{HInv5-inner } s q \rrbracket \Longrightarrow \text{HInv5-inner } s' q$
by(*blast dest: HPhase0Read-HInv5-q HPhase0Read-HInv5-p*)

lemma *HEndPhase0-HInv5-p*:

HEndPhase0 s s' p \Longrightarrow *HInv5-inner s' p*
by(*auto simp add: EndPhase0-def HInv5-inner-def*)

lemma *HEndPhase0-blocksOf-q*:

assumes *act*: *HEndPhase0 s s' p*
and *pnq*: $p \neq q$
shows $\text{blocksOf } s' q \subseteq \text{blocksOf } s q$

proof –

from *act pnq*
have *dblock*: $\{\text{dblock } s' q\} \subseteq \{\text{dblock } s q\}$
and *disk*: $\text{disk } s' = \text{disk } s$


```

    and blks: blocksRead s' q = blocksRead s q
  by(auto simp add: EndPhase0-def InitializePhase-def)
  from disk
  have disk': {disk s' d q | d . d ∈ UNIV} ⊆ {disk s d q | d . d ∈ UNIV} (is ?D'
⊆ ?D)
  by auto
  from p n q act
  have (UN qq d. rdBy s' q qq d) ⊆ (UN qq d. rdBy s q qq d)
  by(auto simp add: EndPhase0-def InitializePhase-def
rdBy-def split: if-split-asm, blast)
  hence {block br | br. br ∈ (UN qq d. rdBy s' q qq d)} ⊆
{block br | br. br ∈ (UN qq d. rdBy s q qq d)}
  (is ?R' ⊆ ?R)
  by auto blast
  from union-inclusion[OF dblock union-inclusion[OF disk' this]]
  show ?thesis
  by(auto simp add: blocksOf-def)
qed

```

lemma *HEndPhase0-allBlocks*:

```

  assumes act: HEndPhase0 s s' p
  shows allBlocks s' ⊆ allBlocks s ∪ {dblock s' p}
  proof(auto simp del: HEndPhase0-def simp add: allBlocks-def
dest: HEndPhase0-blocksOf-q[OF act])
    fix x pa
    assume x-pa: x ∈ blocksOf s' pa and
x-nblks: ∀ xa. x ∉ blocksOf s xa
    show x=dblock s' p
    proof(cases p=pa)
      case True
      from x-nblks
      have x ∉ blocksOf s p
      by auto
      with True subsetD[OF HEndPhase0-blocksOf[OF act] x-pa]
      show ?thesis
      by auto
    next
      case False
      from x-nblks subsetD[OF HEndPhase0-blocksOf-q[OF act False] x-pa]
      show ?thesis
      by auto
    qed
  qed

```

lemma *HEndPhase0-HInv5-q1*:

```

  assumes act: HEndPhase0 s s' p
  and p n q: p ≠ q
  and inv1: Inv1 s
  and inv5-1: maxBalInp s (bal(dblock s q)) (inp(dblock s q))

```

```

shows  $\text{maxBalInp } s' (\text{bal}(\text{dblock } s' q)) (\text{inp}(\text{dblock } s' q))$ 
proof(auto simp add: maxBalInp-def)
  fix  $bk$ 
  assume  $bk: bk \in \text{allBlocks } s'$ 
  and  $\text{bal}: \text{bal}(\text{dblock } s' q) \leq \text{bal } bk$ 
  from  $\text{act } p n q$ 
  have  $\text{dblock}' : \text{dblock } s' q = \text{dblock } s q$  by(auto simp add: EndPhase0-def)
  from  $\text{subsetD}[OF \text{HEndPhase0-allBlocks}[OF \text{act}]] bk$ 
  show  $\text{inp } bk = \text{inp}(\text{dblock } s' q)$ 
  proof
    assume  $bk: bk \in \text{allBlocks } s$ 
    with  $\text{inv5-1 } \text{dblock}' \text{ bal}$ 
    show ?thesis
    by(auto simp add: maxBalInp-def)
  next
    assume  $bk: bk \in \{\text{dblock } s' p\}$ 
    with  $\text{HEndPhase0-some}[OF \text{act } \text{inv1}] \text{act}$ 
    have  $\exists ba \in \text{allBlocksRead } s p. \text{bal } ba = \text{bal}(\text{dblock } s' p) \wedge \text{inp } ba = \text{inp}(\text{dblock } s' p)$ 
    by(auto simp add: EndPhase0-def)
    then obtain  $ba$ 
    where  $\text{ba-blksread}: ba \in \text{allBlocksRead } s p$ 
    and  $\text{ba-balinp}: \text{bal } ba = \text{bal}(\text{dblock } s' p) \wedge \text{inp } ba = \text{inp}(\text{dblock } s' p)$ 
    by auto
    have  $\text{allBlocksRead } s p \subseteq \text{allBlocks } s$ 
    by(auto simp add: allBlocksRead-def allRdBlks-def allBlocks-def blocksOf-def rdBy-def)
    from  $\text{subsetD}[OF \text{this } \text{ba-blksread}] \text{ba-balinp } \text{bal } bk \text{dblock}' \text{inv5-1}$ 
    show ?thesis
    by(auto simp add: maxBalInp-def)
  qed
qed

lemma  $\text{HEndPhase0-HInv5-q2}$ :
  assumes  $\text{act}: \text{HEndPhase0 } s s' p$ 
  and  $\text{pnq}: p \neq q$ 
  and  $\text{inv5-2}: \exists D \in \text{MajoritySet}. \exists qq. (\forall d \in D. \text{bal}(\text{dblock } s q) < \text{mbal}(\text{disk } s d qq) \wedge \neg \text{hasRead } s q d qq)$ 
  shows  $\exists D \in \text{MajoritySet}. \exists qq. (\forall d \in D. \text{bal}(\text{dblock } s' q) < \text{mbal}(\text{disk } s' d qq) \wedge \neg \text{hasRead } s' q d qq)$ 

proof –
  from  $\text{act } p n q$ 
  have  $\text{disk}: \text{disk } s' = \text{disk } s$ 
  and  $\text{blocksRead}: \forall d. \text{blocksRead } s' q d = \text{blocksRead } s q d$ 
  and  $\text{dblock}: \text{dblock } s' q = \text{dblock } s q$ 
  by(auto simp add: EndPhase0-def InitializePhase-def)
  with  $\text{inv5-2}$ 
  show ?thesis

```

by(*auto simp add: hasRead-def*)
qed

lemma *HEndPhase0-HInv5-q*:
assumes *act: HEndPhase0 s s' p*
and *inv: HInv5-inner s q*
and *inv1: Inv1 s*
and *pnq: p ≠ q*
shows *HInv5-inner s' q*
using *assms and*
HEndPhase0-HInv5-q1[OF act pnq inv1]
HEndPhase0-HInv5-q2[OF act pnq]
by(*auto simp add: HInv5-inner-def HInv5-inner-R-def EndPhase0-def*)

theorem *HEndPhase0-HInv5*:
 $\llbracket \text{HEndPhase0 } s \text{ } s' \text{ } p; \text{HInv5-inner } s \text{ } q; \text{Inv1 } s \rrbracket \implies \text{HInv5-inner } s' \text{ } q$
by(*blast dest: HEndPhase0-HInv5-q HEndPhase0-HInv5-p*)

$\text{HInv1} \wedge \text{HInv2} \wedge \text{HInv3} \wedge \text{HInv4} \wedge \text{HInv5}$ is an invariant of *HNext*.

lemma *I2e*:
assumes *nxt: HNext s s'*
and *inv: HInv1 s ∧ HInv2 s ∧ HInv2 s' ∧ HInv3 s ∧ HInv4 s ∧ HInv5 s*
shows *HInv5 s'*
using *assms*
by(*auto simp add: HInv5-def HNext-def Next-def,*
auto simp add: HInv2-def intro: HStartBallot-HInv5,
auto intro: HPhase0Read-HInv5,
auto simp add: HInv4-def intro: HPhase1or2Write-HInv5,
auto simp add: Phase1or2Read-def
intro: HPhase1or2ReadThen-HInv5
HPhase1or2ReadElse-HInv5,
auto simp add: EndPhase1or2-def HInv1-def HInv4-def HInv5-def
intro: HEndPhase1-HInv5
HEndPhase2-HInv5,
auto intro: HFail-HInv5,
auto intro: HEndPhase0-HInv5 simp add: HInv1-def)

end

theory *DiskPaxos-Chosen imports DiskPaxos-Inv5 begin*

C.6 Lemma I2f

To prove the final conjunct we will use the predicate $\text{valueChosen}(v)$. This predicate is true if v is the only possible value that can be chosen as output. It also asserts that, for every disk d in D , if q has already read $\text{disk}sdp$, then it has read a block with bal field at least b .

definition $valueChosen :: state \Rightarrow InputsOrNi \Rightarrow bool$

where

$$\begin{aligned}
valueChosen\ s\ v = & \\
& (\exists b \in (UN\ p.\ Ballot\ p). \\
& \quad maxBallInp\ s\ b\ v \\
& \quad \wedge (\exists p.\ \exists D \in MajoritySet. (\forall d \in D.\ b \leq bal(disk\ s\ d\ p) \\
& \quad \wedge (\forall q. (phase\ s\ q = 1 \\
& \quad \wedge b \leq mbal(dblock\ s\ q) \\
& \quad \wedge hasRead\ s\ q\ d\ p \\
& \quad) \longrightarrow (\exists br \in blocksRead\ s\ q\ d.\ b \leq bal(block\ br)) \\
& \quad))))
\end{aligned}$$

lemma $HEndPhase1-valueChosen-inp$:

assumes $act: HEndPhase1\ s\ s'\ q$

and $inv2a: Inv2a\ s$

and $asm1: b \in (UN\ p.\ Ballot\ p)$

and $bk-blocksOf: bk \in blocksOf\ s\ r$

and $bk: bk \in blocksSeen\ s\ q$

and $b-bal: b \leq bal\ bk$

and $asm3: maxBallInp\ s\ b\ v$

and $inv1: Inv1\ s$

shows $inp(dblock\ s'\ q) = v$

proof –

from $bk-blocksOf\ inv2a$

have $inv2a-bk: Inv2a-innermost\ s\ r\ bk$

by($auto\ simp\ add: Inv2a-def\ Inv2a-inner-def$)

from $Ballot-nzero\ asm1$

have $0 < b$ **by** $auto$

with $b-bal$

have $0 < bal\ bk$ **by** $auto$

with $inv2a-bk$

have $inp\ bk \neq NotAnInput$

by($auto\ simp\ add: Inv2a-innermost-def$)

with $bk\ InputsOrNi$

have $bk-noninit: bk \in nonInitBlks\ s\ q$

by($auto\ simp\ add: nonInitBlks-def\ blocksSeen-def$
 $allBlocksRead-def\ allRdBlks-def$)

with $maxBlk-in-nonInitBlks[OF\ this\ inv1]\ b-bal$

have $maxBlk-b: b \leq bal\ (maxBlk\ s\ q)$

by $auto$

from $maxBlk-in-nonInitBlks[OF\ bk-noninit\ inv1]$

have $\exists p\ d.\ maxBlk\ s\ q \in blocksSeen\ s\ p$

by($auto\ simp\ add: nonInitBlks-def\ blocksSeen-def$)

hence $\exists p.\ maxBlk\ s\ q \in blocksOf\ s\ p$

by($auto\ simp\ add: blocksOf-def\ blocksSeen-def$
 $allBlocksRead-def\ allRdBlks-def\ rdBy-def, force$)

with $maxBlk-b\ asm3$

have $inp(maxBlk\ s\ q) = v$

by($auto\ simp\ add: maxBallInp-def\ allBlocks-def$)

```

with bk-noninit act
show ?thesis
  by(auto simp add: EndPhase1-def)
qed

lemma HEndPhase1-maxBalInp:
assumes act: HEndPhase1 s s' q
and asm1: b ∈ (UN p. Ballot p)
and asm2: D ∈ MajoritySet
and asm3: maxBalInp s b v
and asm4: ∀ d ∈ D. b ≤ bal(disk s d p)
       $\wedge (\forall q. ( \text{phase } s \ q = 1$ 
       $\wedge b \leq \text{mbal}(\text{dblock } s \ q)$ 
       $\wedge \text{hasRead } s \ q \ d \ p$ 
       $) \longrightarrow (\exists br \in \text{blocksRead } s \ q \ d. b \leq \text{bal}(\text{block } br)))$ 

and inv1: Inv1 s
and inv2a: Inv2a s
and inv2b: Inv2b s
shows maxBalInp s' b v
proof(cases b ≤ mbal(dblock s q))
  case True
    show ?thesis
    proof(cases p ≠ q)
      assume pnq: p ≠ q
      have  $\exists d \in D. \text{hasRead } s \ q \ d \ p$ 
      proof –
        from act
        have IsMajority( $\{d. d \in \text{disksWritten } s \ q \wedge (\forall r \in \text{UNIV} - \{q\}. \text{hasRead } s \ q \ d \ r)\}$ )
          (is IsMajority(?M))
          by(auto simp add: EndPhase1-def)
        with majorities-intersect asm2
        have  $D \cap ?M \neq \{\}$ 
          by(auto simp add: MajoritySet-def)
        hence  $\exists d \in D. (\forall r \in \text{UNIV} - \{q\}. \text{hasRead } s \ q \ d \ r)$ 
          by auto
        with pnq
        show ?thesis
          by auto
      qed
    then obtain d where p41: d ∈ D ∧ hasRead s q d p by auto
    with asm4 asm3 act True
    have p42: ∃ br ∈ blocksRead s q d. b ≤ bal(block br)
      by(auto simp add: EndPhase1-def)
    from True act
    have thesis-L: b ≤ bal (dblock s' q)
      by(auto simp add: EndPhase1-def)
    from p42
    have inp(dblock s' q) = v

```

```

proof auto
  fix br
  assume br:  $br \in \text{blocksRead } s \ q \ d$ 
  and b-bal:  $b \leq \text{bal}(\text{block } br)$ 
  hence br-rdBy:  $br \in (\text{UN } q \ d. \text{rdBy } s \ (\text{proc } br) \ q \ d)$ 
  by(auto simp add: rdBy-def)
  hence br-blksof:  $\text{block } br \in \text{blocksOf } s \ (\text{proc } br)$ 
  by(auto simp add: blocksOf-def)
  from br have br-bseen:  $\text{block } br \in \text{blocksSeen } s \ q$ 
  by(auto simp add: blocksSeen-def allBlocksRead-def allRdBlks-def)
  from HEndPhase1-valueChosen-inp[OF act inv2a asm1 br-blksof br-bseen b-bal
asm3 inv1]
  show ?thesis .
qed
with asm3 HEndPhase1-allBlocks[OF act]
show ?thesis
  by(auto simp add: maxBalInp-def)
next
  case False
  from asm4
  have p41:  $\forall d \in D. b \leq \text{bal}(\text{disk } s \ d \ p)$ 
  by auto
  have p42:  $\exists d \in D. \text{disk } s \ d \ p = \text{dblock } s \ p$ 
  proof –
  from act
  have IsMajority  $\{d. d \in \text{disksWritten } s \ q \wedge (\forall p \in \text{UNIV} - \{q\}. \text{hasRead } s \ q \ d$ 
p)\} (is IsMajority ?S)
  by(auto simp add: EndPhase1-def)
  with majorities-intersect asm2
  have  $D \cap ?S \neq \{\}$ 
  by(auto simp add: MajoritySet-def)
  hence  $\exists d \in D. d \in \text{disksWritten } s \ q$ 
  by auto
  with inv2b False
  show ?thesis
  by(auto simp add: Inv2b-def Inv2b-inner-def)
qed
have  $\text{inp}(\text{dblock } s' \ q) = v$ 
proof –
  from p42 p41 False
  have b-bal:  $b \leq \text{bal}(\text{dblock } s \ q)$  by auto
  have db-blksof:  $(\text{dblock } s \ q) \in \text{blocksOf } s \ q$ 
  by(auto simp add: blocksOf-def)
  have db-bseen:  $(\text{dblock } s \ q) \in \text{blocksSeen } s \ q$ 
  by(auto simp add: blocksSeen-def)
  from HEndPhase1-valueChosen-inp[OF act inv2a asm1 db-blksof db-bseen
b-bal asm3 inv1]
  show ?thesis .
qed

```

```

    with asm3 HEndPhase1-allBlocks[OF act]
    show ?thesis
      by(auto simp add: maxBalInp-def)
  qed
next
case False
have dblock s' q ∈ allBlocks s'
  by(auto simp add: allBlocks-def blocksOf-def)
show ?thesis
proof(auto simp add: maxBalInp-def)
  fix bk
  assume bk: bk ∈ allBlocks s'
  and b-bal: b ≤ bal bk
  from subsetD[OF HEndPhase1-allBlocks[OF act] bk]
  show inp bk = v
  proof
    assume bk: bk ∈ allBlocks s
    with asm3 b-bal
    show ?thesis
      by(auto simp add: maxBalInp-def)
  next
    assume bk: bk ∈ {dblock s' q}
    from act False
    have ¬ b ≤ bal (dblock s' q)
      by(auto simp add: EndPhase1-def)
    with bk b-bal
    show ?thesis
      by(auto)
  qed
qed
qed
qed

lemma HEndPhase1-valueChosen2:
  assumes act: HEndPhase1 s s' q
  and asm4: ∀ d ∈ D. b ≤ bal(disk s d p)
    ∧ (∀ q. ( phase s q = 1
      ∧ b ≤ mbal(dblock s q)
      ∧ hasRead s q d p
    ) → (∃ br ∈ blocksRead s q d. b ≤ bal(block br))) (is ?P s)
  shows ?P s'
proof(auto)
  fix d
  assume d: d ∈ D
  with act asm4
  show b ≤ bal (disk s' d p)
    by(auto simp add: EndPhase1-def)
  fix d q
  assume d: d ∈ D
  and phase': phase s' q = Suc 0

```

and $dbl\text{-}mbal: b \leq mbal (dblock\ s'\ q)$
with act
have $p31: phase\ s\ q = 1$
and $p32: dblock\ s'\ q = dblock\ s\ q$
by($auto\ simp\ add: EndPhase1\text{-}def\ split: if\text{-}split\text{-}asm$)
with $dbl\text{-}mbal$
have $b \leq mbal(dblock\ s\ q)$ **by** $auto$
moreover
assume $hasRead: hasRead\ s'\ q\ d\ p$
with act
have $hasRead\ s\ q\ d\ p$
by($auto\ simp\ add: EndPhase1\text{-}def\ InitializePhase\text{-}def\ hasRead\text{-}def\ split: if\text{-}split\text{-}asm$)
ultimately
have $\exists br \in blocksRead\ s\ q\ d. b \leq bal(block\ br)$
using $p31\ asm4\ d$
by $blast$
with $act\ hasRead$
show $\exists br \in blocksRead\ s'\ q\ d. b \leq bal(block\ br)$
by($auto\ simp\ add: EndPhase1\text{-}def\ InitializePhase\text{-}def\ hasRead\text{-}def$)
qed

theorem $HEndPhase1\text{-}valueChosen:$

assumes $act: HEndPhase1\ s\ s'\ q$
and $vc: valueChosen\ s\ v$
and $inv1: Inv1\ s$
and $inv2a: Inv2a\ s$
and $inv2b: Inv2b\ s$
and $v\text{-}input: v \in Inputs$
shows $valueChosen\ s'\ v$
proof –
from vc
obtain $b\ p\ D$ **where**
 $asm1: b \in (UN\ p. Ballot\ p)$
and $asm2: D \in MajoritySet$
and $asm3: maxBalInp\ s\ b\ v$
and $asm4: \forall d \in D. b \leq bal(disk\ s\ d\ p)$
 $\wedge (\forall q. (phase\ s\ q = 1$
 $\wedge b \leq mbal(dblock\ s\ q)$
 $\wedge hasRead\ s\ q\ d\ p$
 $) \longrightarrow (\exists br \in blocksRead\ s\ q\ d. b \leq bal(block\ br)))$
by($auto\ simp\ add: valueChosen\text{-}def$)
from $HEndPhase1\text{-}maxBalInp[OF\ act\ asm1\ asm2\ asm3\ asm4\ inv1\ inv2a\ inv2b]$
have $maxBalInp\ s'\ b\ v$.
with $HEndPhase1\text{-}valueChosen2[OF\ act\ asm4]\ asm1\ asm2$
show $?thesis$
by($auto\ simp\ add: valueChosen\text{-}def$)
qed


```

lemma HStartBallot-maxBalInp:
  assumes act: HStartBallot s s' q
    and asm3: maxBalInp s b v
  shows maxBalInp s' b v
proof(auto simp add: maxBalInp-def)
  fix bk
  assume bk: bk ∈ allBlocks s'
    and b-bal: b ≤ bal bk
  from subsetD[OF HStartBallot-allBlocks[OF act] bk]
  show inp bk = v
  proof
    assume bk: bk ∈ allBlocks s
    with asm3 b-bal
    show ?thesis
    by(auto simp add: maxBalInp-def)
  next
    assume bk: bk ∈ {dblock s' q}
    from asm3
    have b ≤ bal(dblock s q) ⇒ inp(dblock s q) = v
    by(auto simp add: maxBalInp-def allBlocks-def blocksOf-def)
    with act bk b-bal
    show ?thesis
    by(auto simp add: StartBallot-def)
  qed
qed

lemma HStartBallot-valueChosen2:
  assumes act: HStartBallot s s' q
    and asm4:  $\forall d \in D. \quad b \leq \text{bal}(\text{disk } s \ d \ p)$ 
       $\wedge (\forall q. (\text{phase } s \ q = 1$ 
         $\wedge b \leq \text{mbal}(\text{dblock } s \ q)$ 
         $\wedge \text{hasRead } s \ q \ d \ p$ 
         $) \longrightarrow (\exists br \in \text{blocksRead } s \ q \ d. b \leq \text{bal}(\text{block } br)))$  (is ?P s)

  shows ?P s'
proof(auto)
  fix d
  assume d: d ∈ D
  with act asm4
  show b ≤ bal (disk s' d p)
    by(auto simp add: StartBallot-def)
  fix d q
  assume d: d ∈ D
    and phase': phase s' q = Suc 0
    and dblk-mbal: b ≤ mbal (dblock s' q)
    and hasRead: hasRead s' q d p
  from phase' act hasRead
  have p31: phase s q = 1
  and p32: dblock s' q = dblock s q
  by(auto simp add: StartBallot-def InitializePhase-def)

```

hasRead-def split : if-split-asm)

with *dblk-mbal*
have $b \leq \text{mbal}(\text{dblock } s \ q)$ **by** *auto*
moreover
from *act hasRead*
have *hasRead s q d p*
by(*auto simp add: StartBallot-def InitializePhase-def*
hasRead-def split: if-split-asm)
ultimately
have $\exists br \in \text{blocksRead } s \ q \ d. b \leq \text{bal}(\text{block } br)$
using *p31 asm4 d*
by *blast*
with *act hasRead*
show $\exists br \in \text{blocksRead } s' \ q \ d. b \leq \text{bal}(\text{block } br)$
by(*auto simp add: StartBallot-def InitializePhase-def*
hasRead-def)

qed

theorem *HStartBallot-valueChosen:*

assumes *act: HStartBallot s s' q*

and *vc: valueChosen s v*

and *v-input: v ∈ Inputs*

shows *valueChosen s' v*

proof –

from *vc*

obtain *b p D* **where**

asm1: b ∈ (UN p. Ballot p)

and *asm2: D ∈ MajoritySet*

and *asm3: maxBalInp s b v*

and *asm4: ∀ d ∈ D. b ≤ bal(disk s d p)*

$\wedge (\forall q. (\text{phase } s \ q = 1$
 $\wedge b \leq \text{mbal}(\text{dblock } s \ q)$
 $\wedge \text{hasRead } s \ q \ d \ p$

$) \longrightarrow (\exists br \in \text{blocksRead } s \ q \ d. b \leq \text{bal}(\text{block } br)))$

by(*auto simp add: valueChosen-def*)

from *HStartBallot-maxBalInp[OF act asm3]*

have *maxBalInp s' b v .*

with *HStartBallot-valueChosen2[OF act asm4] asm1 asm2*

show *?thesis*

by(*auto simp add: valueChosen-def*)

qed

lemma *HPhase1or2Write-maxBalInp:*

assumes *act: HPhase1or2Write s s' q d*

and *asm3: maxBalInp s b v*

shows *maxBalInp s' b v*

proof(*auto simp add: maxBalInp-def*)

fix *bk*

assume *bk: bk ∈ allBlocks s'*

```

    and b-bal:  $b \leq \text{bal } bk$ 
  from subsetD[OF HPhase1or2Write-allBlocks[OF act] bk] asm3 b-bal
  show  $\text{inp } bk = v$ 
    by(auto simp add: maxBalInp-def)
qed

lemma HPhase1or2Write-valueChosen2:
  assumes act: HPhase1or2Write s s' pp d
    and asm2:  $D \in \text{MajoritySet}$ 
    and asm4:  $\forall d \in D. \quad b \leq \text{bal}(\text{disk } s \ d \ p)$ 
       $\wedge (\forall q. (\text{phase } s \ q = 1$ 
         $\wedge b \leq \text{mbal}(\text{dblock } s \ q)$ 
         $\wedge \text{hasRead } s \ q \ d \ p$ 
         $) \longrightarrow (\exists br \in \text{blocksRead } s \ q \ d. b \leq \text{bal}(\text{block } br)))$  (is ?P s)
    and inv4:  $\text{HInv4a } s \ pp$ 
  shows ?P s'
  proof(auto)
    fix d1
    assume d:  $d1 \in D$ 
    show  $b \leq \text{bal}(\text{disk } s' \ d1 \ p)$ 
    proof(cases  $d1 = d \wedge pp = p$ )
      case True
      with inv4 act
      have  $\text{HInv4a2 } s \ p$ 
        by(auto simp add: Phase1or2Write-def HInv4a-def)
      with asm2 majorities-intersect
      have  $\exists dd \in D. \text{bal}(\text{disk } s \ dd \ p) \leq \text{bal}(\text{dblock } s \ p)$ 
        by(auto simp add: HInv4a2-def MajoritySet-def)
      then obtain dd where p41:  $dd \in D \wedge \text{bal}(\text{disk } s \ dd \ p) \leq \text{bal}(\text{dblock } s \ p)$ 
        by auto
      from asm4 p41
      have  $b \leq \text{bal}(\text{disk } s \ dd \ p)$ 
        by auto
      with p41
      have p42:  $b \leq \text{bal}(\text{dblock } s \ p)$ 
        by auto
      from act True
      have  $\text{dblock } s \ p = \text{disk } s' \ d \ p$ 
        by(auto simp add: Phase1or2Write-def)
      with p42 True
      show ?thesis
        by auto
    next
    case False
    with act asm4 d
    show ?thesis
      by(auto simp add: Phase1or2Write-def)
  qed
next

```

```

fix  $d\ q$ 
assume  $d: d \in D$ 
  and  $phase'$ :  $phase\ s'\ q = Suc\ 0$ 
  and  $dblk\ mbal$ :  $b \leq mbal\ (dblock\ s'\ q)$ 
  and  $hasRead$ :  $hasRead\ s'\ q\ d\ p$ 
from  $phase'$  act hasRead
have  $p31$ :  $phase\ s\ q = 1$ 
  and  $p32$ :  $dblock\ s'\ q = dblock\ s\ q$ 
  by(auto simp add: Phase1or2Write-def InitializePhase-def
      hasRead-def split : if-split-asm)
with  $dblk\ mbal$ 
have  $b \leq mbal\ (dblock\ s\ q)$  by auto
moreover
from act hasRead
have  $hasRead\ s\ q\ d\ p$ 
  by(auto simp add: Phase1or2Write-def InitializePhase-def
      hasRead-def split: if-split-asm)
ultimately
have  $\exists br \in blocksRead\ s\ q\ d. b \leq bal\ (block\ br)$ 
  using  $p31\ asm4\ d$ 
  by blast
with act hasRead
show  $\exists br \in blocksRead\ s'\ q\ d. b \leq bal\ (block\ br)$ 
  by(auto simp add: Phase1or2Write-def InitializePhase-def
      hasRead-def)
qed

```

```

theorem HPhase1or2Write-valueChosen:
  assumes  $act$ : HPhase1or2Write  $s\ s'\ q\ d$ 
  and  $vc$ : valueChosen  $s\ v$ 
  and  $v\ input$ :  $v \in Inputs$ 
  and  $inv4$ : HInv4  $s\ q$ 
  shows valueChosen  $s'\ v$ 
proof –
  from  $vc$ 
  obtain  $b\ p\ D$  where
     $asm1$ :  $b \in (UN\ p. Ballot\ p)$ 
    and  $asm2$ :  $D \in MajoritySet$ 
    and  $asm3$ :  $maxBallInp\ s\ b\ v$ 
    and  $asm4$ :  $\forall d \in D. b \leq bal\ (disk\ s\ d\ p)$ 
       $\wedge (\forall q. ( phase\ s\ q = 1$ 
         $\wedge b \leq mbal\ (dblock\ s\ q)$ 
         $\wedge hasRead\ s\ q\ d\ p$ 
         $) \longrightarrow (\exists br \in blocksRead\ s\ q\ d. b \leq bal\ (block\ br)))$ 
    by(auto simp add: valueChosen-def)
  from HPhase1or2Write-maxBallInp[OF act asm3]
  have  $maxBallInp\ s'\ b\ v$  .
  with HPhase1or2Write-valueChosen2[OF act asm2 asm4 inv4]  $asm1\ asm2$ 
  show ?thesis

```

by(auto simp add: valueChosen-def)
qed

lemma *HPhase1or2ReadThen-maxBalInp*:
assumes *act*: *HPhase1or2ReadThen* *s s' q d p*
and *asm3*: *maxBalInp* *s b v*
shows *maxBalInp* *s' b v*
proof(auto simp add: *maxBalInp-def*)
fix *bk*
assume *bk*: *bk* \in *allBlocks* *s'*
and *b-bal*: $b \leq \text{bal } bk$
from *subsetD*[*OF HPhase1or2ReadThen-allBlocks*[*OF act*] *bk*] *asm3 b-bal*
show *inp* *bk* = *v*
by(auto simp add: *maxBalInp-def*)
qed

lemma *HPhase1or2ReadThen-valueChosen2*:
assumes *act*: *HPhase1or2ReadThen* *s s' q d pp*
and *asm4*: $\forall d \in D. \quad b \leq \text{bal}(\text{disk } s \ d \ p)$
 $\wedge (\forall q. (\text{phase } s \ q = 1$
 $\wedge b \leq \text{mbal}(\text{dblock } s \ q)$
 $\wedge \text{hasRead } s \ q \ d \ p$
 $) \longrightarrow (\exists br \in \text{blocksRead } s \ q \ d. b \leq \text{bal}(\text{block } br)))$ (**is** *?P s*)
shows *?P s'*
proof(auto)
fix *dd*
assume *d*: *dd* \in *D*
with *act asm4*
show $b \leq \text{bal}(\text{disk } s' \ dd \ p)$
by(auto simp add: *Phase1or2ReadThen-def*)
fix *dd qq*
assume *d*: *dd* \in *D*
and *phase'*: *phase* *s' qq* = *Suc 0*
and *dblk-mbal*: $b \leq \text{mbal}(\text{dblock } s' \ qq)$
and *hasRead*: *hasRead* *s' qq dd p*
show $\exists br \in \text{blocksRead } s' \ qq \ dd. b \leq \text{bal}(\text{block } br)$
proof(cases *d=dd* \wedge *qq=q* \wedge *pp=p*)
case *True*
from *d asm4*
have $b \leq \text{bal}(\text{disk } s \ dd \ p)$
by auto
with *act True*
show *?thesis*
by(auto simp add: *Phase1or2ReadThen-def*)
next
case *False*
with *phase' act*
have *p31*: *phase* *s qq* = *1*

```

    and p32: dblock s' qq = dblock s qq
    by(auto simp add: Phase1or2ReadThen-def)
  with dblk-mbal
  have b≤mbal(dblock s qq) by auto
  moreover
  from act hasRead False
  have hasRead s qq dd p
    by(auto simp add: Phase1or2ReadThen-def
hasRead-def split: if-split-asm)
  ultimately
  have ∃ br∈blocksRead s qq dd. b≤ bal(block br)
    using p31 asm4 d
    by blast
  with act hasRead
  show ∃ br∈blocksRead s' qq dd. b≤ bal(block br)
    by(auto simp add: Phase1or2ReadThen-def hasRead-def)
qed
qed

```

theorem *HPhase1or2ReadThen-valueChosen:*

```

  assumes act: HPhase1or2ReadThen s s' q d p
  and vc: valueChosen s v
  and v-input: v ∈ Inputs
  shows valueChosen s' v
proof –
  from vc
  obtain b p D where
    asm1: b ∈ (UN p. Ballot p)
  and asm2: D∈MajoritySet
  and asm3: maxBalInp s b v
  and asm4: ∀ d∈D. b ≤ bal(disk s d p)
    ∧ (∀ q.( phase s q = 1
    ∧ b ≤mbal(dblock s q)
    ∧ hasRead s q d p
    ) → (∃ br∈blocksRead s q d. b ≤ bal(block br)))
  by(auto simp add: valueChosen-def)
  from HPhase1or2ReadThen-maxBalInp[OF act asm3]
  have maxBalInp s' b v .
  with HPhase1or2ReadThen-valueChosen2[OF act asm4] asm1 asm2
  show ?thesis
  by(auto simp add: valueChosen-def)
qed

```

theorem *HPhase1or2ReadElse-valueChosen:*

```

  [ HPhase1or2ReadElse s s' p d r; valueChosen s v; v ∈ Inputs ]
  ⇒ valueChosen s' v
  using HStartBallot-valueChosen
  by(auto simp add: Phase1or2ReadElse-def)

```

```

lemma HEndPhase2-maxBalInp:
  assumes act: HEndPhase2 s s' q
    and asm3: maxBalInp s b v
  shows maxBalInp s' b v
proof(auto simp add: maxBalInp-def)
  fix bk
  assume bk: bk ∈ allBlocks s'
    and b-bal:  $b \leq \text{bal } bk$ 
  from subsetD[OF HEndPhase2-allBlocks[OF act] bk] asm3 b-bal
  show inp bk = v
    by(auto simp add: maxBalInp-def)
qed

lemma HEndPhase2-valueChosen2:
  assumes act: HEndPhase2 s s' q
    and asm4:  $\forall d \in D. \quad b \leq \text{bal}(\text{disk } s \ d \ p)$ 
       $\wedge (\forall q. (\text{phase } s \ q = 1$ 
         $\wedge b \leq \text{mbal}(\text{dblock } s \ q)$ 
         $\wedge \text{hasRead } s \ q \ d \ p$ 
         $) \longrightarrow (\exists br \in \text{blocksRead } s \ q \ d. b \leq \text{bal}(\text{block } br)))$  (is ?P s)

  shows ?P s'
proof(auto)
  fix d
  assume d: d ∈ D
  with act asm4
  show  $b \leq \text{bal}(\text{disk } s' \ d \ p)$ 
    by(auto simp add: EndPhase2-def)
  fix d q
  assume d: d ∈ D
    and phase': phase s' q = Suc 0
    and dbl-mbal:  $b \leq \text{mbal}(\text{dblock } s' \ q)$ 
    and hasRead: hasRead s' q d p
  from phase' act hasRead
  have p31: phase s q = 1
    and p32: dblock s' q = dblock s q
    by(auto simp add: EndPhase2-def InitializePhase-def
      hasRead-def split : if-split-asm)
  with dbl-mbal
  have  $b \leq \text{mbal}(\text{dblock } s \ q)$  by auto
  moreover
  from act hasRead
  have hasRead s q d p
    by(auto simp add: EndPhase2-def InitializePhase-def
      hasRead-def split: if-split-asm)
  ultimately
  have  $\exists br \in \text{blocksRead } s \ q \ d. b \leq \text{bal}(\text{block } br)$ 
    using p31 asm4 d
    by blast
  with act hasRead

```

show $\exists br \in \text{blocksRead } s' q d. b \leq \text{bal}(\text{block } br)$
by(*auto simp add: EndPhase2-def InitializePhase-def hasRead-def*)

qed

theorem *HEndPhase2-valueChosen*:
assumes *act: HEndPhase2 s s' q*
and *vc: valueChosen s v*
and *v-input: v ∈ Inputs*
shows *valueChosen s' v*
proof –
from *vc*
obtain *b p D* **where**
asm1: b ∈ (UN p. Ballot p)
and *asm2: D ∈ MajoritySet*
and *asm3: maxBalInp s b v*
and *asm4: $\forall d \in D. b \leq \text{bal}(\text{disk } s d p)$*
 $\wedge (\forall q. (\text{phase } s q = 1$
 $\wedge b \leq \text{mbal}(\text{dblock } s q)$
 $\wedge \text{hasRead } s q d p$
 $) \longrightarrow (\exists br \in \text{blocksRead } s q d. b \leq \text{bal}(\text{block } br)))$
by(*auto simp add: valueChosen-def*)
from *HEndPhase2-maxBalInp[OF act asm3]*
have *maxBalInp s' b v* .
with *HEndPhase2-valueChosen2[OF act asm4] asm1 asm2*
show *?thesis*
by(*auto simp add: valueChosen-def*)

qed

lemma *HFail-maxBalInp*:
assumes *act: HFail s s' q*
and *asm1: b ∈ (UN p. Ballot p)*
and *asm3: maxBalInp s b v*
shows *maxBalInp s' b v*
proof(*auto simp add: maxBalInp-def*)
fix *bk*
assume *bk: bk ∈ allBlocks s'*
and *b-bal: b ≤ bal bk*
from *subsetD[OF HFail-allBlocks[OF act] bk]*
show *inp bk = v*
proof
assume *bk: bk ∈ allBlocks s*
with *asm3 b-bal*
show *?thesis*
by(*auto simp add: maxBalInp-def*)

next
assume *bk: bk ∈ {dblock s' q}*
with *act*
have *bal bk = 0*


```

    by(auto simp add: Fail-def InitDB-def)
  moreover
  from Ballot-nzero asm1
  have 0 < b
    by auto
  ultimately
  show ?thesis
    using b-bal
    by auto
qed
qed

lemma HFail-valueChosen2:
  assumes act: HFail s s' q
  and asm4:  $\forall d \in D. \quad b \leq \text{bal}(\text{disk } s \ d \ p)$ 
            $\wedge (\forall q. (\text{phase } s \ q = 1$ 
                     $\wedge b \leq \text{mbal}(\text{dblock } s \ q)$ 
                     $\wedge \text{hasRead } s \ q \ d \ p$ 
                     $) \longrightarrow (\exists br \in \text{blocksRead } s \ q \ d. b \leq \text{bal}(\text{block } br)))$  (is ?P s)
  shows ?P s'
proof(auto)
  fix d
  assume d:  $d \in D$ 
  with act asm4
  show  $b \leq \text{bal}(\text{disk } s' \ d \ p)$ 
    by(auto simp add: Fail-def)
  fix d q
  assume d:  $d \in D$ 
  and phase':  $\text{phase } s' \ q = \text{Suc } 0$ 
  and dblk-mbal:  $b \leq \text{mbal}(\text{dblock } s' \ q)$ 
  and hasRead:  $\text{hasRead } s' \ q \ d \ p$ 
  from phase' act hasRead
  have p31:  $\text{phase } s \ q = 1$ 
  and p32:  $\text{dblock } s' \ q = \text{dblock } s \ q$ 
  by(auto simp add: Fail-def InitializePhase-def
                hasRead-def split : if-split-asm)
  with dblk-mbal
  have  $b \leq \text{mbal}(\text{dblock } s \ q)$  by auto
  moreover
  from act hasRead
  have hasRead s q d p
    by(auto simp add: Fail-def InitializePhase-def
                    hasRead-def split: if-split-asm)
  ultimately
  have  $\exists br \in \text{blocksRead } s \ q \ d. b \leq \text{bal}(\text{block } br)$ 
    using p31 asm4 d
    by blast
  with act hasRead
  show  $\exists br \in \text{blocksRead } s' \ q \ d. b \leq \text{bal}(\text{block } br)$ 

```

by(auto simp add: Fail-def InitializePhase-def hasRead-def)
qed

theorem *HFail-valueChosen*:

assumes *act*: *HFail* *s s' q*
and *vc*: *valueChosen* *s v*
and *v-input*: *v* ∈ *Inputs*
shows *valueChosen* *s' v*

proof –

from *vc*

obtain *b p D* where

asm1: $b \in (UN\ p.\ Ballot\ p)$

and *asm2*: $D \in MajoritySet$

and *asm3*: $maxBalInp\ s\ b\ v$

and *asm4*: $\forall d \in D.\ b \leq bal(disk\ s\ d\ p)$

$\wedge (\forall q. (phase\ s\ q = 1$
 $\wedge b \leq mbal(dblock\ s\ q)$
 $\wedge hasRead\ s\ q\ d\ p$
 $) \longrightarrow (\exists br \in blocksRead\ s\ q\ d.\ b \leq bal(block\ br)))$

by(auto simp add: valueChosen-def)

from *HFail-maxBalInp*[*OF act asm1 asm3*]

have *maxBalInp* *s' b v* .

with *HFail-valueChosen2*[*OF act asm4*] *asm1 asm2*

show *?thesis*

by(auto simp add: valueChosen-def)

qed

lemma *HPhase0Read-maxBalInp*:

assumes *act*: *HPhase0Read* *s s' q d*

and *asm3*: $maxBalInp\ s\ b\ v$

shows $maxBalInp\ s'\ b\ v$

proof(auto simp add: *maxBalInp-def*)

fix *bk*

assume *bk*: $bk \in allBlocks\ s'$

and *b-bal*: $b \leq bal\ bk$

from *subsetD*[*OF HPhase0Read-allBlocks*[*OF act*] *bk*] *asm3 b-bal*

show *inp* *bk* = *v*

by(auto simp add: *maxBalInp-def*)

qed

lemma *HPhase0Read-valueChosen2*:

assumes *act*: *HPhase0Read* *s s' qq dd*

and *asm4*: $\forall d \in D.\ b \leq bal(disk\ s\ d\ p)$

$\wedge (\forall q. (phase\ s\ q = 1$
 $\wedge b \leq mbal(dblock\ s\ q)$
 $\wedge hasRead\ s\ q\ d\ p$
 $) \longrightarrow (\exists br \in blocksRead\ s\ q\ d.\ b \leq bal(block\ br)))$ (**is** *?P s*)

shows *?P s'*

proof(auto)

```

fix  $d$ 
assume  $d: d \in D$ 
with  $act\ asm_4$ 
show  $b \leq bal\ (disk\ s'\ d\ p)$ 
  by( $auto\ simp\ add: Phase0Read-def$ )
next
fix  $d\ q$ 
assume  $d: d \in D$ 
  and  $phase': phase\ s'\ q = Suc\ 0$ 
  and  $dblk-mbal: b \leq mbal\ (dblock\ s'\ q)$ 
  and  $hasRead: hasRead\ s'\ q\ d\ p$ 
from  $phase'\ act$ 
have  $qqnq: qq \neq q$ 
  by( $auto\ simp\ add: Phase0Read-def$ )
show  $\exists br \in blocksRead\ s'\ q\ d. b \leq bal\ (block\ br)$ 
proof –
  from  $phase'\ act\ hasRead$ 
  have  $p31: phase\ s\ q = 1$ 
    and  $p32: dblock\ s'\ q = dblock\ s\ q$ 
    by( $auto\ simp\ add: Phase0Read-def\ hasRead-def$ )
  with  $dblk-mbal$ 
  have  $b \leq mbal(dblock\ s\ q)$  by  $auto$ 
moreover
from  $act\ hasRead\ qqnq$ 
have  $hasRead\ s\ q\ d\ p$ 
  by( $auto\ simp\ add: Phase0Read-def\ hasRead-def$ 
     $split: if-split-asm$ )
ultimately
have  $\exists br \in blocksRead\ s\ q\ d. b \leq bal(block\ br)$ 
  using  $p31\ asm_4\ d$ 
  by  $blast$ 
with  $act\ hasRead$ 
show  $\exists br \in blocksRead\ s'\ q\ d. b \leq bal(block\ br)$ 
  by( $auto\ simp\ add: Phase0Read-def\ InitializePhase-def$ 
     $hasRead-def$ )

qed
qed

```

```

theorem  $HPhase0Read-valueChosen:$ 
assumes  $act: HPhase0Read\ s\ s'\ q\ d$ 
and  $vc: valueChosen\ s\ v$ 
and  $v-input: v \in Inputs$ 
shows  $valueChosen\ s'\ v$ 

```

```

proof –
from  $vc$ 
obtain  $b\ p\ D$  where
   $asm1: b \in (UN\ p. Ballot\ p)$ 
  and  $asm2: D \in MajoritySet$ 
  and  $asm3: maxBallInp\ s\ b\ v$ 

```

and $asm4: \forall d \in D. b \leq bal(disk\ s\ d\ p)$
 $\wedge (\forall q. (phase\ s\ q = 1$
 $\wedge b \leq mbal(dblock\ s\ q)$
 $\wedge hasRead\ s\ q\ d\ p$
 $) \longrightarrow (\exists br \in blocksRead\ s\ q\ d. b \leq bal(block\ br)))$
by(*auto simp add: valueChosen-def*)
from *HPhase0Read-maxBalInp[OF act asm3]*
have $maxBalInp\ s'\ b\ v$.
with *HPhase0Read-valueChosen2[OF act asm4] asm1 asm2*
show *?thesis*
by(*auto simp add: valueChosen-def*)
qed

lemma *HEndPhase0-maxBalInp:*
assumes $act: HEndPhase0\ s'\ q$
and $asm3: maxBalInp\ s\ b\ v$
and $inv1: Inv1\ s$
shows $maxBalInp\ s'\ b\ v$
proof(*auto simp add: maxBalInp-def*)
fix bk
assume $bk: bk \in allBlocks\ s'$
and $b-bal: b \leq bal\ bk$
from $subsetD[OF\ HEndPhase0-allBlocks[OF\ act]\ bk]$
show $inp\ bk = v$
proof
assume $bk: bk \in allBlocks\ s$
with $asm3\ b-bal$
show *?thesis*
by(*auto simp add: maxBalInp-def*)
next
assume $bk: bk \in \{dblock\ s'\ q\}$
with $HEndPhase0-some[OF\ act\ inv1]\ act$
have $\exists ba \in allBlocksRead\ s\ q. bal\ ba = bal\ (dblock\ s'\ q) \wedge inp\ ba = inp\ (dblock\ s'\ q)$
by(*auto simp add: EndPhase0-def*)
then obtain ba
where $ba-blksread: ba \in allBlocksRead\ s\ q$
and $ba-balinp: bal\ ba = bal\ (dblock\ s'\ q) \wedge inp\ ba = inp\ (dblock\ s'\ q)$
by *auto*
have $allBlocksRead\ s\ q \subseteq allBlocks\ s$
by(*auto simp add: allBlocksRead-def allRdBlks-def*
 $allBlocks-def\ blocksOf-def\ rdBy-def$)
from $subsetD[OF\ this\ ba-blksread]\ ba-balinp\ bk\ b-bal\ asm3$
show *?thesis*
by(*auto simp add: maxBalInp-def*)
qed
qed

lemma *HEndPhase0-valueChosen2*:
assumes *act*: *HEndPhase0 s s' q*
and *asm4*: $\forall d \in D. \quad b \leq \text{bal}(\text{disk } s \ d \ p)$
 $\wedge (\forall q. (\text{phase } s \ q = 1$
 $\wedge b \leq \text{mbal}(\text{dblock } s \ q)$
 $\wedge \text{hasRead } s \ q \ d \ p$
 $) \longrightarrow (\exists br \in \text{blocksRead } s \ q \ d. b \leq \text{bal}(\text{block } br)))$ (**is** *?P s*)

shows *?P s'*

proof(*auto*)
fix *d*
assume *d*: $d \in D$
with *act asm4*
show $b \leq \text{bal}(\text{disk } s' \ d \ p)$
by(*auto simp add: EndPhase0-def*)
fix *d q*
assume *d*: $d \in D$
and *phase'*: $\text{phase } s' \ q = \text{Suc } 0$
and *dblk-mbal*: $b \leq \text{mbal}(\text{dblock } s' \ q)$
and *hasRead*: $\text{hasRead } s' \ q \ d \ p$
from *phase' act hasRead*
have *p31*: $\text{phase } s \ q = 1$
and *p32*: $\text{dblock } s' \ q = \text{dblock } s \ q$
by(*auto simp add: EndPhase0-def InitializePhase-def*
hasRead-def split : if-split-asm)
with *dblk-mbal*
have $b \leq \text{mbal}(\text{dblock } s \ q)$ **by** *auto*
moreover
from *act hasRead*
have $\text{hasRead } s \ q \ d \ p$
by(*auto simp add: EndPhase0-def InitializePhase-def*
hasRead-def split: if-split-asm)
ultimately
have $\exists br \in \text{blocksRead } s \ q \ d. b \leq \text{bal}(\text{block } br)$
using *p31 asm4 d*
by *blast*
with *act hasRead*
show $\exists br \in \text{blocksRead } s' \ q \ d. b \leq \text{bal}(\text{block } br)$
by(*auto simp add: EndPhase0-def InitializePhase-def*
hasRead-def)

qed

theorem *HEndPhase0-valueChosen*:
assumes *act*: *HEndPhase0 s s' q*
and *vc*: *valueChosen s v*
and *v-input*: $v \in \text{Inputs}$
and *inv1*: *Inv1 s*
shows *valueChosen s' v*

proof –
from *vc*

```

obtain  $b p D$  where
   $asm1: b \in (UN\ p.\ Ballot\ p)$ 
and  $asm2: D \in MajoritySet$ 
and  $asm3: maxBalInp\ s\ b\ v$ 
and  $asm4: \forall d \in D. b \leq bal(disk\ s\ d\ p)$ 
       $\wedge (\forall q. ( phase\ s\ q = 1$ 
         $\wedge b \leq mbal(dblock\ s\ q)$ 
         $\wedge hasRead\ s\ q\ d\ p$ 
      )  $\longrightarrow (\exists br \in blocksRead\ s\ q\ d. b \leq bal(block\ br)))$ 
  by(auto simp add: valueChosen-def)
from  $HEndPhase0-maxBalInp[OF\ act\ asm3\ inv1]$ 
have  $maxBalInp\ s'\ b\ v$  .
with  $HEndPhase0-valueChosen2[OF\ act\ asm4]\ asm1\ asm2$ 
show ?thesis
  by(auto simp add: valueChosen-def)
qed

end

```

```

theory DiskPaxos-Inv6 imports DiskPaxos-Chosen begin

```

C.7 Invariant 6

The final conjunct of $HInv$ asserts that, once an output has been chosen, $valueChosen(chosen)$ holds, and each processor's output equals either $chosen$ or $NotAnInput$.

definition $HInv6 :: state \Rightarrow bool$

where

$$HInv6\ s = ((chosen\ s \neq NotAnInput \longrightarrow valueChosen\ s\ (chosen\ s)) \wedge (\forall p. outpt\ s\ p \in \{chosen\ s, NotAnInput\}))$$

theorem $HInit-HInv6: HInit\ s \Longrightarrow HInv6\ s$

by(*auto simp add: HInit-def Init-def InitDB-def HInv6-def*)

lemma $HEndPhase2-Inv6-1:$

assumes $act: HEndPhase2\ s\ s'\ p$

and $inv: HInv6\ s$

and $inv2b: Inv2b\ s$

and $inv2c: Inv2c\ s$

and $inv3: HInv3\ s$

and $inv5: HInv5-inner\ s\ p$

and $chosen': chosen\ s' \neq NotAnInput$

shows $valueChosen\ s'\ (chosen\ s')$

proof(*cases\ chosen\ s=NotAnInput*)

from $inv5\ act$

have $inv5R: HInv5-inner-R\ s\ p$

and $phase: phase\ s\ p = 2$

and $ep2-maj: IsMajority\ \{d . d \in disksWritten\ s\ p$

```

       $\wedge (\forall q \in UNIV - \{p\}. hasRead\ s\ p\ d\ q)\}$ 
    by(auto simp add: EndPhase2-def HInv5-inner-def)
  case True
  have p32: maxBalInp s (bal(dblock s p)) (inp(dblock s p))
  proof -
    have  $\neg(\exists D \in MajoritySet. \exists q. (\forall d \in D. bal(dblock\ s\ p) < mbal(disk\ s\ d\ q) \wedge$ 
 $\neg hasRead\ s\ p\ d\ q))$ 
    proof auto
      fix D q
      assume Dmaj:  $D \in MajoritySet$ 
      from ep2-maj Dmaj majorities-intersect
      have  $\exists d \in D. d \in disksWritten\ s\ p$ 
       $\wedge (\forall q \in UNIV - \{p\}. hasRead\ s\ p\ d\ q)$ 
      by(auto simp add: MajoritySet-def, blast)
      then obtain d
      where dinD:  $d \in D$ 
      and ddisk:  $d \in disksWritten\ s\ p$ 
      and dhasR:  $\forall q \in UNIV - \{p\}. hasRead\ s\ p\ d\ q$ 
      by auto
      from inv2b
      have Inv2b-inner s p d
      by(auto simp add: Inv2b-def)
      with ddisk
      have disk s d p = dblock s p
      by(auto simp add: Inv2b-inner-def)
      with inv2c phase
      have bal(dblock s p) = mbal(disk s d p)
      by(auto simp add: Inv2c-def Inv2c-inner-def)
      with dhasR dinD
      show  $\exists d \in D. bal(dblock\ s\ p) < mbal(disk\ s\ d\ q) \longrightarrow hasRead\ s\ p\ d\ q$ 
      by auto
    qed
  with inv5R
  show ?thesis
  by(auto simp add: HInv5-inner-R-def)
qed
have p33: maxBalInp s' (bal(dblock s' p)) (chosen s')
proof -
  from act
  have outpt': outpt s' = (outpt s) (p:= inp(dblock s p))
  by(auto simp add: EndPhase2-def)
  have outpt'-q:  $\forall q. p \neq q \longrightarrow outpt\ s'\ q = NotAnInput$ 
  proof auto
    fix q
    assume pnq:  $p \neq q$ 
    from outpt' pnq
    have outpt s' q = outpt s q
    by(auto simp add: EndPhase2-def)
    with True inv2c
  
```

```

    show outpt s' q = NotAnInput
      by(auto simp add: Inv2c-def Inv2c-inner-def)
  qed
  from True act chosen'
  have chosen s' = inp (dblock s p)
  proof(auto simp add: HNextPart-def split: if-split-asm)
    fix pa
    assume outpt'-pa: outpt s' pa ≠ NotAnInput
    from outpt'-q
    have someeq2: ∧pa. outpt s' pa ≠ NotAnInput ⇒ pa=p
      by auto
    with outpt'-pa
    have outpt s' p ≠ NotAnInput
      by auto
    from some-equality[of λp. outpt s' p ≠ NotAnInput, OF this someeq2]
    have (SOME p. outpt s' p ≠ NotAnInput) = p .
    with outpt'
    show outpt s' (SOME p. outpt s' p ≠ NotAnInput) = inp (dblock s p)
      by auto
  qed
  moreover
  from act
  have bal(dblock s' p) = bal(dblock s p)
    by(auto simp add: EndPhase2-def)
  ultimately
  have maxBalInp s (bal(dblock s' p)) (chosen s')
    using p32
    by auto
  with HEndPhase2-allBlocks[OF act]
  show ?thesis
    by(auto simp add: maxBalInp-def)
  qed
  from ep2-maj inv2b majorities-intersect
  have  $\exists D \in \text{MajoritySet}. (\forall d \in D. \text{disk } s \ d \ p = \text{dblock } s \ p$ 
     $\wedge (\forall q \in \text{UNIV} - \{p\}. \text{hasRead } s \ p \ d \ q))$ 
    by(auto simp add: Inv2b-def Inv2b-inner-def MajoritySet-def)
  then obtain D
    where Dmaj: D ∈ MajoritySet
    and p34: ∀ d ∈ D. disk s d p = dblock s p
     $\wedge (\forall q \in \text{UNIV} - \{p\}. \text{hasRead } s \ p \ d \ q)$ 
    by auto
  have p35: ∀ q. ∀ d ∈ D. ( phase s q = 1 ∧ bal(dblock s p) ≤ mbal(dblock s q) ∧ hasRead
s q d p)
     $\longrightarrow (\text{block} = \text{dblock } s \ p, \text{proc} = p) \in \text{blocksRead } s \ q \ d$ 
  proof auto
    fix q d
    assume dD: d ∈ D and phase-q: phase s q = Suc 0
    and bal-mbal: bal(dblock s p) ≤ mbal(dblock s q) and hasRead: hasRead s q d p
    from phase inv2c

```


have $bal(dblock\ s\ p) = mbal(dblock\ s\ p)$
by (*auto simp add: Inv2c-def Inv2c-inner-def*)
moreover
from *inv2c phase*
have $\forall br \in blocksRead\ s\ p\ d. mbal(block\ br) < mbal(dblock\ s\ p)$
by (*auto simp add: Inv2c-def Inv2c-inner-def*)
ultimately
have $p41: (\text{block} = dblock\ s\ q, \text{proc} = q) \notin blocksRead\ s\ p\ d$
using *bal-mbal*
by *auto*
from *phase phase-q*
have $p \neq q$ **by** *auto*
with $p34\ dD$
have $hasRead\ s\ p\ d\ q$
by *auto*
with *phase phase-q hasRead inv3 p41*
show $(\text{block} = dblock\ s\ p, \text{proc} = p) \in blocksRead\ s\ q\ d$
by (*auto simp add: HInv3-def HInv3-inner-def*
HInv3-L-def HInv3-R-def)
qed
have $p36: \forall q. \forall d \in D. phase\ s'\ q = 1 \wedge bal(dblock\ s\ p) \leq mbal(dblock\ s'\ q) \wedge$
 $hasRead\ s'\ q\ d\ p$
 $\longrightarrow (\exists br \in blocksRead\ s'\ q\ d. bal(block\ br) = bal(dblock\ s\ p))$
proof (*auto*)
fix $q\ d$
assume $dD: d \in D$ **and** *phase-q: phase s' q = Suc 0*
and $bal: bal(dblock\ s\ p) \leq mbal(dblock\ s'\ q)$
and $hasRead: hasRead\ s'\ q\ d\ p$
from *phase-q act*
have $phase\ s'\ q = phase\ s\ q \wedge dblock\ s'\ q = dblock\ s\ q \wedge hasRead\ s'\ q\ d\ p = hasRead$
 $s\ q\ d\ p \wedge blocksRead\ s'\ q\ d = blocksRead\ s\ q\ d$
by (*auto simp add: EndPhase2-def hasRead-def InitializePhase-def*)
with $p35\ phase-q\ bal\ hasRead\ dD$
have $(\text{block} = dblock\ s\ p, \text{proc} = p) \in blocksRead\ s'\ q\ d$
by *auto*
thus $\exists br \in blocksRead\ s'\ q\ d. bal(block\ br) = bal(dblock\ s\ p)$
by *force*
qed
hence $p36-2: \forall q. \forall d \in D. phase\ s'\ q = 1 \wedge bal(dblock\ s\ p) \leq mbal(dblock\ s'\ q) \wedge$
 $hasRead\ s'\ q\ d\ p$
 $\longrightarrow (\exists br \in blocksRead\ s'\ q\ d. bal(dblock\ s\ p) \leq bal(block\ br))$
by *force*
from *act*
have $bal-dblock: bal(dblock\ s'\ p) = bal(dblock\ s\ p)$
and $disk: disk\ s' = disk\ s$
by (*auto simp add: EndPhase2-def*)
from *bal-dblock p33*
have $maxBalInp\ s' (bal(dblock\ s\ p)) (chosen\ s')$
by *auto*

```

moreover
from disk p34
have  $\forall d \in D. \text{bal}(\text{dblock } s \ p) \leq \text{bal}(\text{disk } s' \ d \ p)$ 
  by auto
ultimately
have  $\text{maxBalInp } s' \ (\text{bal}(\text{dblock } s \ p)) \ (\text{chosen } s') \wedge$ 
   $(\exists D \in \text{MajoritySet}.$ 
     $\forall d \in D. \text{bal}(\text{dblock } s \ p) \leq \text{bal}(\text{disk } s' \ d \ p) \wedge$ 
     $(\forall q. \text{phase } s' \ q = \text{Suc } 0 \wedge$ 
       $\text{bal}(\text{dblock } s \ p) \leq \text{mbal}(\text{dblock } s' \ q) \wedge \text{hasRead } s' \ q \ d \ p \longrightarrow$ 
       $(\exists br \in \text{blocksRead } s' \ q \ d. \text{bal}(\text{dblock } s \ p) \leq \text{bal}(\text{block } br))))$ 
  using p36-2 Dmaj
  by auto
moreover
from phase inv2c
have  $\text{bal}(\text{dblock } s \ p) \in \text{Ballot } p$ 
  by (auto simp add: Inv2c-def Inv2c-inner-def)
ultimately
show ?thesis
  by (auto simp add: valueChosen-def)
next
case False
with act
have p31: chosen s' = chosen s
  by (auto simp add: HNextPart-def)
from False inv
have  $\text{valueChosen } s \ (\text{chosen } s)$ 
  by (auto simp add: HInv6-def)
from HEndPhase2-valueChosen[OF act this] p31 False InputsOrNi
show ?thesis
  by auto
qed

lemma valueChosen-equal-case:
assumes max-v: maxBalInp s b v
and Dmaj: D ∈ MajoritySet
and asm-v:  $\forall d \in D. b \leq \text{bal}(\text{disk } s \ d \ p)$ 
and max-w: maxBalInp s ba w
and Damaj: Da ∈ MajoritySet
and asm-w:  $\forall d \in Da. ba \leq \text{bal}(\text{disk } s \ d \ pa)$ 
and b-ba:  $b \leq ba$ 
shows v=w
proof –
have  $\forall d. \text{disk } s \ d \ pa \in \text{allBlocks } s$ 
  by (auto simp add: allBlocks-def blocksOf-def)
with majorities-intersect Dmaj Damaj
have  $\exists d \in D \cap Da. \text{disk } s \ d \ pa \in \text{allBlocks } s$ 
  by (auto simp add: MajoritySet-def, blast)
then obtain d

```

where $dinmaj$: $d \in D \cap Da$ **and** dab : $disk\ s\ d\ pa \in allBlocks\ s$
by *auto*
with *asm-w*
have ba : $ba \leq bal\ (disk\ s\ d\ pa)$
by *auto*
with *b-ba*
have $b \leq bal\ (disk\ s\ d\ pa)$
by *auto*
with *max-v dab*
have v -value: $inp\ (disk\ s\ d\ pa) = v$
by(*auto simp add: maxBalInp-def*)
from ba *max-w dab*
have w -value: $inp\ (disk\ s\ d\ pa) = w$
by(*auto simp add: maxBalInp-def*)
with v -value
show *?thesis* **by** *auto*
qed

lemma *valueChosen-equal*:
assumes v : *valueChosen* $s\ v$
and w : *valueChosen* $s\ w$
shows $v=w$ **using** *assms*
proof (*auto simp add: valueChosen-def*)
fix $a\ b\ aa\ ba\ p\ D\ pa\ Da$
assume max - v : *maxBalInp* $s\ b\ v$
and $Dmaj$: $D \in MajoritySet$
and asm - v : $\forall d \in D. b \leq bal\ (disk\ s\ d\ p) \wedge$
 $(\forall q. phase\ s\ q = Suc\ 0 \wedge$
 $b \leq mbal\ (dblock\ s\ q) \wedge hasRead\ s\ q\ d\ p \longrightarrow$
 $(\exists br \in blocksRead\ s\ q\ d. b \leq bal\ (block\ br)))$
and max - w : *maxBalInp* $s\ ba\ w$
and $Damaj$: $Da \in MajoritySet$
and asm - w : $\forall d \in Da. ba \leq bal\ (disk\ s\ d\ pa) \wedge$
 $(\forall q. phase\ s\ q = Suc\ 0 \wedge$
 $ba \leq mbal\ (dblock\ s\ q) \wedge hasRead\ s\ q\ d\ pa \longrightarrow$
 $(\exists br \in blocksRead\ s\ q\ d. ba \leq bal\ (block\ br)))$
from asm - v
have asm - v : $\forall d \in D. b \leq bal\ (disk\ s\ d\ p)$ **by** *auto*
from asm - w
have asm - w : $\forall d \in Da. ba \leq bal\ (disk\ s\ d\ pa)$ **by** *auto*
show $v=w$
proof(*cases* $b \leq ba$)
case *True*
from *valueChosen-equal-case*[*OF* max - $v\ Dmaj\ asm$ - $v\ max$ - $w\ Damaj\ asm$ - $w\ True$]
show *?thesis* .
next
case *False*
from *valueChosen-equal-case*[*OF* max - $w\ Damaj\ asm$ - $w\ max$ - $v\ Dmaj\ asm$ - v]
show *?thesis*

```

    by auto
  qed
qed

lemma HEndPhase2-Inv6-2:
  assumes act: HEndPhase2 s s' p
  and inv: HInv6 s
  and inv2b: Inv2b s
  and inv2c: Inv2c s
  and inv3: HInv3 s
  and inv5: HInv5-inner s p
  and asm: outpt s' r ≠ NotAnInput
  shows outpt s' r = chosen s'
proof(cases chosen s=NotAnInput)
  case True
  with inv2c
  have ∀ q. outpt s q = NotAnInput
    by(auto simp add: Inv2c-def Inv2c-inner-def)
  with True act asm
  show ?thesis
    by(auto simp add: EndPhase2-def HNextPart-def
      split: if-split-asm)
next
  case False
  with inv
  have p31: valueChosen s (chosen s)
    by(auto simp add: HInv6-def)
  with False act
  have chosen s' ≠ NotAnInput
    by(auto simp add: HNextPart-def)
  from HEndPhase2-Inv6-1[OF act inv inv2b inv2c inv3 inv5 this]
  have p32: valueChosen s'(chosen s') .
  from False InputsOrNi
  have chosen s ∈ Inputs by auto
  from valueChosen-equal[OF HEndPhase2-valueChosen[OF act p31 this] p32]
  have p33: chosen s = chosen s' .
  from act
  have maj: IsMajority {d . d ∈ disksWritten s p
    ∧ (∀ q ∈ UNIV - {p}. hasRead s p d q)} (is IsMajority ?D)
    and phase: phase s p = 2
    by(auto simp add: EndPhase2-def)
  show ?thesis
proof(cases outpt s r = NotAnInput)
  case True
  with asm act
  have p41: r=p
    by(auto simp add: EndPhase2-def split: if-split-asm)
  from maj
  have p42: ∃ D ∈ MajoritySet. ∀ d ∈ D. ∀ q ∈ UNIV - {p}. hasRead s p d q

```

```

    by(auto simp add: MajoritySet-def)
  have p43: ¬(∃ D∈MajoritySet. ∃ q. (∀ d∈D. bal(dblock s p) < mbal(disk s d
q)
    ∧ ¬hasRead s p d q))

proof auto
  fix D q
  assume Dmaj: D ∈ MajoritySet
  show ∃ d∈D. bal (dblock s p) < mbal (disk s d q) → hasRead s p d q
  proof(cases p=q)
    assume pq: p=q
    thus ?thesis
    proof auto
      from maj majorities-intersect Dmaj
      have ?D∩D≠{}
        by(auto simp add: MajoritySet-def)
      hence ∃ d∈?D∩D. d ∈ disksWritten s p by auto
      then obtain d where d: d ∈ disksWritten s p and d ∈ ?D∩D
        by auto
      hence dD: d ∈ D by auto
      from d inv2b
      have disk s d p = dblock s p
        by(auto simp add: Inv2b-def Inv2b-inner-def)
      with inv2c phase
      have bal(dblock s p) = mbal(disk s d p)
        by(auto simp add: Inv2c-def Inv2c-inner-def)
      with dD pq
      show ∃ d∈D. bal (dblock s q) < mbal (disk s d q) → hasRead s q d q
        by auto
    qed
  next
  case False
  with p42
  have ∃ D∈MajoritySet. ∀ d∈D. hasRead s p d q
    by auto
  with majorities-intersect Dmaj
  show ?thesis
    by(auto simp add: MajoritySet-def, blast)
  qed
  qed
  with inv5 act
  have p44: maxBalInp s (bal(dblock s p)) (inp(dblock s p))
    by(auto simp add: EndPhase2-def HInv5-inner-def
      HInv5-inner-R-def)
  have ∃ bk∈allBlocks s. ∃ b∈(UN p. Ballot p). (maxBalInp s b (chosen s)) ∧ b ≤
bal bk
  proof -
    have disk-allblks: ∀ d p. disk s d p ∈ allBlocks s
      by(auto simp add: allBlocks-def blocksOf-def)
    from p31

```

```

have  $\exists b \in (UN\ p.\ Ballot\ p).\ maxBalInp\ s\ b\ (chosen\ s) \wedge$ 
 $(\exists p.\ \exists D \in MajoritySet.\ (\forall d \in D.\ b \leq bal(disk\ s\ d\ p)))$ 
  by(auto simp add: valueChosen-def, force)
with majority-nonempty obtain  $b\ p\ D\ d$ 
  where  $IsMajority\ D \wedge b \in (UN\ p.\ Ballot\ p) \wedge$ 
 $maxBalInp\ s\ b\ (chosen\ s) \wedge d \in D \wedge b \leq bal(disk\ s\ d\ p)$ 
  by(auto simp add: MajoritySet-def, blast)
with disk-allblks
show ?thesis
  by(auto)
qed
then obtain  $bk\ b$ 
  where  $p_{45}\text{-}bk: bk \in allBlocks\ s \wedge b \leq bal\ bk$ 
  and  $p_{45}\text{-}b: b \in (UN\ p.\ Ballot\ p) \wedge (maxBalInp\ s\ b\ (chosen\ s))$ 
  by auto
have  $p_{46}: inp(dblock\ s\ p) = chosen\ s$ 
proof(cases  $b \leq bal(dblock\ s\ p)$ )
  case True
    have  $dblock\ s\ p \in allBlocks\ s$ 
      by(auto simp add: allBlocks-def blocksOf-def)
    with  $p_{45}\text{-}b$  True
    show ?thesis
      by(auto simp add: maxBalInp-def)
  next
    case False
    from  $p_{44}\ p_{45}\text{-}bk$  False
    have  $inp\ bk = inp(dblock\ s\ p)$ 
      by(auto simp add: maxBalInp-def)
    with  $p_{45}\text{-}b\ p_{45}\text{-}bk$ 
    show ?thesis
      by(auto simp add: maxBalInp-def)
  qed
with  $p_{41}\ p_{33}$  act
show ?thesis
  by(auto simp add: EndPhase2-def)
next
  case False
  from inv2c
  have  $Inv2c\text{-}inner\ s\ r$ 
    by(auto simp add: Inv2c-def)
  with False asm inv2c act
  have  $outpt\ s'\ r = outpt\ s\ r$ 
    by(auto simp add: Inv2c-inner-def EndPhase2-def
      split: if-split-asm)
  with inv p33 False
  show ?thesis
    by(auto simp add: HInv6-def)
qed
qed

```

theorem *HEndPhase2-Inv6*:
assumes *act: HEndPhase2 s s' p*
and *inv: HInv6 s*
and *inv2b: Inv2b s*
and *inv2c: Inv2c s*
and *inv3: HInv3 s*
and *inv5: HInv5-inner s p*
shows *HInv6 s'*
proof(*auto simp add: HInv6-def*)
assume *chosen s' ≠ NotAnInput*
from *HEndPhase2-Inv6-1[OF act inv inv2b inv2c inv3 inv5 this]*
show *valueChosen s' (chosen s')* .
next
fix *p*
assume *outpt s' p ≠ NotAnInput*
from *HEndPhase2-Inv6-2[OF act inv inv2b inv2c inv3 inv5 this]*
show *outpt s' p = chosen s'* .
qed

lemma *outpt-chosen*:
assumes *outpt: outpt s = outpt s'*
and *inv2c: Inv2c s*
and *nextp: HNextPart s s'*
shows *chosen s' = chosen s*
proof –
from *inv2c*
have *chosen s = NotAnInput* \longrightarrow $(\forall p. outpt s p = NotAnInput)$
by(*auto simp add: Inv2c-inner-def Inv2c-def*)
with *outpt nextp*
show *?thesis*
by(*auto simp add: HNextPart-def*)
qed

lemma *outpt-Inv6*:
 $\llbracket outpt s = outpt s'; \forall p. outpt s p \in \{chosen s, NotAnInput\};$
 $Inv2c s; HNextPart s s' \rrbracket \implies \forall p. outpt s' p \in \{chosen s', NotAnInput\}$
using *outpt-chosen*
by *auto*

theorem *HStartBallot-Inv6*:
assumes *act: HStartBallot s s' p*
and *inv: HInv6 s*
and *inv2c: Inv2c s*
shows *HInv6 s'*
proof –
from *outpt-chosen act inv2c inv*
have *chosen s' ≠ NotAnInput* \longrightarrow *valueChosen s (chosen s')*
by(*auto simp add: StartBallot-def HInv6-def*)

```

from HStartBallot-valueChosen[OF act] this InputsOrNi
have t1: chosen s' ≠ NotAnInput  $\longrightarrow$  valueChosen s' (chosen s')
  by auto
from act
have outpt: outpt s = outpt s'
  by(auto simp add: StartBallot-def)
from outpt-Inv6[OF outpt] act inv2c inv
have  $\forall p. outpt s' p = chosen s' \vee outpt s' p = NotAnInput$ 
  by(auto simp add: HInv6-def)
with t1
show ?thesis
  by(simp add: HInv6-def)
qed

```

theorem *HPhase1or2Write-Inv6*:

```

assumes act: HPhase1or2Write s s' p d
and inv: HInv6 s
and inv4: HInv4a s p
and inv2c: Inv2c s
shows HInv6 s'

```

proof –

```

from outpt-chosen act inv2c inv
have chosen s' ≠ NotAnInput  $\longrightarrow$  valueChosen s (chosen s')
  by(auto simp add: Phase1or2Write-def HInv6-def)
from HPhase1or2Write-valueChosen[OF act] inv4 this InputsOrNi
have t1: chosen s' ≠ NotAnInput  $\longrightarrow$  valueChosen s' (chosen s')
  by auto
from act
have outpt: outpt s = outpt s'
  by(auto simp add: Phase1or2Write-def)
from outpt-Inv6[OF outpt] act inv2c inv
have  $\forall p. outpt s' p = chosen s' \vee outpt s' p = NotAnInput$ 
  by(auto simp add: HInv6-def)
with t1
show ?thesis
  by(simp add: HInv6-def)
qed

```

theorem *HPhase1or2ReadThen-Inv6*:

```

assumes act: HPhase1or2ReadThen s s' p d q
and inv: HInv6 s
and inv2c: Inv2c s
shows HInv6 s'

```

proof –

```

from outpt-chosen act inv2c inv
have chosen s' ≠ NotAnInput  $\longrightarrow$  valueChosen s (chosen s')
  by(auto simp add: Phase1or2ReadThen-def HInv6-def)
from HPhase1or2ReadThen-valueChosen[OF act] this InputsOrNi
have t1: chosen s' ≠ NotAnInput  $\longrightarrow$  valueChosen s' (chosen s')

```


by *auto*
 from *act*
 have *outpt*: $outpt\ s = outpt\ s'$
 by(*auto simp add: Phase1or2ReadThen-def*)
 from *outpt-Inv6*[*OF outpt*] *act inv2c inv*
 have $\forall p. outpt\ s'\ p = chosen\ s' \vee outpt\ s'\ p = NotAnInput$
 by(*auto simp add: HInv6-def*)
 with *t1*
 show *?thesis*
 by(*simp add: HInv6-def*)
 qed

theorem *HPhase1or2ReadElse-Inv6*:
 assumes *act*: *HPhase1or2ReadElse* *s s' p d q*
 and *inv*: *HInv6* *s*
 and *inv2c*: *Inv2c* *s*
 shows *HInv6* *s'*
 using *assms* and *HStartBallot-Inv6*
 by(*auto simp add: Phase1or2ReadElse-def*)

theorem *HEndPhase1-Inv6*:
 assumes *act*: *HEndPhase1* *s s' p*
 and *inv*: *HInv6* *s*
 and *inv1*: *Inv1* *s*
 and *inv2a*: *Inv2a* *s*
 and *inv2b*: *Inv2b* *s*
 and *inv2c*: *Inv2c* *s*
 shows *HInv6* *s'*

proof –
 from *outpt-chosen* *act inv2c inv*
 have $chosen\ s' \neq NotAnInput \longrightarrow valueChosen\ s\ (chosen\ s')$
 by(*auto simp add: EndPhase1-def HInv6-def*)
 from *HEndPhase1-valueChosen*[*OF act*] *inv1 inv2a inv2b this InputsOrNi*
 have *t1*: $chosen\ s' \neq NotAnInput \longrightarrow valueChosen\ s'\ (chosen\ s')$
 by *auto*
 from *act*
 have *outpt*: $outpt\ s = outpt\ s'$
 by(*auto simp add: EndPhase1-def*)
 from *outpt-Inv6*[*OF outpt*] *act inv2c inv*
 have $\forall p. outpt\ s'\ p = chosen\ s' \vee outpt\ s'\ p = NotAnInput$
 by(*auto simp add: HInv6-def*)
 with *t1*
 show *?thesis*
 by(*simp add: HInv6-def*)
 qed

lemma *outpt-chosen-2*:
 assumes *outpt*: $outpt\ s' = (outpt\ s)\ (p := NotAnInput)$
 and *inv2c*: *Inv2c* *s*

and $nextp: HNextPart\ s\ s'$
shows $chosen\ s = chosen\ s'$
proof –
from $inv2c$
have $chosen\ s = NotAnInput \longrightarrow (\forall p. outpt\ s\ p = NotAnInput)$
by($auto\ simp\ add: Inv2c\text{-inner-def}\ Inv2c\text{-def}$)
with $outpt\ nextp$
show $?thesis$
by($auto\ simp\ add: HNextPart\text{-def}$)
qed

lemma $outpt\ HInv6\text{-2}$:
assumes $outpt: outpt\ s' = (outpt\ s)\ (p:= NotAnInput)$
and $inv: \forall p. outpt\ s\ p \in \{chosen\ s, NotAnInput\}$
and $inv2c: Inv2c\ s$
and $nextp: HNextPart\ s\ s'$
shows $\forall p. outpt\ s'\ p \in \{chosen\ s', NotAnInput\}$
proof –
from $outpt\text{-chosen-2}[OF\ outpt\ inv2c\ nextp]$
have $chosen\ s = chosen\ s'$.
with $inv\ outpt$
show $?thesis$
by $auto$
qed

theorem $HFail\text{-Inv6}$:
assumes $act: HFail\ s\ s'\ p$
and $inv: HInv6\ s$
and $inv2c: Inv2c\ s$
shows $HInv6\ s'$
proof –
from $outpt\text{-chosen-2}\ act\ inv2c\ inv$
have $chosen\ s' \neq NotAnInput \longrightarrow valueChosen\ s\ (chosen\ s')$
by($auto\ simp\ add: Fail\text{-def}\ HInv6\text{-def}$)
from $HFail\text{-valueChosen}[OF\ act]\ this\ InputsOrNi$
have $t1: chosen\ s' \neq NotAnInput \longrightarrow valueChosen\ s'\ (chosen\ s')$
by $auto$
from act
have $outpt: outpt\ s' = (outpt\ s)\ (p:=NotAnInput)$
by($auto\ simp\ add: Fail\text{-def}$)
from $outpt\text{-HInv6-2}[OF\ outpt]\ act\ inv2c\ inv$
have $\forall p. outpt\ s'\ p = chosen\ s' \vee outpt\ s'\ p = NotAnInput$
by($auto\ simp\ add: HInv6\text{-def}$)
with $t1$
show $?thesis$
by($simp\ add: HInv6\text{-def}$)
qed

theorem $HPhase0Read\text{-Inv6}$:

assumes $act: HPhase0Read\ s\ s'\ p\ d$
and $inv: HInv6\ s$
and $inv2c: Inv2c\ s$
shows $HInv6\ s'$
proof –
from $outpt\text{-}chosen\ act\ inv2c\ inv$
have $chosen\ s' \neq NotAnInput \longrightarrow valueChosen\ s\ (chosen\ s')$
by($auto\ simp\ add: Phase0Read\text{-}def\ HInv6\text{-}def$)
from $HPhase0Read\text{-}valueChosen[OF\ act]\ this\ InputsOrNi$
have $t1: chosen\ s' \neq NotAnInput \longrightarrow valueChosen\ s'\ (chosen\ s')$
by $auto$
from act
have $outpt: outpt\ s = outpt\ s'$
by($auto\ simp\ add: Phase0Read\text{-}def$)
from $outpt\text{-}Inv6[OF\ outpt]\ act\ inv2c\ inv$
have $\forall p. outpt\ s'\ p = chosen\ s' \vee outpt\ s'\ p = NotAnInput$
by($auto\ simp\ add: HInv6\text{-}def$)
with $t1$
show $?thesis$
by($simp\ add: HInv6\text{-}def$)
qed

theorem $HEndPhase0\text{-}Inv6$:
assumes $act: HEndPhase0\ s\ s'\ p$
and $inv: HInv6\ s$
and $inv1: Inv1\ s$
and $inv2c: Inv2c\ s$
shows $HInv6\ s'$
proof –
from $outpt\text{-}chosen\ act\ inv2c\ inv$
have $chosen\ s' \neq NotAnInput \longrightarrow valueChosen\ s\ (chosen\ s')$
by($auto\ simp\ add: EndPhase0\text{-}def\ HInv6\text{-}def$)
from $HEndPhase0\text{-}valueChosen[OF\ act]\ inv1\ this\ InputsOrNi$
have $t1: chosen\ s' \neq NotAnInput \longrightarrow valueChosen\ s'\ (chosen\ s')$
by $auto$
from act
have $outpt: outpt\ s = outpt\ s'$
by($auto\ simp\ add: EndPhase0\text{-}def$)
from $outpt\text{-}Inv6[OF\ outpt]\ act\ inv2c\ inv$
have $\forall p. outpt\ s'\ p = chosen\ s' \vee outpt\ s'\ p = NotAnInput$
by($auto\ simp\ add: HInv6\text{-}def$)
with $t1$
show $?thesis$
by($simp\ add: HInv6\text{-}def$)
qed

$HInv1 \wedge HInv2 \wedge HInv2' \wedge HInv3 \wedge HInv4 \wedge HInv5 \wedge HInv6$ is an invariant of $HNext$.

lemma $I2f$:

```

assumes next: HNext s s'
and inv: HInv1 s  $\wedge$  HInv2 s  $\wedge$  HInv2 s'  $\wedge$  HInv3 s  $\wedge$  HInv4 s  $\wedge$  HInv5 s  $\wedge$  HInv6
s
shows HInv6 s' using assms
by(auto simp add: HNext-def Next-def,
    auto simp add: HInv2-def intro: HStartBallot-Inv6,
    auto intro: HPhase0Read-Inv6,
    auto simp add: HInv4-def intro: HPhase1or2Write-Inv6,
    auto simp add: Phase1or2Read-def
    intro: HPhase1or2ReadThen-Inv6
    HPhase1or2ReadElse-Inv6,
    auto simp add: EndPhase1or2-def HInv1-def HInv5-def
    intro: HEndPhase1-Inv6
    HEndPhase2-Inv6,
    auto intro: HFail-Inv6,
    auto intro: HEndPhase0-Inv6)

end

```

```

theory DiskPaxos-Invariant imports DiskPaxos-Inv6 begin

```

C.8 The Complete Invariant

```

definition HInv :: state  $\Rightarrow$  bool

```

```

where

```

```

HInv s = (HInv1 s
     $\wedge$  HInv2 s
     $\wedge$  HInv3 s
     $\wedge$  HInv4 s
     $\wedge$  HInv5 s
     $\wedge$  HInv6 s)

```

```

theorem I1:

```

```

HInit s  $\Longrightarrow$  HInv s
using HInit-HInv1 HInit-HInv2 HInit-HInv3
    HInit-HInv4 HInit-HInv5 HInit-HInv6
by(auto simp add: HInv-def)

```

```

theorem I2:

```

```

assumes inv: HInv s
and next: HNext s s'
shows HInv s'
using inv I2a[OF next] I2b[OF next] I2c[OF next]
    I2d[OF next] I2e[OF next] I2f[OF next]
by(simp add: HInv-def)

```

```

end

```

theory *DiskPaxos* **imports** *DiskPaxos-Invariant* **begin**

C.9 Inner Module

record

Istate =
iinput :: *Proc* \Rightarrow *InputsOrNi*
ioutput :: *Proc* \Rightarrow *InputsOrNi*
ichosen :: *InputsOrNi*
iallInput :: *InputsOrNi* set

definition *IInit* :: *Istate* \Rightarrow *bool*

where

$$\begin{aligned} IInit\ s = & \text{ (range (iinput } s) \subseteq Inputs \\ & \wedge ioutput\ s = (\lambda p. NotAnInput) \\ & \wedge ichosen\ s = NotAnInput \\ & \wedge iallInput\ s = range (iinput\ s)) \end{aligned}$$

definition *IChoose* :: *Istate* \Rightarrow *Istate* \Rightarrow *Proc* \Rightarrow *bool*

where

$$\begin{aligned} IChoose\ s\ s'\ p = & \text{ (ioutput } s\ p = NotAnInput \\ & \wedge \text{ (if (ichosen } s = NotAnInput) \\ & \quad \text{then } (\exists ip \in iallInput\ s. ichosen\ s' = ip \\ & \quad \quad \wedge ioutput\ s' = (ioutput\ s)\ (p := ip)) \\ & \quad \text{else (ioutput } s' = (ioutput\ s)\ (p := ichosen\ s) \\ & \quad \quad \wedge ichosen\ s' = ichosen\ s)) \\ & \wedge iinput\ s' = iinput\ s \wedge iallInput\ s' = iallInput\ s) \end{aligned}$$

definition *IFail* :: *Istate* \Rightarrow *Istate* \Rightarrow *Proc* \Rightarrow *bool*

where

$$\begin{aligned} IFail\ s\ s'\ p = & \text{ (ioutput } s' = (ioutput\ s)\ (p := NotAnInput) \\ & \wedge (\exists ip \in Inputs. iinput\ s' = (iinput\ s)\ (p := ip) \\ & \quad \wedge iallInput\ s' = iallInput\ s \cup \{ip\}) \\ & \wedge ichosen\ s' = ichosen\ s) \end{aligned}$$

definition *INext* :: *Istate* \Rightarrow *Istate* \Rightarrow *bool*

where *INext* *s* *s'* = $(\exists p. IChoose\ s\ s'\ p \vee IFail\ s\ s'\ p)$

definition *s2is* :: *state* \Rightarrow *Istate*

where

$$\begin{aligned} s2is\ s = & \text{ (iinput = inpt } s, \\ & \text{ ioutput = outpt } s, \\ & \text{ ichosen = chosen } s, \\ & \text{ iallInput = allInput } s) \end{aligned}$$

theorem *R1*:

$[[\ HInit\ s; is = s2is\ s]] \implies IInit\ is$

by(*auto simp add: HInit-def IInit-def s2is-def Init-def*)

theorem R2b:

assumes *inv: HInv s*

and *inv': HInv s'*

and *nxt: HNext s s'*

and *srel: is=s2is s \wedge is'=s2is s'*

shows $(\exists p. IFail\ is\ is'\ p \vee IChoose\ is\ is'\ p) \vee is = is'$

proof(*auto*)

assume *chg-vars: is \neq is'*

with *srel*

have *s-change: inpt s \neq inpt s' \vee outpt s \neq outpt s'*
 \vee *chosen s \neq chosen s' \vee allInput s \neq allInput s'*

by(*auto simp add: s2is-def*)

from *inv*

have *inv2c5: $\forall p. inpt\ s\ p \in allInput\ s$*
 \wedge *(chosen s = NotAnInput \longrightarrow outpt s p = NotAnInput)*

by(*auto simp add: HInv-def HInv2-def Inv2c-def Inv2c-inner-def*)

from *nxt s-change inv2c5*

have *inpt s' \neq inpt s \vee outpt s' \neq outpt s*

by(*auto simp add: HNext-def Next-def HNextPart-def*)

with *nxt*

have $\exists p. Fail\ s\ s'\ p \vee EndPhase2\ s\ s'\ p$

by(*auto simp add: HNext-def Next-def*

StartBallot-def Phase0Read-def Phase1or2Write-def

Phase1or2Read-def Phase1or2ReadThen-def Phase1or2ReadElse-def

EndPhase1or2-def EndPhase1-def EndPhase0-def)

then obtain *p where fail-or-endphase2: Fail s s' p \vee EndPhase2 s s' p*

by *auto*

from *inv*

have *inv2c: Inv2c-inner s p*

by(*auto simp add: HInv-def HInv2-def Inv2c-def*)

from *fail-or-endphase2* **have** *IFail is is' p \vee IChoose is is' p*

proof

assume *fail: Fail s s' p*

hence *phase': phase s' p = 0*

and *outpt: outpt s' = (outpt s) (p:= NotAnInput)*

by(*auto simp add: Fail-def*)

have *IFail is is' p*

proof –

from *fail srel*

have *ioutput is' = (ioutput is) (p:= NotAnInput)*

by(*auto simp add: Fail-def s2is-def*)

moreover

from *nxt*

have *all-nxt: allInput s' = allInput s \cup (range (inpt s'))*

by(*auto simp add: HNext-def HNextPart-def*)

from *fail srel*

have $\exists ip \in Inputs. iinput\ is' = (iinput\ is)(p:= ip)$

```

    by(auto simp add: Fail-def s2is-def)
  then obtain ip where ip-Input: ip∈Inputs and iinput is' = (iinput is)(p:=
ip)
    by auto
  with inv2c5 srel all-nxt
  have iinput is' = (iinput is)(p:= ip)
    ∧ iallInput is' = iallInput is ∪ {ip}
    by(auto simp add: s2is-def)
  moreover
  from outpt srel nxt inv2c
  have ichosen is' = ichosen is
    by(auto simp add: HNext-def HNextPart-def s2is-def Inv2c-inner-def)
  ultimately
  show ?thesis
    using ip-Input
    by(auto simp add: IFail-def)
qed
thus ?thesis
  by auto
next
assume endphase2: EndPhase2 s s' p
from endphase2
have phase s p = 2
  by(auto simp add: EndPhase2-def)
with inv2c Ballot-nzero
have bal-dblk-nzero: bal(dblock s p) ≠ 0
  by(auto simp add: Inv2c-inner-def)
moreover
from inv
have inv2a-dblock: Inv2a-innermost s p (dblock s p)
  by(auto simp add: HInv-def HInv2-def Inv2a-def Inv2a-inner-def blocksOf-def)
ultimately
have p22: inp (dblock s p) ∈ allInput s
  by(auto simp add: Inv2a-innermost-def)
from inv
have allInput s ⊆ Inputs
  by(auto simp add: HInv-def HInv1-def)
with p22 NotAnInput endphase2
have outpt-nni: outpt s' p ≠ NotAnInput
  by(auto simp add: EndPhase2-def)
show ?thesis
proof(cases chosen s = NotAnInput)
  case True
  with inv2c5
  have p31: ∀ q. outpt s q = NotAnInput
    by auto
  with endphase2
  have p32: ∀ q ∈ UNIV -{p}. outpt s' q = NotAnInput
    by(auto simp add: EndPhase2-def)

```

```

hence some-eq: ( $\bigwedge x. \text{outpt } s' x \neq \text{NotAnInput} \implies x = p$ )
  by auto
from p32 True nst some-equality[of  $\lambda p. \text{outpt } s' p \neq \text{NotAnInput}, \text{OF } \text{outpt-nni}$ 
some-eq]
  have p33: chosen  $s' = \text{outpt } s' p$ 
    by(auto simp add: HNext-def HNextPart-def)
  with endphase2
  have chosen  $s' = \text{inp}(\text{dblock } s p) \wedge \text{outpt } s' = (\text{outpt } s)(p := \text{inp}(\text{dblock } s p))$ 
    by(auto simp add: EndPhase2-def)
  with True p22
  have if (chosen  $s = \text{NotAnInput}$ )
    then ( $\exists ip \in \text{allInput } s. \text{chosen } s' = ip$ 
       $\wedge \text{outpt } s' = (\text{outpt } s) (p := ip)$ )
    else ( $\text{outpt } s' = (\text{outpt } s) (p := \text{chosen } s)$ 
       $\wedge \text{chosen } s' = \text{chosen } s$ )

    by auto
  moreover
from endphase2 inv2c5 nst
have inpt  $s' = \text{inpt } s \wedge \text{allInput } s' = \text{allInput } s$ 
  by(auto simp add: EndPhase2-def HNext-def HNextPart-def)
ultimately
show ?thesis
  using srel p31
  by(auto simp add: IChoose-def s2is-def)
next
case False
with nst
have p31: chosen  $s' = \text{chosen } s$ 
  by(auto simp add: HNext-def HNextPart-def)
from inv'
have inv6: HInv6  $s'$ 
  by(auto simp add: HInv-def)
have p32: outpt  $s' p = \text{chosen } s$ 
proof-
  from endphase2
  have outpt  $s' p = \text{inp}(\text{dblock } s p)$ 
    by(auto simp add: EndPhase2-def)
  moreover
from inv6 p31
have outpt  $s' p \in \{\text{chosen } s, \text{NotAnInput}\}$ 
  by(auto simp add: HInv6-def)
ultimately
show ?thesis
  using outpt-nni
  by auto
qed
from srel False
have IChoose is is' p
proof(clarsimp simp add: IChoose-def s2is-def)

```



```

from endphase2 inv2c
have outpt s p = NotAnInput
  by(auto simp add: EndPhase2-def Inv2c-inner-def)
moreover
from endphase2 p31 p32 False
have outpt s' = (outpt s) (p := chosen s) ∧ chosen s' = chosen s
  by(auto simp add: EndPhase2-def)
moreover
from endphase2 nxt inv2c5
have inpt s' = inpt s ∧ allInput s' = allInput s
  by(auto simp add: EndPhase2-def HNext-def HNextPart-def)
ultimately
show outpt s p = NotAnInput
   $\wedge$  outpt s' = (outpt s)(p := chosen s) ∧ chosen s' = chosen s
   $\wedge$  inpt s' = inpt s ∧ allInput s' = allInput s
  by auto
qed
thus ?thesis
  by auto
qed
qed
thus  $\exists p. IFail\ is\ is'\ p \vee IChoose\ is\ is'\ p$ 
  by auto
qed
end

```