Brief Announcement: What's Live? Understanding Distributed Consensus

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ABSTRACT

Distributed consensus algorithms such as Paxos have been studied extensively. Many different liveness properties and assumptions have been stated for them, but there are no systematic comparisons for better understanding of these properties.

This paper systematically studies and compares different liveness properties stated for over 30 prominent consensus algorithms and variants. We introduced a precise high-level language and formally specified these properties in the language. We then create a hierarchy of liveness properties combining two hierarchies of the assumptions used and a hierarchy of the assertions made, and compare the strengths and weaknesses of algorithms that ensure these properties. Our formal specifications and systematic comparisons led to the discovery of a range of problems in various stated liveness properties. We also developed TLA+ specifications of these liveness properties, and we used model checking of execution steps to illustrate liveness patterns for Paxos.

CCS CONCEPTS

• **Computing methodologies** → **Distributed computing methodologies**.

KEYWORDS

distributed consensus, liveness

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The full version of this paper is available at [10].

1 INTRODUCTION

Distributed consensus is a fundamental problem in distributed systems. Many algorithms and variations have been created for distributed consensus. These algorithms are required to be safe in that only a single value or a single sequence of values have been agreed on at any time, and the value or values agreed on are among the values proposed by the processes.

However, liveness of these algorithms—certain desired progress has been made in reaching agreement—has many variations and lacks systematic comparisons. Furthermore, it is sometimes unclear or ambiguous what exactly liveness means for these algorithms.

This paper considers the most prominent consensus algorithms and variants listed in Table 1 and presents our results from precisely specifying, comparing, and analyzing their liveness properties that are stated in the literature, including the assumptions under which the properties are satisfied. We categorize the assumptions into (1) link assumptions, i.e., what is assumed about the communication links, and (2) server assumptions, i.e., what is assumed about the servers in the system. We relate different assumptions and assertions by creating three hierarchies. Together they form an overall hierarchy of liveness properties, which includes all the liveness properties stated for the algorithms and variants considered.

We introduced a precise high-level language and formally specified all these assumptions and assertions. In fact, it was the precise language and formal specifications that allowed us to establish the precise relationships among all the assumptions and assertions. The overall hierarchy not only helps in understanding liveness, but also helps in finding tighter results. It led us to the discovery of a range of problems in various stated liveness properties, from lacking assumptions or too weak assumptions under which no liveness assertions can hold, to too strong assumptions making it trivial or uninteresting to satisfy the liveness assertions. For example,

- EPaxos [36] assumes that eventually, there is always some quorum of servers that is non-faulty (what we call **Alw-Q**), but this is too weak, because each such quorum might not stay non-faulty long enough to make progress.
- Zab [20], Paxso-EPR [39], and some others assume that eventually, there is a server P and a quorum Q of servers, such that always, P is non-faulty and is the primary and Q is non-faulty (what we call **PQ-Alw**). Such strong assumptions make it trivial to reach consensus.

This also led to the question of what the right liveness properties are. In fact, many protocols assert stronger properties than necessary.

2 CONSENSUS PROBLEM AND ALGORITHMS

A distributed system is a set of processes each operating on its local data and communicating with other processes by sending and receiving messages. A process may crash and may later recover, and a message may be lost, delayed, put out of order, or duplicated. A process is said to be *non-faulty* if "it eventually performs the actions that it should, such as responding to messages" [30].

The basic consensus problem, called single-value consensus, is to ensure that a single value is chosen by non-faulty processes

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from among the set of values proposed by the processes. The more general consensus problem, called multi-value consensus, is to choose a single sequence of values, instead of a single value.

We identify two types of processes: *servers* execute some consensus algorithm and together provide consensus as a service, and *clients* use this service. For multi-value consensus, clients send values to servers for them to order, and each server maintains a *log*, i.e., a sequence of chosen values, with indices called *slots*.

A server is said to be *primary* if it is explicitly elected by the algorithm to be the single primary or leader among all servers in the system. In general, the defining property of the primary is that it is the only server that can propose values to other servers. Note that some consensus algorithms do not use a primary.

A *quorum system Qs* is a set of subsets, called quorums, of servers such that any two quorums overlap. A quorum is said to be *non-faulty* if each server in it is non-faulty, and *faulty* otherwise.

Table 1 shows the algorithms and variants studied in five groups:

(1) algorithms based on Virtual Synchrony [6], the first algorithm for reliable group communication using broadcast primitives.
(2) an algorithm and variant called Viewstamped Replication [37], the earliest that has a primary-backup architecture.
(3) an algorithm and three core variants in the Paxos [28] family, the earliest algorithm based on symmetric leader election.
(4) two single-value consensus algorithms with failure detection, for crash failure model and crash-recover failure model.
(5) other algorithm variations, where the earliest (14-15) and latest (25-31) are specified formally, in languages with automated checking, and with proof support or compilation and execution.

In essence, all algorithms in Table 1 are quorum-based and run in *rounds*. A round is identified by a unique number, and is started by at most one server. Multiple rounds may run simultaneously.

- A server initiates a new round once it thinks that the current round has died, i.e., stopped making progress. Different algorithms use different conditions to decide this.
- A server *learns* a value upon either receiving *votes* from a quorum of servers for that value in some round or a message from some other server informing it about the value learned.
- If the server is maintaining a state machine, it then *executes* the learned value on the state machine.
- The *result* of executing a value is sent to the client as a *response* to the value it initially *requested*.

3 LIVENESS SPECIFICATION AND HIERARCHY

Table 2 shows the total order of link assumptions, in increasing strength from top to bottom. Figure 1 shows the hierarchies for server assumptions and liveness assertions. An arrow from node A to node B denotes that A implies B; we say that A is *stronger* than B. These assumptions and assertions are summarized below.

Link assumptions.

(1) **Raw**: messages sent may or may not be received.
(2) **Fair**: all links between servers are *fair*, that is "if a correct process repeatedly sends a message to another correct process, at least one copy is eventually delivered" [40].
(3) **Sure**: the time between a message being sent and the message being received has a known upper bound.

	Name	Description	Language used
1	VS-ISIS	Reliable group communication, Birman-Joseph 1987 [7]	English (items)
2	VS-ISIS2	Virtual synchrony, Birman-Joseph 1987 [6]	English
3	EVS	Extended virtual synchrony for network partition, Amir et al 1995 [2, 3]	pseudocode
4	Paxos-VS	Virtually synchronous Paxos, Birman-Malkhi-van Renesse 2012 [8]	pseudocode
5	Derecho	Virtually synchronous state machine replication, Jha et al 2019 [19]	pseudocode
6	VR	Viewstamped replication, Oki-Liskov 1988 [37]	pseudocode (coarse)
7	VR-Revisit	VR revisited, Liskov 2012 [32]	English (items)
8	Paxos-Synod	Paxos in part-time parliament, Lamport 1998 [28]	TLA (single-value)
9	Paxos-Basic	Single-value Paxos, Lamport 2001 [29]	English (items)
10	Paxos-Fast	Single-value Paxos with replicas proposing, Lamport 2006 [30]	English (items), TLA+
11	Paxos-Vertical	Single-value Paxos with external starting of leader election, Lamport-Malkhi-Zhou 2009 [31]	PlusCal
12	CT	Single-value consensus with crash failures, Chandra-Toueg 1996 [13]	pseudocode
13	ACT	Single-value consensus in crash-recovery model, Aguilera-Chen-Toueg 2000 [1]	pseudocode
14	Paxos-Time	Paxos with time analysis, De Prisco-Lampson-Lynch 2001 [14]	IOA (single-value)
15	Paxos-PVS	Single-value Paxos for proof, Kellomäki 2004 [25]	PVS
16	Chubby	Paxos in Google's Chubby lock service, Burrows 2006 [9]	English (partial items)
17	Chubby-Live	Chubby in Paxos made live, Chandra-Griesemer-Redstone 2007 [12]	English
18	Paxos-SB	Paxos for system builders, Kirsch-Amir 2008 [27]	pseudocode
19	Mencius	Paxos with leaders proposing in turn, Mao et al 2008 [34]	English (items)
20	Zab	Yahoo/Apache's Zookeeper atomic broadcast, Junqueira-Reed-Serafini 2011 [20]	English (items)
21	Zab-FLE	Zab with fast leader election, Medeiros 2012 [35]	pseudocode
22	EPaxos	Egalitarian Paxos, Moraru-Andersen-Kaminsky 2013 [36]	pseudocode
23	Raft	Consensus in RAMCloud, Ongaro-Ousterhout 2014 [38]	pseudocode
24	Paxos-Complex	Paxos made moderately complex, van Renesse-Altinbuken 2015 [40]	pseudocode, Python
25	IronRSL	Paxos in Microsoft's IronFleet for proof, Hawblitzel et al 2015 [18]	Dafny
26	Paxos-TLA	Paxos for proof using TLAPS, Chand-Liu-Stoller 2016 [11]	TLA+
27	LastVoting-PSync	Single-value Paxos in Heard-Of model for proof, Drăgoi-Henzinger-Zufferey 2016 [15]	PSync
28	Raft-Verdi	Raft for proof using Coq, Wilcox-Sergey-Tatlock 2017 [41]	Verdi
29	Paxos-EPR	Paxos in effectively propositional logic for proof, Padon et al 2017 [39]	Ivy
30	Paxos-Decon	Paxos deconstructed, Garcia et al 2018 [16, 17]	Scala/Akka
31	Paxos-High	Paxos in high-level executable specification, Liu-Chand-Stoller 2019 [33]	DistAlgo

Table 1: Distributed consensus algorithms and variants, and languages used to express them.

Asm	Algorithms and Variants
Raw	VS-ISIS, VS-ISIS2, Derecho, VR, VR-Revisit, Paxos-Basic, Paxos-Vertical, Paxos-PVS, Chubby, Zab-FLE, Raft, Paxos-TLA, Raft-Verdi, Paxos-Decon, Paxos-High
Fair	EVS, Paxos-VS, Paxos-Fast, CT, ACT, Paxos-SB, Mencius, EPaxos, Paxos-Complex, Paxos-EPR
Sure	Paxos-Synod, Paxos-Time, Chubby-Live, Zab, IronRSL, LastVoting-PSync

Table 2: Link assumptions used by algorithms and variants.

Server assumptions. All definitions are implicitly prefixed with "eventually".

Alw-Q: there is always some quorum of servers that is non-faulty.
Q-Alw: there is some quorum of servers that is always non-faulty.

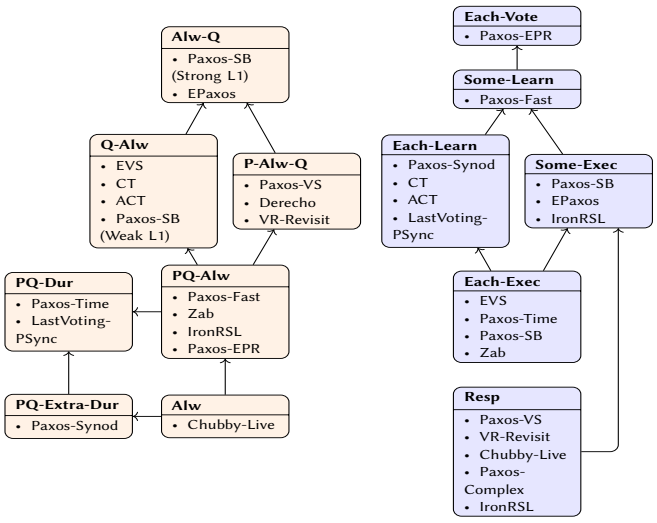

Figure 1: Hierarchies of server assumptions (left) and liveness assertions (right) as stated by the algorithms' authors.

P-Alw-Q: there is a server P such that, always, P is non-faulty and is the primary and there is some quorum Q that is non-faulty.
PQ-Alw: there is a server P and a quorum Q of servers, such that always, P is non-faulty and is the primary and Q is non-faulty.
Alw: all servers are always non-faulty, i.e., non-faulty forever from that time on.
PQ-Dur: there is a server P and a quorum Q such that P and Q are non-faulty and P is the primary, for some duration of time.
PQ-Extra-Dur: there is a duration of time $D1 + D2$ such that (1) the set of non-faulty servers does not change in the duration, (2) after duration $D1$, primary is selected, and (3) at least a fixed quorum of servers is non-faulty during the entire duration.

Liveness assertions. For brevity, we omit describing slots here. All definitions are implicitly prefixed with "eventually".

Each-Vote: in some round, each server of some quorum sends a vote for the same value in that round.
Some-Learn: some non-faulty server learns a value.
Each-Learn: each server of some quorum learns the same value.
Some-Exec: some non-faulty server executes a value.
Each-Exec: each server of some quorum executes the same value.
Resp: each client request is responded to.

4 LIVENESS PROPERTIES AND ANALYSIS

Table 3 summarizes the assumptions, assertions, the kind of proofs of the algorithms discussed, and our analysis.

Proposition 1 (**Each-Vote** insufficient). **Each-Vote** *is not strong enough as a liveness assertion.*

Proposition 2 (None from **Raw**). *No algorithm can satisfy any liveness assertion described above under* **Raw**.

Proposition 3 (All from **Q-Alw** single). *There is an algorithm that solves single-value consensus and satisfies all liveness assertions described above under* **Fair** *and* **Q-Alw**.

Proposition 4 (All from **Q-Alw**). *There is an algorithm that claims to solve consensus and satisfies all liveness properties described above under* **Fair** *and* **Q-Alw**.

	Name	Assumptions: Link	Assumptions: Server	Assertions	Proofs	Analysis
3	EVS	**Fair**	**Q-Alw**	**Each-Exec**	Systematic	(Prop 4)
4	Paxos-VS	**Fair**	**P-Alw-Q**	**Resp**	-	(Prop 5)
5	Derecho	**Fair**	**P-Alw-Q**	"progress"	-	lacking assertions
7	VR-Revisit	**Raw**	**P-Alw-Q**	**Resp**	Prose	(Prop 2)
8	Paxos-Synod	**Sure**	**PQ-Extra-Dur**	**Each-Learn**+	Prose	assuming primary
10	Paxos-Fast	**Fair**	**PQ-Alw**	**Some-Learn**	Systematic	(Cor 5.1)
12	CT	**Fair**	**Q-Alw**	**Each-Learn**	Systematic	(Prop 3)
13	ACT	**Fair**	**Q-Alw**	**Each-Learn**	Systematic	(Prop 3)
14	Paxos-Time	**Sure**	**PQ-Dur**	**Each-Exec**+	Systematic	assuming primary
17	Chubby-Live	**Sure**	**Alw**	**Resp**	-	(Cor 5.1), trivial from **Alw**
18	Paxos-SB	**Fair**	**Q-Alw**	**Some-Exec**	-	(Prop 4)
19	Mencius	**Fair**	-	"liveness"	-	lacking assumptions
20	Zab	**Sure**	**PQ-Alw**	**Each-Exec**	Sketch	(Cor 5.1)
22	EPaxos	**Fair**	**Alw-Q**	**Some-Exec**	-	(Prop 7)
24	Paxos-Complex	**Fair**	-	**Resp**	-	lacking assumptions, (Prop 6)
25	IronRSL	**Sure**	**PQ-Alw**	**Some-Exec**, **Resp**	Formal (Dafny)	(Cor 5.1)
26	LastVoting-PSync	**Sure**	**PQ-Dur**	**Each-Learn**+	Formal (PSync)	assuming primary
29	Paxos-EPR	**Fair**	**PQ-Alw**	**Each-Vote**	Formal (Ivy)	(Cor 5.1), (Prop 1)

Table 3: Assumptions, assertions, and proofs, as provided by the respective authors, together with our analysis. "-" indicates that the information is not provided. "+" in Assertions indicates that the calculation of the bound after which the assertion would be satisfied is also given.

Proposition 5 (**Resp** from **P-Alw-Q**). *There is an algorithm that claims to solve consensus and satisfy* **Resp** *under* **Fair** *and* **P-Alw-Q**.

Corollary 5.1 (Weak from **PQ-Alw**). *A liveness property that assumes* **PQ-Alw** *is a weak property, because the assumption is stronger than necessary.*

Proposition 6 (Not **Resp**). *Paxos-Complex cannot satisfy* **Resp**, *even with* **Alw**.

The following impossibility result was also discussed by Kirsch and Amir [26, Strong L1] and proved by Keidar and Shraer [23, 24].

Proposition 7 (None from **Alw-Q**). *No quorum-based consensus algorithm that executes in rounds can satisfy* **Some-Learn** *under* **Fair** *and* **Alw-Q**.

What are the right liveness properties? Clearly, **Resp** guarantees server response to client requests, and **Each-Exec** and **Each-Learn** are not needed for **Resp**. One can also see in existing algorithms that **Some-Learn** ensures consensus, while **Each-Vote** might not, and **Fair** with either **Q-Alw** or **P-Alw-Q** can ensure **Some-Learn**. Stronger assumptions with durations can yield stronger assertions.

5 RELATED WORK AND CONCLUSION

Besides the works already discussed, there are additional studies of consensus algorithms and variants, building on earlier works, relating existing algorithms, and discussing liveness, e.g., COReL [21, 22], Congruity [4, 5], and GIRAF [23, 24]. Our work is a first step in precise specification of the wide variety of liveness properties. Much future work is needed for precise complexity analysis for liveness.

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