Cloud Computing and Distributed Systems
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Lecture - 13
Consensus in Cloud Computing and Paxos

Consensus in Cloud Computing and Paxos protocol.

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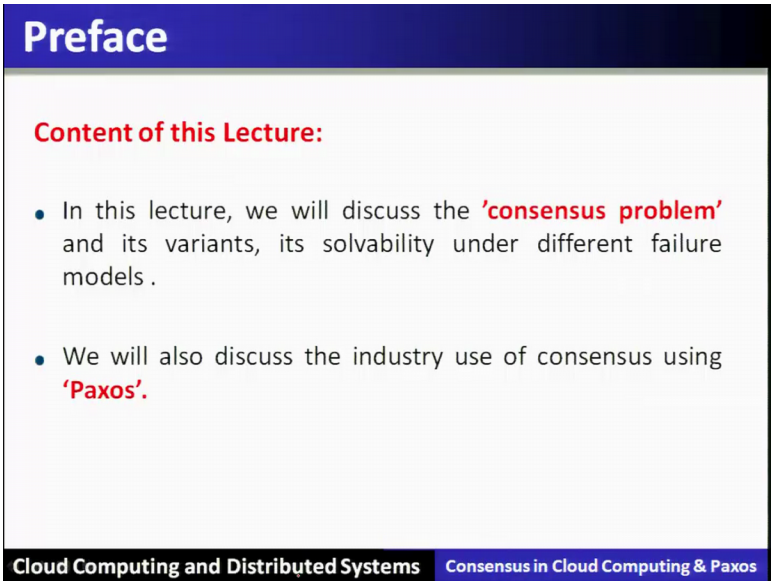

Preface content of this lecture. We will cover consensus problem and it is variants. It is solvability under different failure models. We will discuss in this part of a lecture. We will also discuss the industry variant of consensus using a well-known protocol which is called Paxos.

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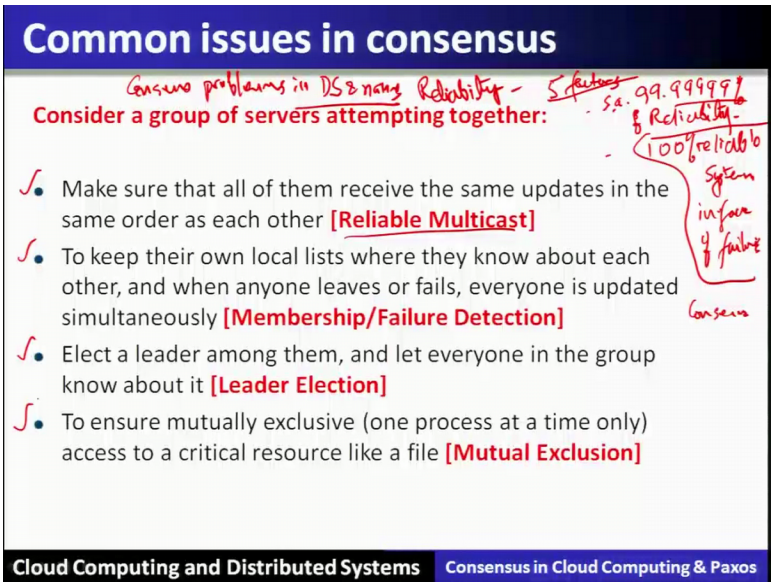

Let us understand what a consensus is. So, before going ahead let us see the importance of this problem in cloud and distributed computing.

So, in a cloud computing different vendors they provide the reliability support for the services. The reliability services ensures that it is, let us say 5 number of factors such as 99.99999 percentage of reliability; that means, it is not possible to provide 100 percent reliable system in the face of failures. So, that means, if the underlying systems are the servers are failing how about the services reliability. So, none of the vendors or none of them can provide 100 percent reliability in their services; however, they support the reliabilities, and it is mentioned that 99 point how many number of 9's; that means, how reliable the system is, but it is not 100 percent reliable.

Now, the this particular reliability how they are ensuring that is achieved through the consensus protocols. So, that means, when a group of servers are attempting together to solve a particular problem in spite of failure they have to reach to a consensus. And therefore, they achieve this kind of solutions. But this is not so trivial it is very, very complex in different models that we will cover in this part of discussion.

So, let us understand where this consensus problems lies and what are their names in the distributed systems. So, let us consider a group of servers who are attempting together to make sure that all of them receives the same updates in the same order as they send. So,

this kind of problem is known as reliable multicast problem. And this requires the solution of consensus to be involved.

The second kind of problem is that to keep their own local list; where they know about each other and when they and when anyone leaves or fails. So, everyone updates simultaneously. So, this kind of problem is called membership problem or a failure detection problem. This also requires the consensus or this particular problem is also equivalent to the consensus, that we will see the later part.

Similarly, a group of servers who are attempting together to elect a leader among them, and this particular decision of electing the leader is known to everyone in that group is called a leader election problem. So, leader election under this particular failure requires the solution of consensus. So, if you can solve the consensus problem then you can solve the leader election, and that is why if they are all equivalent problems.

Similarly there is another problem which is considering that a group of servers attempting together to ensure the mutually exclusive access to the critical resources, such as files writing on a file and so on or an update on the replicated database. Which requires access to the competing access to one process among the competing processes at a particular instant of time. So, that is this problem is called as a mutual exclusion problem. In the failure this problem is also requires the consensus protocols for reliability aspect.

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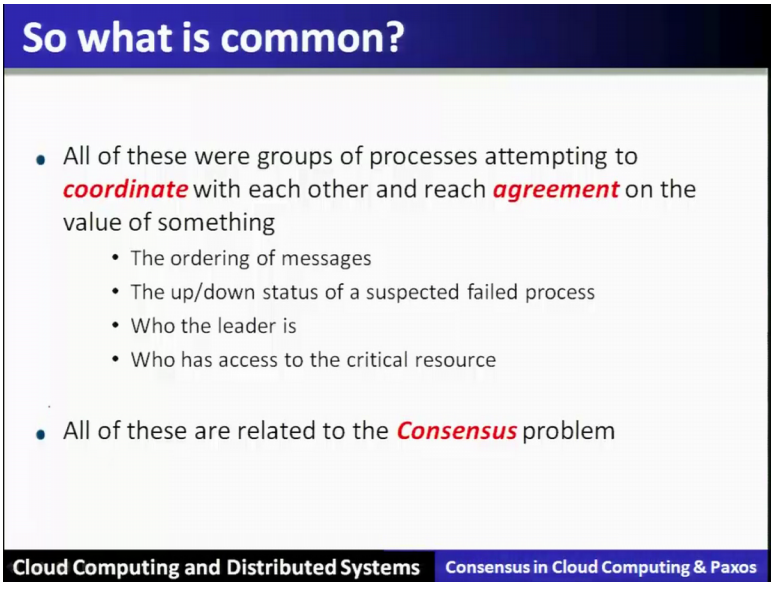

So, let us see that what is common in all these problems. So, here we have seen that all of these group of processes, they are attempting to coordinate with each other and reach an agreement on something in different problems that we have seen leader election mutual exclusion and so on. So, the agreement on that values depends upon different problems, let us understand what kind of agreement is required to solve this consensus problem.

So, it depends upon whether it is an ordering of messages at all the processes in the groups the up or down status of the suspected field process and who is a leader and who has the access to the critical resource. So, that depends upon different values to be agreed upon to solve this particular these kind of problems. All of these are related to the consensus problem.

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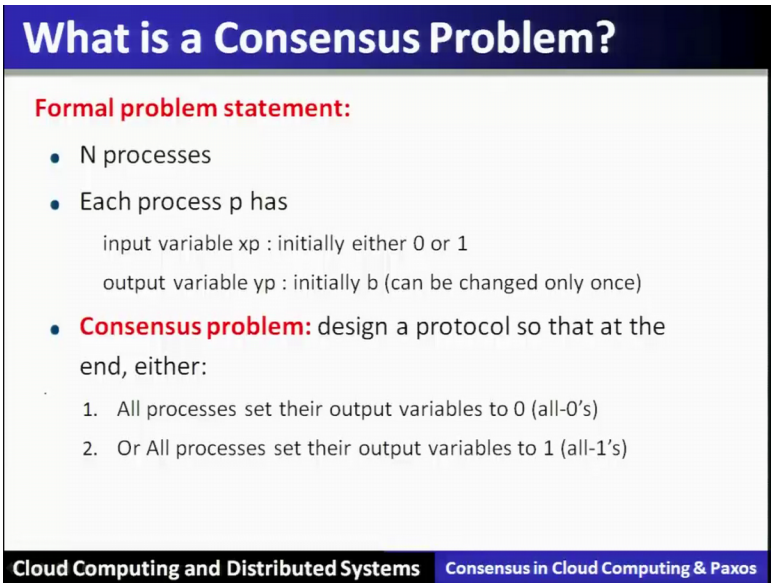

So, having known what a consensus is. So, let us formally define what a consensus problem is for our discussion in this lecture.

So, the formally statement says that, let us have a system of N processes where each process has the input variable xp. Initially it can have the values either 0 or 1 in that variable xp. Similarly, the output variable yp initially which is assigned to b which can be changed only once and once output means, whatever value is assigned it will not be changed then after the end of consensus algorithm. So, consensus problem says to design a protocol. So, the at the end either all the processes in that particular group. They set

their output variables to 0s; that means, all 0's or the processes sets their output variables to 1, that is all 1's. Then only this particular statement is called the consensus problem.

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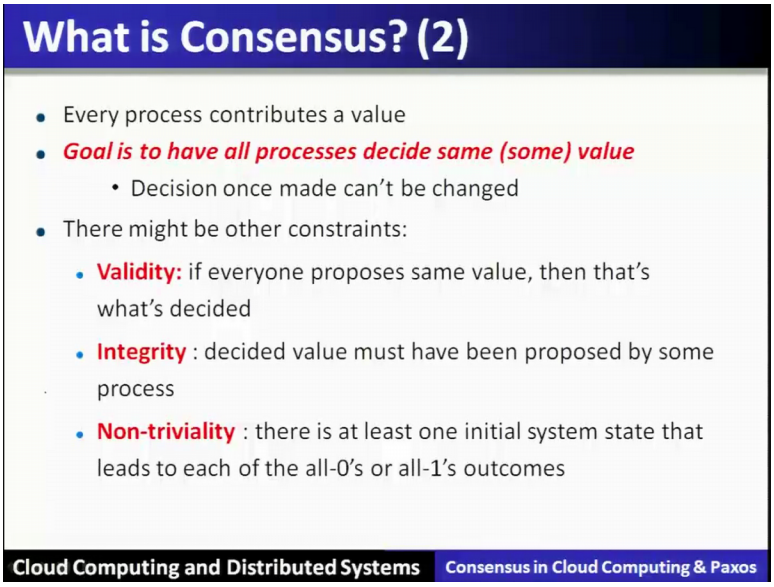

Now, here in this particular consensus problem, every process will contributes toward value and the goal is to have all the processes decides on some value. So, once the decision is finalized it cannot be changed. There are some other constraints let us see, which will required to be enforced to solve this particular consensus problem. The first constraint is called validity that everyone proposes same value, then that is what is being decided called validity.

Integrity means that decided value must have been proposed by some process. Non triviality says that there is at least one initial state that leads to each of the all 0's or all ones outcomes. So, 3 different properties or constraints they have to be satisfied. Then only we can say that the consensus problem is solved validity integrity non triviality.

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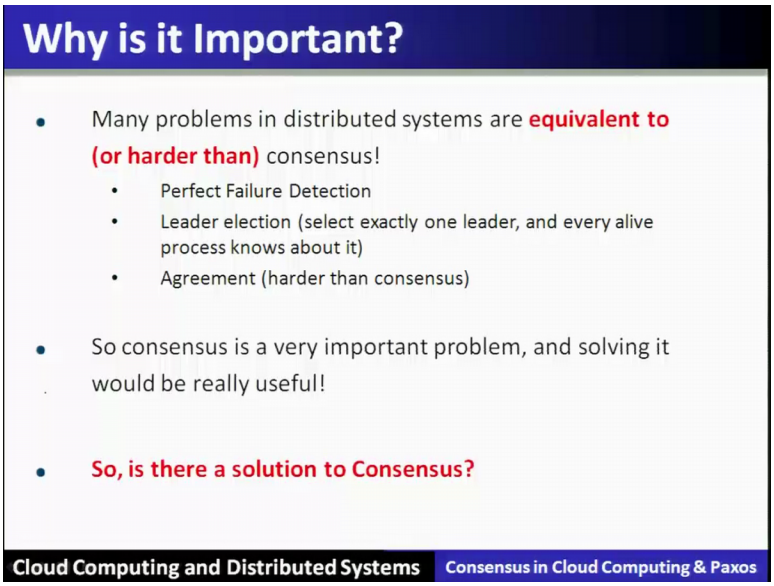

Why this consensus problem is important? So, here we can see in many problems in the distributed systems they are equivalent to the consensus problem or even harder than that; that means, if you can solve consensus problem those problems in the distributed systems are also been solved.

For example, failure detection. So, if you can detect a failure; that means, you can solve the consensus problem. Or consensus problem if it is, solvable then you can also detect the failures similarly leader election exactly one leader, and every alive process knows about it called leader election problem, if leader election problem is equivalent to the consensus problem. Similarly, the agreement problem; that means, they can reach all of them reach to an agreement to a common value is harder than consensus problem.

So, the consensus is very important problem and solving it would be really useful. So, is there any solution to a consensus problem we will see that it is very, very complex problem. It is not trivial to solve this particular problem in some of the models.

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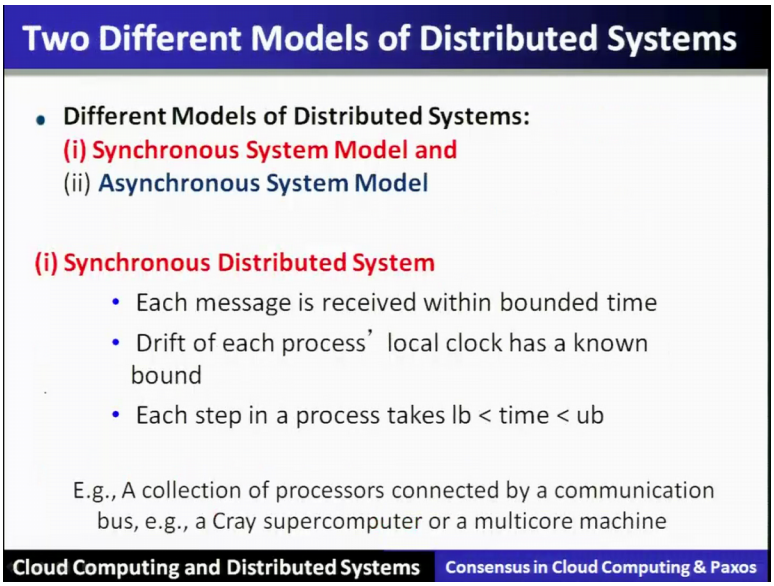

So, there are 2 different models of distributed system which also is applied to the cloud computing systems. So, we will see under these models how the consensus problem can be solved.

So, the first of these 2 models is called synchronous distributed system. So, synchronous model says that each message is received within a bounded time. And the drift of each processes local clock is also bounded. And each step in a process is bounded in a time between the lower and upper bounds. So, meaning in the sense that in the synchronous distributed system, the assumptions are being made that each process is delivered within a bounded period of time and the processes local clocks also when they drift that also is bounded and each step in a process is also bounded then only it is called synchronous distributed systems.

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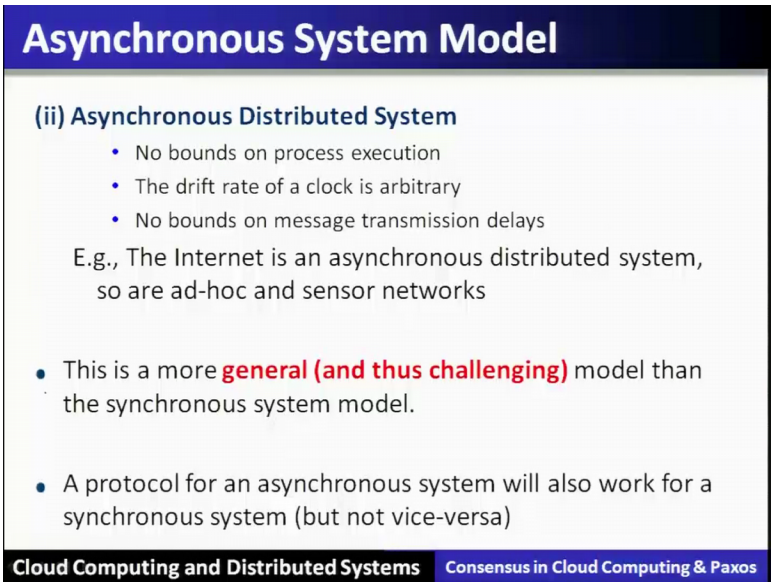

Asynchronous on the other hand, does not have any bounds specified on the process execution. Similarly, the clocks when they drift that particular bound is also arbitrary and the message transmission delays; that means, when the message is received, that particular delay also is not bounded then that model is called asynchronous distributed or asynchronous model. Internet is a perfect example of asynchronous distributed system model and there are many other networks which is an example of a asynchronous model.

So, there is a more general model than the synchronous system model; that means, if you can solve the problem under this model asynchronous system model. That means, that problem also can be solved in a synchronous model, but vice versa is not valid.

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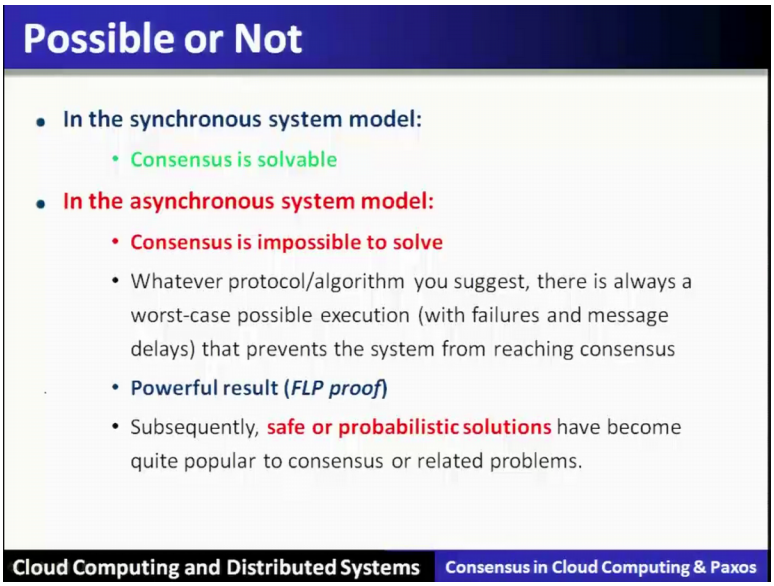

So, let us see the consensus problem in this the 2 models scenarios. So, if the model is synchronous distributed system, then consensus is solvable that is being proved and we will see in this part of the lecture.

However, in asynchronous system model the consensus is impossible to solve, that is also being proved. So, that means, that whatever protocol algorithms, you have there is always a worst possible execution scenario with the failures and the message delays, that will prevent the system from reaching the consensus. That is why the consensus is impossible to solve. And this was proved in FLP a famous proof of this FLP we will see has proved that consensus in a asynchronous system is impossible.

So, using this particular results safe or probabilistic solutions to this particular problem have become quite popular to the consensus problem, because it has a lot of use.

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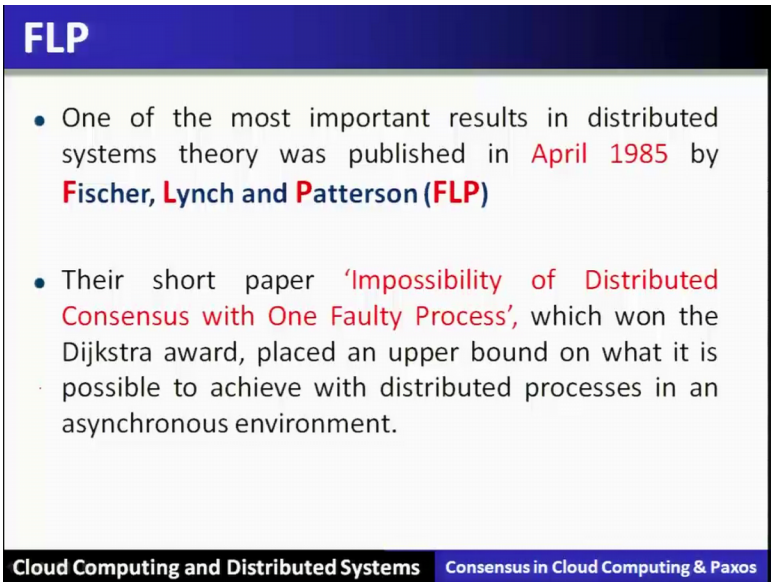

We will see all these. Let us see what FLP is, it is one of the most important results in a distributed system theory, published in April 1985 by Fisher Lynch and Patterson. That is called FLP problem. So, this particular problem, you can refer to that paper which is called as impossibility of distributed, consensus with one faulty process; which won the Dijkstra award, and has shown an upper bound on what it is possible to achieve with the distributed processes in asynchronous environment that we will discuss.

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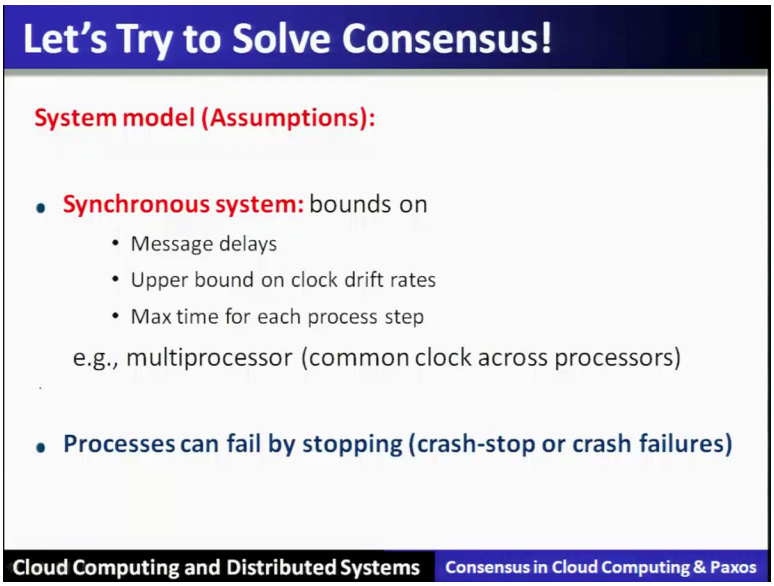

So, with this particular background that, the system model plays a important role whether you can solve the consensus or not. So, we have to study the algorithms accordingly. So, we will first assume the system model to be the synchronous system model, and also we will assume that there exist a bound on the message delays. And they are exist an upper bound on clock drift rates. And there also exist the bound on each processes steps to complete in the model. And that is called synchronous system model that we will assume. We will also assume a failure model which is called a crash fault or a crash failure. This model assumes that the process when fails they will stop that is called crash fault model of failure.

So, with these 2 assumptions that we will assume a synchronous system model and a crash fault system model let us see how we are going to solve the consensus in this model.

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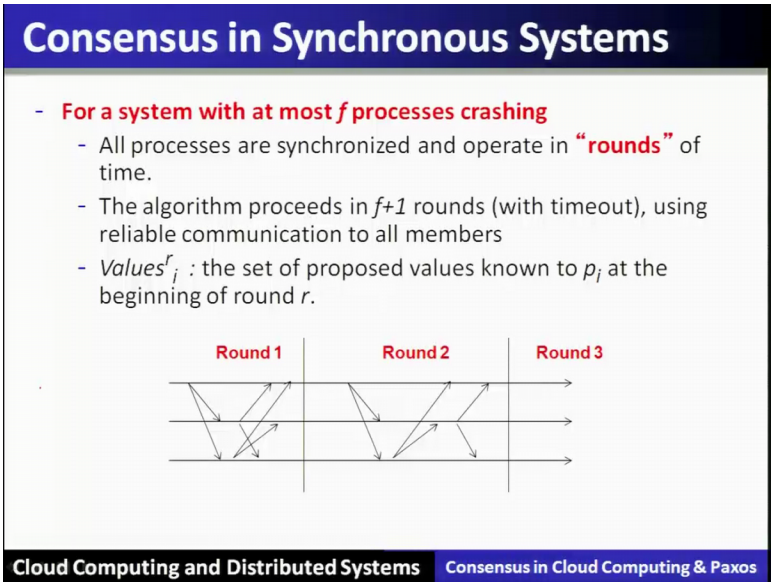

So, the consensus in this particular model, we are assuming that this system can have at most f processes crashing. So, there is a limit that is called f processes which can crash. All the processes are synchronized operates in the rounds of time. By round we mean that if the messages send it will be delivered when before the next round starts.

So, the algorithm proceeds in f plus 1 rounds using a reliable communication to all the members. Now here in this round every round we will, every process will exchange the values with other processes which is denoted as values of process i at the round r. So, the

set of proposed values known to a process i at the beginning of round r is denoted by this particular variable and this variable will be communicated through the multicast among the group who are participating in this consensus problem.

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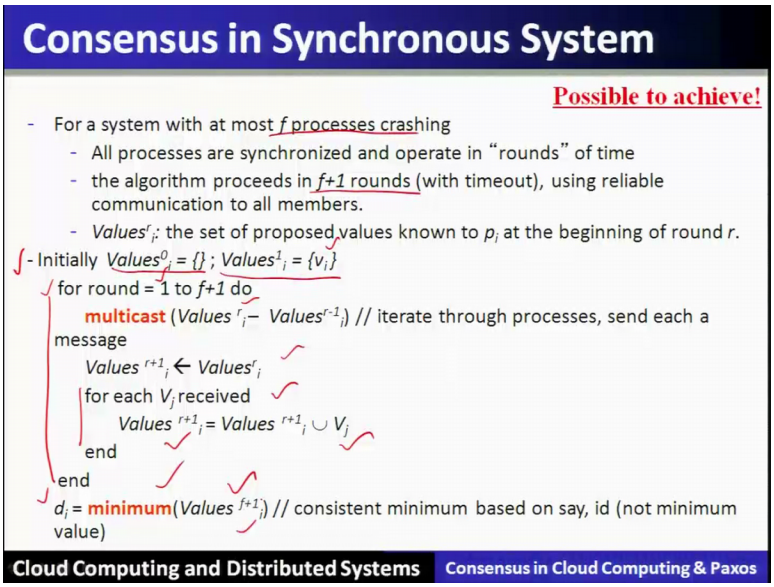

So, let us see the algorithm for this. So, again these particular values which are known to the process i at the beginning of the round r is to be communicate (Refer Time: 18:43). So, let us see that initialize this particular value at the 0th round at the beginning of the 0th round as empty. And for the round number one the process i will have the value V i. So, let us start for round 1 to round f plus 1. Because this particular since we have assumes that there are at most f different processes which can crash. So, algorithm has to take f plus 1 rounds to converge into the consensus problem.

So, let us understand the round number 1. So, round number 1 the process i will have it is value V V i and it will be multi casted. So, this particular values will be received and will be sent to all the processes and it will also receive the same values in the in that particular round 1 from the other processes let us say V j. So, the values which is received out of that V j will also be taken into that particular set of values, which will be collected at the end of round r that is here in this case.

So, when f plus 1 rounds finishes, then these set of values which is received by a process i it will take the minimum of all the values. So, every process like V i, they will take the

minimum, and this particular protocol guarantees that all the processes will have the same value that is d at the end of f plus 1 rounds.

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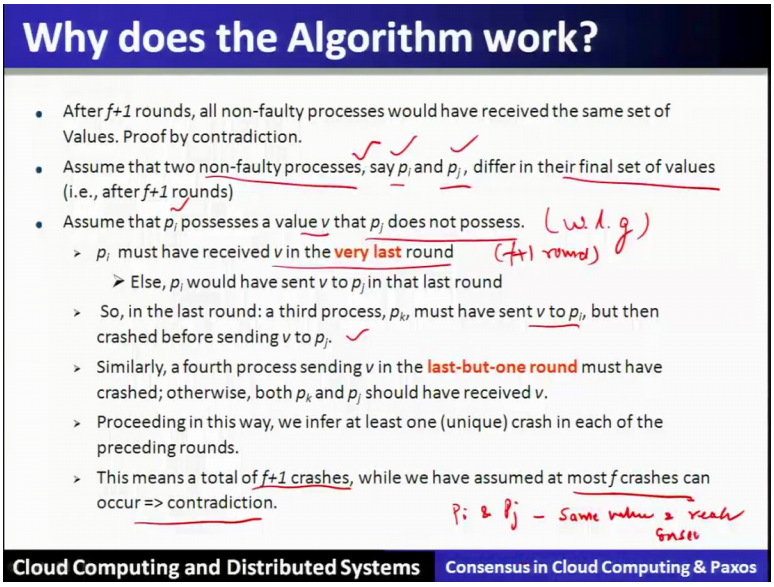

Now, let us see why this algorithm will work to solve the consensus problem. So, after f plus 1 rounds all the non-faulty processor or a processes would have received the same set of values. And we will see that particular proof by the contradiction.

So, let us assume that they are exists 2 non faulty processes. Let us say p i and p j and they differ in their final set of values. Let us say that after f plus 1 rounds that they have different values. Now assume that process p i has the value v without loss of generality. And that p j does not possess this value. It may have a different value, we can change it that p j will have this vale, but p i does not have that we have already assumed that without loss of generality.

Now, if p i must have received the v in the very last round, that is f plus 1th round, else p would have p i would have send value v to p j in that last round. So, in this last round a third process p k must have send v to p I, but then crashed before sending v to p j. Similarly, a 4th process sending v in the last, but oneth round must have crashed otherwise both p k and p j should have received v. Proceeding in this way we infer that at least one unique crash in each of the preceding round. This means that a total f plus 1 crashes, which will prevent the value v to be reached at p j. While we have already assumed that there can be at most f crashes.

Therefore, this is a contradiction and this contradiction will say that p i and p j should have received the same value and they will reach the consensus.

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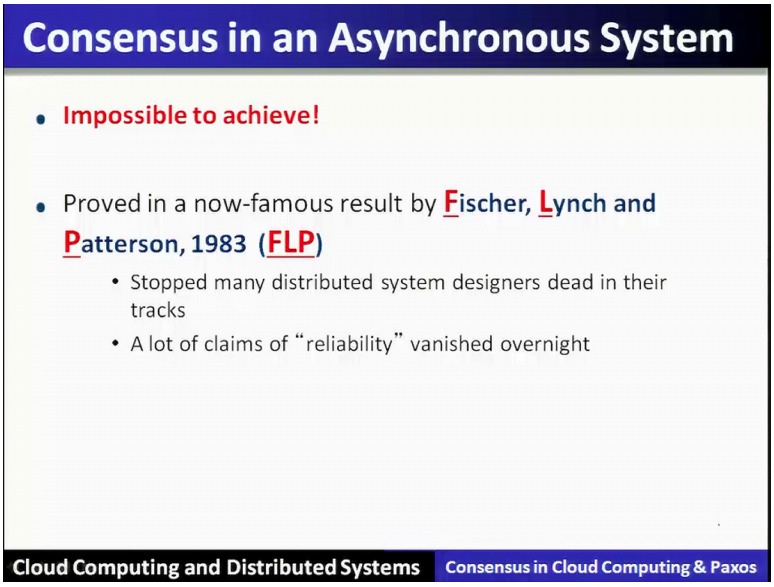

However, this consensus if you change the system model, asynchronous model it will become impossible to achieve. And we have already discussed that FLP that is Fischer Lynch and Patterson have already proved this particular theorem, that is called FLP theorem.

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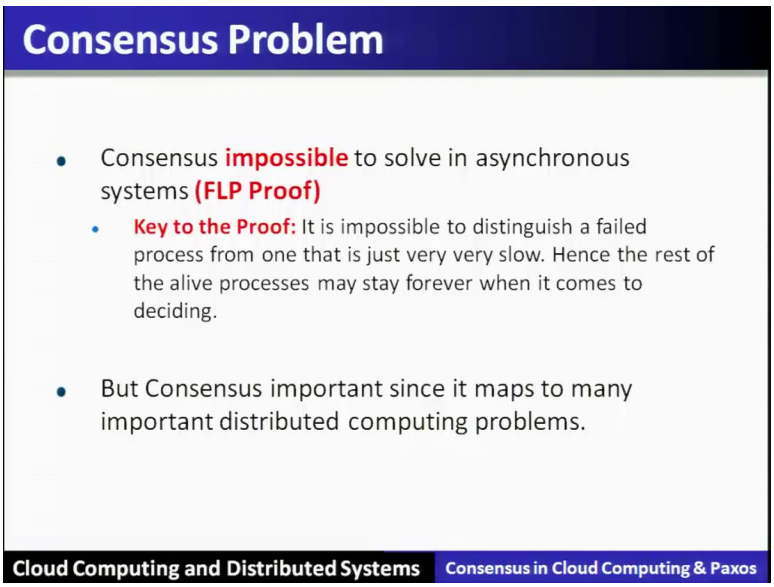

So, consensus problem we have seen that this consensus impossible to be solved in asynchronous system model. And that is given by FLP proof. We will not going to the proof, but let us see what is the key issue which led to this particular proof. Now it is impossible to distinguish a failed process from that is just very, very slow. Hence, the rest of the alive process may stay forever when it comes to the deciding. So, that becomes a proof; that means, a failure or a system becoming very slow it is very difficult to detect it. Quickly it may take very long time to conclude it, and this will lead to that impossibility result that is called FLP.

Now, since consensus is are important problem. Since it maps to many important distributed computing problem. Therefore, we will see that in this asynchronous system model how we are going to solve the consensus.

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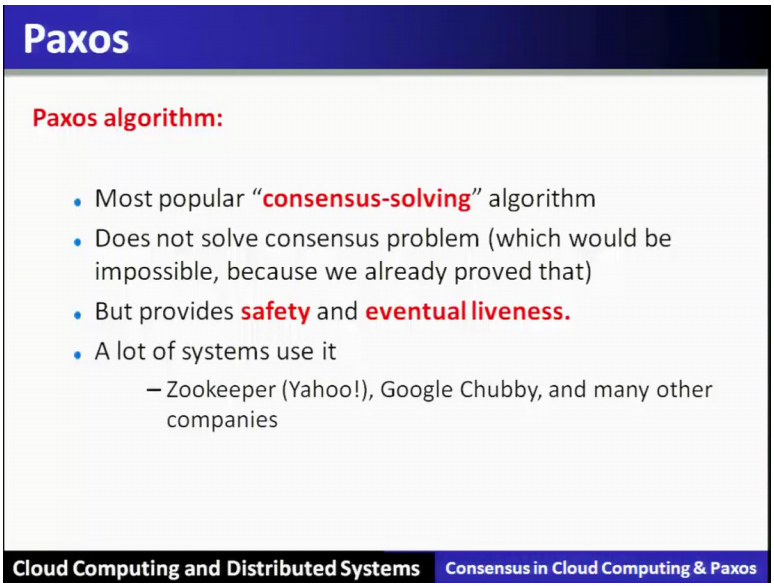

So, once a solution is called Paxos algorithm. This Paxos algorithm is the most popular consensus solving algorithm. In the asynchronous system model; however, we have already seen that consensus in the asynchronous is unsolvable using FLP theorem, but as far as the Paxos is concerned, Paxos provides or solves to some extent the consensus problem in the asynchronous system model. But it provides the safety and eventual liveness, it is not the guaranteed liveness, but it is an eventual liveness.

So, the Paxos algorithm solves the consensus using these 2 constraints safety and eventual liveness. A lot of systems which are already deployed by the industry like

Yahoo and Google, they are using this algorithm Paxos algorithm in the form of Zookeeper. And also the Google stack that is called Chubby and many other companies also use the Paxos. So, that is why the Paxos is the most popular in solving the consensus.

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Paxos is invented by the Leslie Lamport. He is a famous scientist working in Microsoft. And he has the winner of Turing award and several awards for his contribution in the distributed systems. So, he is basically the key to invent this Paxos system. So, Paxos will provide the safety and eventual liveness. So, safety says that consensus is not violated. Meaning to say that, if 2 processes which are non-faulty, they arrive at the decision with the same value.

That is called safety in the consensus; that means, that non faulty processes reach agreement with the same value; that means, if p i and p j. So, at the end they may decide on the same value 0 or let us say 1, but not the scenario whether p i will receive or p i will decide 0 and p j will receive 1. So, both of them either they decide on 0 or all of them decides on 1.

That means, the consensus is not violated and this ensures that Paxos supports or provides the safety or guarantees the safety properties the other property which is called eventual liveness. So, safety says that everything good happens. And eventual liveness says that if the things go well sometime in the future; that means, the messages failures

etcetera, then there is a good chance that consensus will be reached, but it is not guaranteed in this particular situation. That is sometimes a situation may arise that this liveness that eventually everything good happens is not guaranteed by the Paxos.

So, the FLP is still applied why because it is not the liveness, but it is an eventual liveness. So, Paxos is not guaranteed to reach the consensus maybe sometimes within at particular time bound

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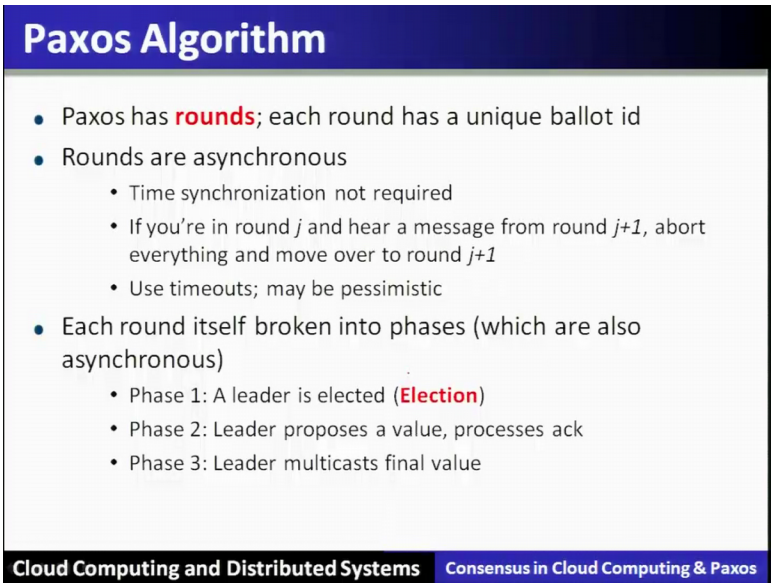

Let us see the Paxos algorithm. Paxos has divided the algorithm in and this operates in the rounds. So, the rounds are asynchronous, that is time synchronization is not required, but if you are in the round j and hear the messages from round j plus 1 then you abort everything and move over to the next to the round j plus 1. But that does not requires the time synchronization to do this. Timeouts can be used but maybe pessimistic so, each round itself broken into the phases which are also asynchronous.

So, let use see what are the phases this around of Paxos algorithm follows. So, the first phase is called the election. That is a leader is elected, second phase is called that the leader proposes a value. And also processes the acknowledgement ack. Phase 3 says that the leader multicast the final values.

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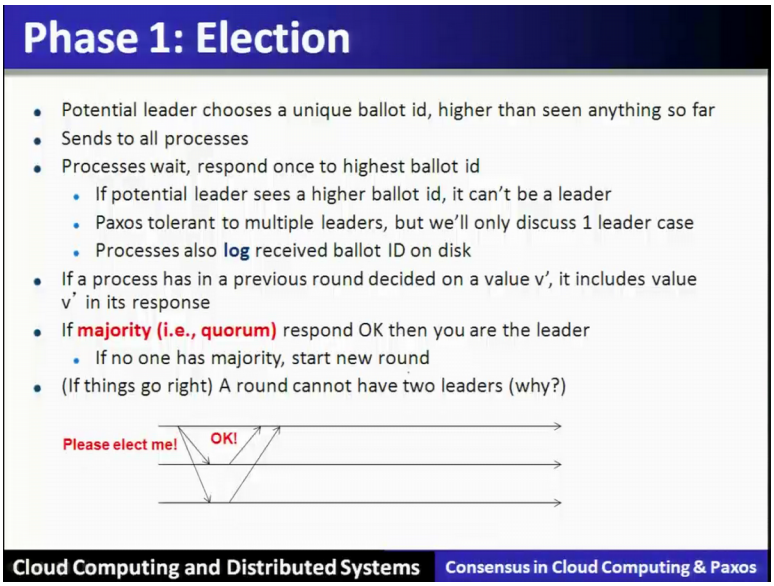

So, the potential leader chooses a unique ballot id; that means, the higher than anything seen so far is being chosen as the ballot ID. It sends it to all the processes. Processes waits and respond once to the highest seen ballot ID.

Now, if the potential leader sees a higher ballot ID then it cannot be the leader. Now the Paxos in some cases is tolerant to the multiple leaders, but let us without loss of generality let us discuss only one leader over here. So, the processes also log the received ballots on the disk. If a process has in the previous round decided a value v prime, it in include that value v prime in it is response. If the majority that is the quorum responded then, that particular process will become the leader if no one has the majority then it will start again the new round. So, the things go right the round cannot have the 2 leaders.

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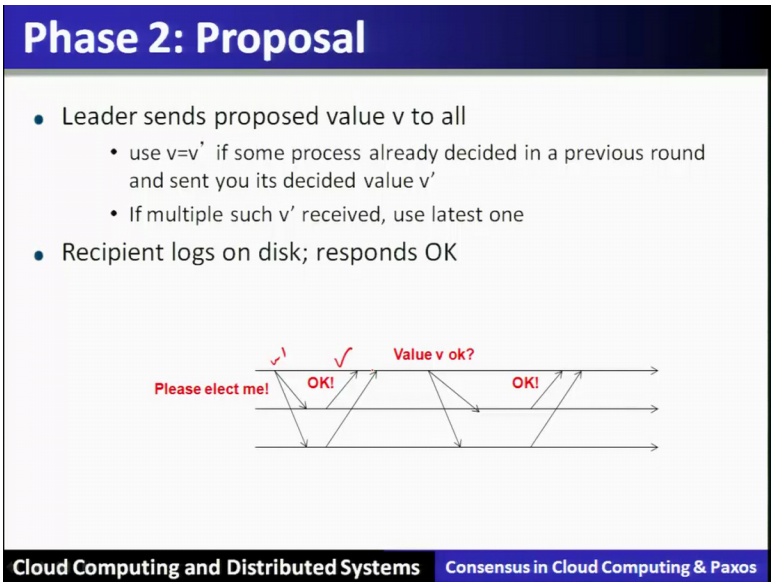

So, this is the phase one which is an election. The phase 2 which is called a proposal that is the leader sends the proposed value v to all, and v prime is the previous round value then the same value can be can be send. So, if multiple such v primes are received then in that case use the latest one.

Recipients logs all these values on the disk and responds to the OK messages here. So, they will send these values. And they will respond with the OK values.

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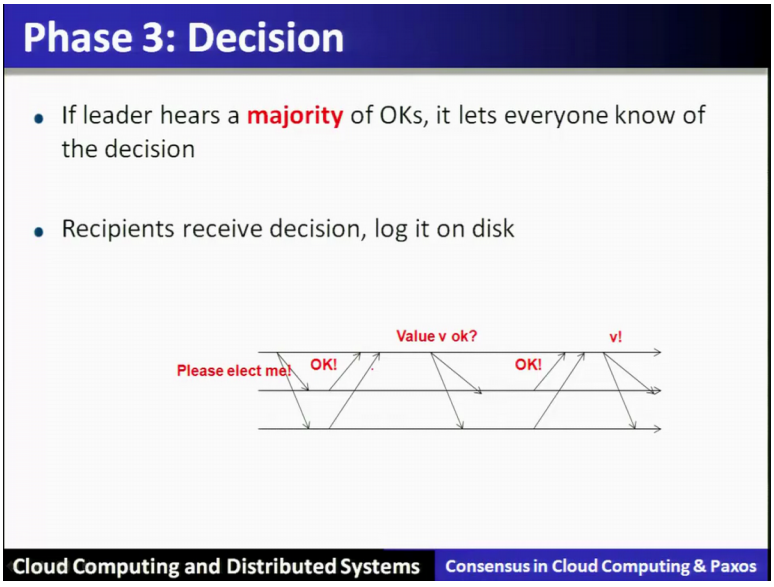

Third phase is called decision if the leader hears a majority of ok. It let us everyone know of the decision. So, recipients receive the decision log on the disk.

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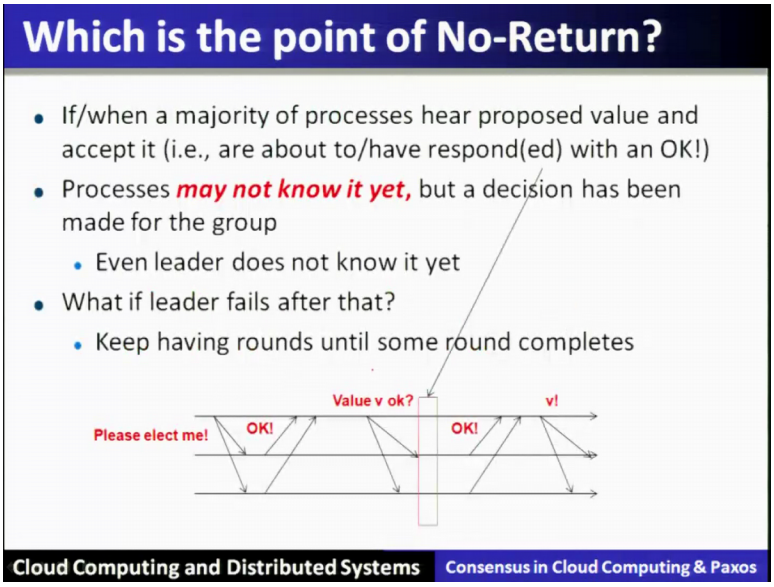

Now, at what stage the agreement is reached? That means, if the majority of the process hears the proposed value and accepted it; that means that is being checked with the help of this messages. Then it is known that the agreement is released and the processes may not know it yet, but the decision have been made in the rounds of this particular protocol Paxos.

But the decision has been made by the group even the leader does not know this particular decision at this point of time, before the algorithm completes. Now the question is if the leader fails, then what will happen? So, it will keep on iterating the rounds until some round completes it.

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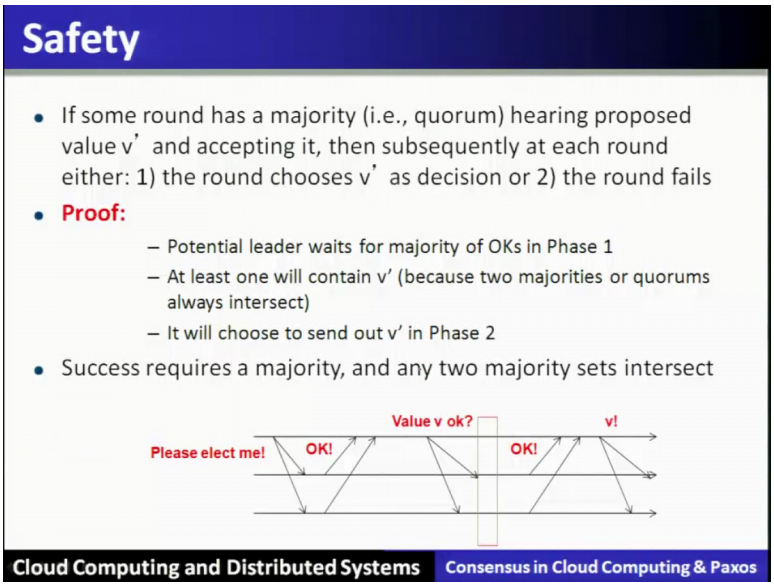

So, let us see that this particular protocol Paxos achieves or guarantees the safety. Now if some round has the majority hearing the proposed value v prime and accepting it then subsequently in each round either the round chooses the same values v prime as the decision or the round fails.

The proof says that the potential leader wait for the majority of ok's in the phase 1. And at least one will contain v prime. And because if there are more than one majorities, but every message has to send only 1 ok. So, it will choose to send out v primes in the phase 2. Success requires a majority and any 2 majority sets the intersect.

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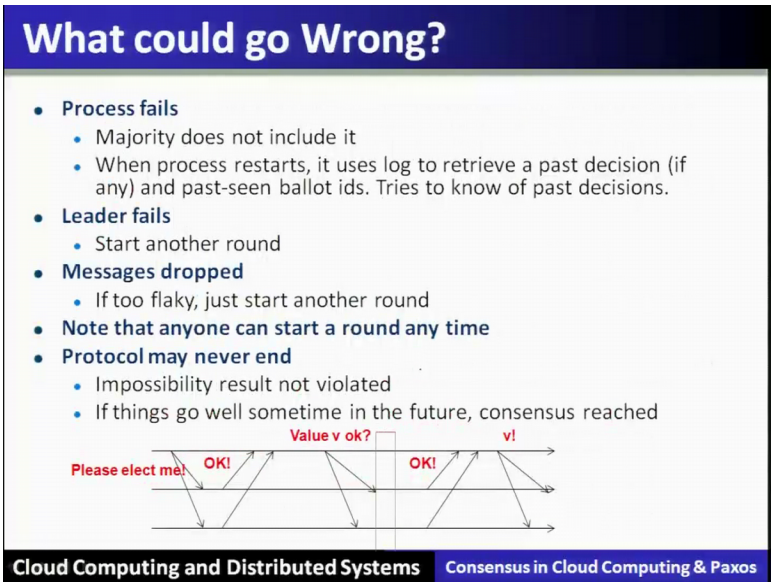

So, it will not validate the safety property; that means, even if the majority sets when we take the intersection. Even then we will found the values v prime to be reached in the agreement.

So, there while the rounds and the phases operates in the Paxos. There may be many type of crashes or a problems happens and let us see how tolerant it is in this particular scenarios. For example, a process fails. So, majority does not include it, and when the process restart it uses the log to retrieve the past decisions and past seen ballot ID's and tries to know the past decisions. Similarly, if the leader fails then it will start another round, messages are dropped and in that case you have to just start another round.

So, anyone can start around at any time and the protocol may never end; that is, impossibility results are not violated. So, if the things go well, sometime in the future consensus is reached, but that is not guaranteed.

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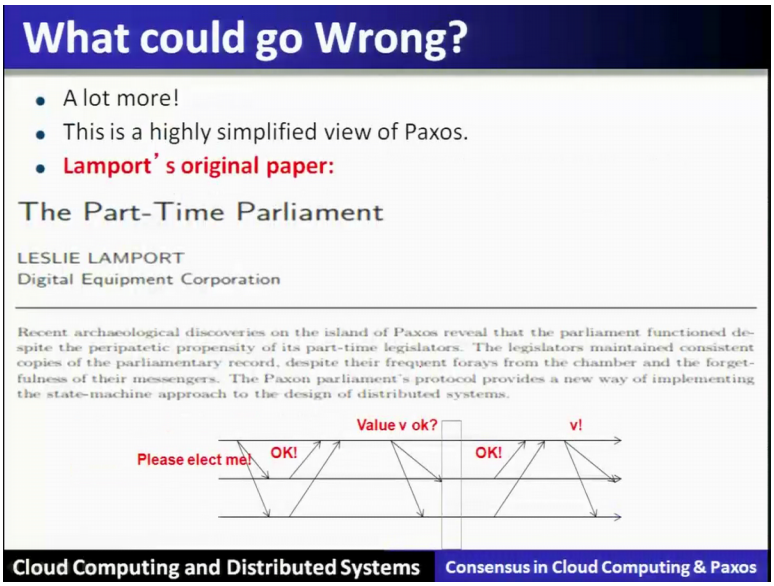

So, here we will we can see here the original Lamports paper on Paxos; which is having a title that part time parliament can see and study conclusion.

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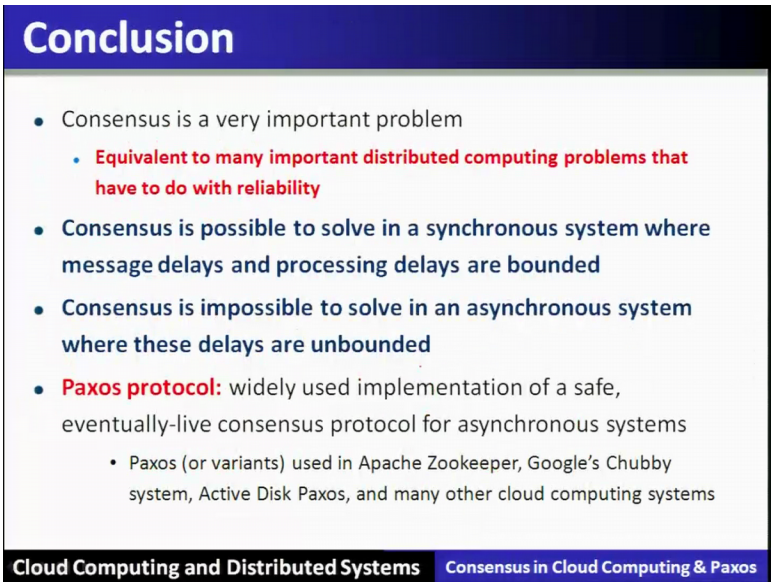

Consensus is very important problem. Equivalent to many important problems in the distributed systems, that have to deal with the reliability. Consensus is possible to be solved in a synchronous system where the message delays and the processing delays are bounded. Consensus problem is impossible to be solved in a model that is asynchronous model where these delays that is the messages and the processing are unbounded.

So, the Paxos is widely used protocol which will implement the safe and eventual live consensus protocol for asynchronous system, and is heavily used in very many industries systems by Yahoo; such as Apache Zookeeper and Google, Google's internal stack such that Chubby system and so on.

Thank you.