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Fault-tolerant Agreement in Synchronous Message-passing Systems

Michel Raynal

SYNTHESIS LECTURES ON DISTRIBUTED COMPUTING THEORY

Nancy Lynch, *Series Editor*

Fault Tolerant Agreement In Synchronous Message Passing Systems Michel Raynal

Chryssis Georgiou,Alexander Shvartsman

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Fault-tolerant Agreement in Synchronous Message-passing Systems Michel Raynal,2010-06-06 Understanding distributed computing is not an easy task This is due to the many facets of uncertainty one has to cope with and master in order to produce correct distributed software A previous book Communication and Agreement Abstraction for Fault tolerant Asynchronous Distributed Systems published by Morgan Claypool 2010 was devoted to the problems created by crash failures in asynchronous message passing systems The present book focuses on the way to cope with the uncertainty created by process failures crash omission failures and Byzantine behavior in synchronous message passing systems i e systems whose progress is governed by the passage of time To that end the book considers fundamental problems that distributed synchronous processes have to solve These fundamental problems concern agreement among processes if processes are unable to agree in one way or another in presence of failures no non trivial problem can be solved They are consensus interactive consistency k set agreement and non blocking atomic commit Being able to solve these basic problems efficiently with provable guarantees allows applications designers to give a precise meaning to the words cooperate and agree despite failures and write distributed synchronous programs with properties that can be stated and proved Hence the aim of the book is to present a comprehensive view of agreement problems algorithms that solve them and associated computability bounds in synchronous message passing distributed systems Table of Contents List of Figures Synchronous Model Failure Models and Agreement Problems Consensus and Interactive Consistency in the Crash Failure Model Expedite Decision in the Crash Failure Model Simultaneous Consensus Despite Crash Failures From Consensus to k Set Agreement Non Blocking Atomic Commit in Presence of Crash Failures k Set Agreement Despite Omission Failures Consensus Despite Byzantine Failures Byzantine Consensus in Enriched Models

Fault-tolerant Agreement in Synchronous Message-passing Systems Michel Raynal,2022-06-01 Understanding distributed computing is not an easy task This is due to the many facets of uncertainty one has to cope with and master in order to produce correct distributed software A previous book Communication and Agreement Abstraction for Fault tolerant Asynchronous Distributed Systems published by Morgan Claypool 2010 was devoted to the problems created by crash failures in asynchronous message passing systems The present book focuses on the way to cope with the uncertainty created by process failures crash omission failures and Byzantine behavior in synchronous message passing systems i e systems whose progress is governed by the passage of time To that end the book considers fundamental problems that distributed synchronous processes have to solve These fundamental problems concern agreement among processes if processes are unable to agree in one way or another in presence of failures no non 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Failures Byzantine Consensus in Enriched Models **Fault-Tolerant Message-Passing Distributed Systems** Michel Raynal,2018-09-08 This book presents the most important fault tolerant distributed programming abstractions and their associated distributed algorithms in particular in terms of reliable communication and agreement which lie at the heart of nearly all distributed applications These programming abstractions distributed objects or services allow software designers and programmers to cope with asynchrony and the most important types of failures such as process crashes message losses and malicious behaviors of computing entities widely known under the term Byzantine fault tolerance The author introduces these notions in an incremental manner starting from a clear specification followed by algorithms which are first described intuitively and then proved correct The book also presents impossibility results in classic distributed computing models along with strategies mainly failure detectors and randomization that allow us to enrich these models In this sense the book constitutes an introduction to the science of distributed computing with applications in all domains of distributed systems such as cloud computing and blockchains Each chapter comes with exercises and bibliographic notes to help the reader approach understand and master the fascinating field of fault tolerant distributed computing **Network Topology and Fault-Tolerant Consensus** Dimitris Sakavalas,Lewis Tseng,2022-05-31 As the structure of contemporary communication networks grows more complex practical networked distributed systems become prone to component failures Fault tolerant consensus in message passing systems allows participants in the system to agree on a common value despite the malfunction or misbehavior of some components It is a task of fundamental importance for distributed computing due to its numerous applications We summarize studies on the topological conditions that determine the feasibility of consensus mainly focusing on directed networks and the case of restricted topology knowledge at each participant Recently significant efforts have been devoted to fully characterize the underlying communication networks in which variations of fault tolerant consensus can be achieved Although the deduction of analogous topological conditions for undirected networks of known topology had shortly followed the introduction of the problem their extension to the directed network case has been proven a highly non trivial task Moreover global knowledge restrictions inherent in modern large scale networks require more elaborate arguments concerning the locality of distributed computations In this work we present the techniques and ideas used to resolve these issues Recent studies indicate a number of parameters that affect the topological conditions under which consensus can be achieved namely the fault model the degree of system synchrony synchronous vs asynchronous the type of agreement exact vs approximate the level of topology knowledge and the algorithm class used general vs iterative We outline the feasibility and impossibility results for various combinations of the above parameters extensively illustrating the relation between network topology and consensus

Synthesis Lectures on Distributed Computing Theory : Fault-tolerant Agreement in Synchronous Message-passing Systems M. Raynal, Concurrent Crash-Prone Shared Memory Systems Michel Raynal,2022-03-22 Theory is what remains true when technology is changing So it is important to know and master the basic concepts and the theoretical tools that underlie the design of the systems we are using today and the systems we will use tomorrow This means that given a computing model we need to know what can be done and what cannot be done in that model Considering systems built on top of an asynchronous read write shared memory prone to process crashes this monograph presents and develops the fundamental notions that are universal constructions consensus numbers distributed recursivity power of the BG simulation and what can be done when one has to cope with process anonymity and or memory anonymity Numerous distributed algorithms are presented the aim of which is being to help the reader better understand the power and the subtleties of the notions that are presented In addition the reader can appreciate the simplicity and beauty of some of these algorithms **Quorum Systems** Marko Vukolic,2022-06-01 A quorum system is a collection of subsets of nodes called quorums with the property that each pair of quorums have a non empty intersection Quorum systems are the key mathematical abstraction for ensuring consistency in fault tolerant and highly available distributed computing Critical for many applications since the early days of distributed computing quorum systems have evolved from simple majorities of a set of processes to complex hierarchical collections of sets tailored for general adversarial structures The initial non empty intersection property has been refined many times to account for e g stronger Byzantine adversarial model latency considerations or better availability This monograph is an overview of the evolution and refinement of quorum systems with emphasis on their role in two fundamental applications distributed read write storage and consensus Table of Contents Introduction Preliminaries Classical Quorum Systems Classical Quorum Based Emulations Byzantine Quorum Systems Latency efficient Quorum Systems Probabilistic Quorum Systems **Consistent Distributed Storage** Vincent Gramoli,Nicolas Nicolaou,Alexander A. Schwarzmann,2022-05-31 Providing a shared memory abstraction in distributed systems is a powerful tool that can simplify the design and implementation of software systems for networked platforms This enables the system designers to work with abstract readable and writable objects without the need to deal with the complexity and dynamism of the underlying platform The key property of shared memory implementations is the consistency guarantee that it provides under concurrent access to the shared objects The most intuitive memory consistency model is atomicity because of its equivalence with a memory system where accesses occur serially one at a time Emulations of shared atomic memory in distributed systems is an active area of research and development The problem proves to be challenging and especially so in distributed message passing settings with unreliable components as is often the case in networked systems We present several approaches to implementing shared memory services with the help of replication on top of message passing distributed platforms subject to a variety of perturbations in the computing medium *Introduction to Distributed Self-Stabilizing Algorithms* Karine Altisen,Stéphane Devismes,Swan Dubois,Franck Petit,2022-05-31 This book aims at being a comprehensive and pedagogical introduction to the concept of self stabilization introduced by Edsger Wybe Dijkstra in 1973 Self stabilization characterizes the ability of a distributed algorithm to converge within finite time to a configuration from which its behavior is correct i e satisfies a given specification regardless the arbitrary initial configuration of the system This arbitrary initial configuration may be the result of the occurrence of a finite number of transient faults Hence self stabilization is actually considered as a versatile non masking fault tolerance approach since it recovers from the effect of any finite number of such faults in an unified manner Another major interest of such an automatic recovery method comes from the difficulty of resetting malfunctioning devices in a large scale and so geographically spread distributed system the Internet Pair to Pair networks and Delay Tolerant Networks are examples of such distributed systems Furthermore self stabilization is usually recognized as a lightweight property to achieve fault tolerance as compared to other classical fault tolerance approaches Indeed the overhead both in terms of time and space of state of the art self stabilizing algorithms is commonly small This makes self stabilization very attractive for distributed systems equipped of processes with low computational and memory capabilities such as wireless sensor networks After more than 40 years of existence self stabilization is now sufficiently established as an important field of research in theoretical distributed computing to justify its teaching in advanced research oriented graduate courses This book is an initiation course which consists of the formal definition of self stabilization and its related concepts followed by a deep review and study of classical simple algorithms commonly used proof schemes and design patterns as well as premium results issued from the self stabilizing community As often happens in the self stabilizing area in this book we focus on the proof of correctness and the analytical complexity of the studied distributed self stabilizing algorithms Finally we underline that most of the algorithms studied in this book are actually dedicated to the high level atomic state model which is the most commonly used computational model in the self stabilizing area However in the last chapter we present general techniques to achieve self stabilization in the low level message passing model as well as example algorithms **Principles of Transactional Memory** Rachid Guerraoui,Michael Kapalka,2022-06-01 Transactional memory TM is an appealing paradigm for concurrent programming on shared memory architectures With a TM threads of an application communicate and synchronize their actions via in memory transactions Each transaction can perform any number of operations on shared data and then either commit or abort When the transaction commits the effects of all its operations become immediately visible to other transactions when it aborts however those effects are entirely discarded Transactions are atomic programmers get the illusion that every transaction executes all its operations instantaneously at some single and unique point in time Yet a TM runs transactions concurrently to leverage the parallelism offered by modern processors The aim of this book is to provide theoretical foundations for transactional memory This includes defining a model of a TM as well as answering precisely when a TM implementation is correct what kind of properties it can ensure what are the power and limitations of a TM and what inherent trade offs are involved in designing a TM algorithm While the focus of this book is on the fundamental principles its goal is to capture the common intuition behind the semantics of TMs and the properties of existing TM implementations Table of Contents Introduction Shared Memory Systems Transactional Memory A Primer TM Correctness Issues Implementing a TM Further Reading Opacity Proving Opacity An Example Opacity vs Atomicity Further Reading The Liveness of a TM Lock Based TMs Obstruction Free TMs General Liveness of TMs Further Reading Conclusions **Distributed Graph Coloring** Leonid Barenboim,Michael Elkin,2022-06-01 The focus of this monograph is on symmetry breaking problems in the message passing model of distributed computing In this model a communication network is represented by a n vertex graph G V E whose vertices host autonomous processors The processors communicate over the edges of G in discrete rounds The goal is to devise algorithms that use as few rounds as possible A typical symmetry breaking problem is the problem of graph coloring Denote by the maximum degree of G While coloring G with 1 colors is trivial in the centralized setting the problem becomes much more challenging in the distributed one One can also compromise on the number of colors if this allows for more efficient algorithms Other typical symmetry breaking problems are the problems of computing a maximal independent set MIS and a maximal matching MM The study of these problems dates back to the very early days of distributed computing The founding fathers of distributed computing laid firm foundations for the area of distributed symmetry breaking already in the eighties In particular they showed that all these problems can be solved in randomized logarithmic time Also Linial showed that an O 2 coloring can be solved very efficiently deterministically However fundamental questions were left open for decades In particular it is not known if the MIS or the 1 coloring can be solved in deterministic polylogarithmic time Moreover until recently it was not known if in deterministic polylogarithmic time one can color a graph with significantly fewer than 2 colors Additionally it was open and still open to some extent if one can have sublogarithmic randomized algorithms for the symmetry breaking problems Recently significant progress was achieved in the study of these questions More efficient deterministic and randomized 1 coloring algorithms were achieved Deterministic 1 o 1 coloring algorithms with polylogarithmic running time were devised Improved and often sublogarithmic time randomized algorithms were devised Drastically improved lower bounds were given Wide families of graphs in which these problems are solvable much faster than on general graphs were identified The objective of our monograph is to cover most of these developments and as a result to provide a treatise on theoretical foundations of distributed symmetry breaking in the message passing model We hope that our monograph will stimulate further progress in this exciting area **Decidability of Parameterized**

Verification Roderick Bloem,Swen Jacobs,Ayrat Kalimov,Igor Konnov,2022-05-31 While the classic model checking problem is to decide whether a finite system satisfies a specification the goal of parameterized model checking is to decide given finite systems n parameterized by n N whether for all n N the system n satisfies a specification In this book we consider the important case of n being a concurrent system where the number of replicated processes depends on the parameter n but each process is independent of n Examples are cache coherence protocols networks of finite state agents and systems that solve mutual exclusion or scheduling problems Further examples are abstractions of systems where the processes of the original systems actually depend on the parameter The literature in this area has studied a wealth of computational models based on a variety of synchronization and communication primitives including token passing broadcast and guarded transitions Often different terminology is used in the literature and results are based on implicit assumptions In this book we introduce a computational model that unites the central synchronization and communication primitives of many models and unveils hidden assumptions from the literature We survey existing decidability and undecidability results and give a systematic view of the basic problems in this exciting research area **Distributed Computing Pearls** Gadi Taubenfeld,2022-05-31 Computers and computer networks are one of the most incredible inventions of the 20th century having an ever expanding role in our daily lives by enabling complex human activities in areas such as entertainment education and commerce One of the most challenging problems in computer science for the 21st century is to improve the design of distributed systems where computing devices have to work together as a team to achieve common goals In this book I have tried to gently introduce the general reader to some of the most fundamental issues and classical results of computer science underlying the design of algorithms for distributed systems so that the reader can get a feel of the nature of this exciting and fascinating field called distributed computing The book will appeal to the educated layperson and requires no computer related background I strongly suspect that also most computer knowledgeable readers will be able to learn something new *New Models for Population Protocols* Othon Michail,Ioannis Chatzigiannakis,Paul G. Spirakis,2022-05-31 Wireless sensor networks are about to be part of everyday life Homes and workplaces capable of self controlling and adapting air conditioning for different temperature and humidity levels sleepless forests ready to detect and react in case of a fire vehicles able to avoid sudden obstacles or possibly able to self organize routes to avoid congestion and so on will probably be commonplace in the very near future Mobility plays a central role in such systems and so does passive mobility that is mobility of the network stemming from the environment itself The population protocol model was an intellectual invention aiming to describe such systems in a minimalistic and analysis friendly way Having as a starting point the inherent limitations but also the fundamental establishments of the population protocol model we try in this monograph to present some realistic and practical enhancements that give birth to some new and surprisingly powerful for these kind of systems computational models Table of Contents Population Protocols The Computational Power of Population Protocols

Enhancing the model Mediated Population Protocols and Symmetry Passively Mobile Machines that Use Restricted Space Conclusions and Open Research Directions Acronyms Authors Biographies **Impossibility Results for Distributed Computing** Hagit Attiya,Faith Ellen,2022-06-01 To understand the power of distributed systems it is necessary to understand their inherent limitations what problems cannot be solved in particular systems or without sufficient resources such as time or space This book presents key techniques for proving such impossibility results and applies them to a variety of different problems in a variety of different system models Insights gained from these results are highlighted aspects of a problem that make it difficult are isolated features of an architecture that make it inadequate for solving certain problems efficiently are identified and different system models are compared **The Theory of Timed I/O Automata, Second Edition** Dilsun Kaynar,Nancy Lynch,Roberto Segala,Frits Vaandrager,2022-06-01 This monograph presents the Timed Input Output Automaton TIOA modeling framework a basic mathematical framework to support description and analysis of timed computing systems Timed systems are systems in which desirable correctness or performance properties of the system depend on the timing of events not just on the order of their occurrence Timed systems are employed in a wide range of domains including communications embedded systems real time operating systems and automated control Many applications involving timed systems have strong safety reliability and predictability requirements which make it important to have methods for systematic design of systems and rigorous analysis of timing dependent behavior The TIOA framework also supports description and analysis of timed distributed algorithms distributed algorithms whose correctness and performance depend on the relative speeds of processors accuracy of local clocks or communication delay bounds Such algorithms arise for example in traditional and wireless communications networks of mobile devices and shared memory multiprocessors The need to prove rigorous theoretical results about timed distributed algorithms makes it important to have a suitable mathematical foundation An important feature of the TIOA framework is its support for decomposing timed system descriptions In particular the framework includes a notion of external behavior for a timed I O automaton which captures its discrete interactions with its environment The framework also defines what it means for one TIOA to implement another based on an inclusion relationship between their external behavior sets and defines notions of simulations which provide sufficient conditions for demonstrating implementation relationships The framework includes a composition operation for TIOAs which respects external behavior and a notion of receptiveness which implies that a TIOA does not block the passage of time The TIOA framework also defines the notion of a property and what it means for a property to be a safety or a liveness property It includes results that capture common proof methods for showing that automata satisfy properties Table of Contents Introduction Mathematical Preliminaries Describing Timed System Behavior Timed Automata Operations on Timed Automata Properties for Timed Automata Timed I O Automata Operations on Timed I O Automata Conclusions and Future Work *Distributed Computing by Oblivious Mobile Robots* Paola Flocchini,Giuseppe Prencipe,Nicola

Santoro,2022-06-01 The study of what can be computed by a team of autonomous mobile robots originally started in robotics and AI has become increasingly popular in theoretical computer science especially in distributed computing where it is now an integral part of the investigations on computability by mobile entities The robots are identical computational entities located and able to move in a spatial universe they operate without explicit communication and are usually unable to remember the past they are extremely simple with limited resources and individually quite weak However collectively the robots are capable of performing complex tasks and form a system with desirable fault tolerant and self stabilizing properties The research has been concerned with the computational aspects of such systems In particular the focus has been on the minimal capabilities that the robots should have in order to solve a problem This book focuses on the recent algorithmic results in the field of distributed computing by oblivious mobile robots unable to remember the past After introducing the computational model with its nuances we focus on basic coordination problems pattern formation gathering scattering leader election as well as on dynamic tasks such as flocking For each of these problems we provide a snapshot of the state of the art reviewing the existing algorithmic results In doing so we outline solution techniques and we analyze the impact of the different assumptions on the robots computability power Table of Contents Introduction Computational Models Gathering and Convergence Pattern Formation Scatterings and Coverings Flocking Other Directions **Cooperative Task-Oriented Computing** Chryssis Georgiou,Alexander Shvartsman,2022-06-01 Cooperative network supercomputing is becoming increasingly popular for harnessing the power of the global Internet computing platform A typical Internet supercomputer consists of a master computer or server and a large number of computers called workers performing computation on behalf of the master Despite the simplicity and benefits of a single master approach as the scale of such computing environments grows it becomes unrealistic to assume the existence of the infallible master that is able to coordinate the activities of multitudes of workers Large scale distributed systems are inherently dynamic and are subject to perturbations such as failures of computers and network links thus it is also necessary to consider fully distributed peer to peer solutions We present a study of cooperative computing with the focus on modeling distributed computing settings algorithmic techniques enabling one to combine efficiency and fault tolerance in distributed systems and the exposition of trade offs between efficiency and fault tolerance for robust cooperative computing The focus of the exposition is on the abstract problem called Do All and formulated in terms of a system of cooperating processors that together need to perform a collection of tasks in the presence of adversity Our presentation deals with models algorithmic techniques and analysis Our goal is to present the most interesting approaches to algorithm design and analysis leading to many fundamental results in cooperative distributed computing The algorithms selected for inclusion are among the most efficient that additionally serve as good pedagogical examples Each chapter concludes with exercises and bibliographic notes that include a wealth of references to related work and relevant advanced results Table of Contents Introduction Distributed Cooperation and Adversity Paradigms and

Techniques Shared Memory Algorithms Message Passing Algorithms The Do All Problem in Other Settings Bibliography Authors Biographies Link Reversal Algorithms Jennifer Welch,Jennifer Walter,2022-05-31 Link reversal is a versatile algorithm design technique that has been used in numerous distributed algorithms for a variety of problems The common thread in these algorithms is that the distributed system is viewed as a graph with vertices representing the computing nodes and edges representing some other feature of the system for instance point to point communication channels or a conflict relationship Each algorithm assigns a virtual direction to the edges of the graph producing a directed version of the original graph As the algorithm proceeds the virtual directions of some of the links in the graph change in order to accomplish some algorithm specific goal The criterion for changing link directions is based on information that is local to a node such as the node having no outgoing links and thus this approach scales well a feature that is desirable for distributed algorithms This monograph presents in a tutorial way a representative sampling of the work on link reversal based distributed algorithms The algorithms considered solve routing leader election mutual exclusion distributed queueing scheduling and resource allocation The algorithms can be roughly divided into two types those that assume a more abstract graph model of the networks and those that take into account more realistic details of the system In particular these more realistic details include the communication between nodes which may be through asynchronous message passing and possible changes in the graph for instance due to movement of the nodes We have not attempted to provide a comprehensive survey of all the literature on these topics Instead we have focused in depth on a smaller number of fundamental papers whose common thread is that link reversal provides a way for nodes in the system to observe their local neighborhoods take only local actions and yet cause global problems to be solved We conjecture that future interesting uses of link reversal are yet to be discovered Table of Contents Introduction Routing in a Graph Correctness Routing in a Graph Complexity Routing and Leader Election in a Distributed System Mutual Exclusion in a Distributed System Distributed Queueing Scheduling in a Graph Resource Allocation in a Distributed System Conclusion **Distributed Algorithms for Message-Passing Systems** Michel Raynal,2013-06-29 Distributed computing is at the heart of many applications It arises as soon as one has to solve a problem in terms of entities such as processes peers processors nodes or agents that individually have only a partial knowledge of the many input parameters associated with the problem In particular each entity cooperating towards the common goal cannot have an instantaneous knowledge of the current state of the other entities Whereas parallel computing is mainly concerned with efficiency and real time computing is mainly concerned with on time computing distributed computing is mainly concerned with mastering uncertainty created by issues such as the multiplicity of control flows asynchronous communication unstable behaviors mobility and dynamicity While some distributed algorithms consist of a few lines only their behavior can be difficult to understand and their properties hard to state and prove The aim of this book is to present in a comprehensive way the basic notions concepts and algorithms of distributed computing when the distributed entities cooperate by sending and receiving messages on top of an asynchronous network The book is composed of seventeen chapters structured into six parts distributed graph algorithms in particular what makes them different from sequential or parallel algorithms logical time and global states the core of the book mutual exclusion and resource allocation high level communication abstractions distributed detection of properties and distributed shared memory The author establishes clear objectives per chapter and the content is supported throughout with illustrative examples summaries exercises and annotated bibliographies This book constitutes an introduction to distributed computing and is suitable for advanced undergraduate students or graduate students in computer science and computer engineering graduate students in mathematics interested in distributed computing and practitioners and engineers involved in the design and implementation of distributed applications The reader should have a basic knowledge of algorithms and operating systems

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