Mastering Concurrent Computing
Through Sequential Thinking:
A Half-century Evolution

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Abstract

Concurrency, the art of doing many things at the same time is slowly becoming a science. It is very difficult to master, yet it arises all over modern computing systems, both when the communication medium is shared memory and when it is by message passing. Concurrent programming is hard because it requires to cope with many possible, unpredictable behaviors of communicating processes interacting with each other. Right from the start in the 1960s, the main way of dealing with concurrency has been by reduction to sequential reasoning. We trace this history, and illustrate it through several examples, from early ideas based on mutual exclusion, passing through consensus and concurrent objects, until today ledgers and blockchains. We conclude with a discussion on the limits that this approach encounters, related to fault-tolerance, performance, and inherently concurrent problems.

Keywords: Agreement, Asynchrony, Atomicity, Concurrent object, Consensus, Consistency condition, Crash failure, Fault-tolerance, Ledger, Linearizability, Message-passing, Mutual exclusion, Progress condition, Read/write register, Sequential thinking, Sequential specification, State machine replication, Synchronization, Total order broadcast, Universal construction.
INTRODUCTION

Sequential reasoning is natural and easier. The human brain behaves as a multiprocessor computer, which performs many tasks simultaneously, naturally and frequently. However, despite the fact we are good at processing parallel information, it is difficult to be aware of the activities we perform concurrently, and when we try to raise awareness, we end up distracting ourselves and reducing the quality of what we are doing. Only after intense training can we, like a musician, conduct several activities simultaneously.

It is infinitely easier to reason sequentially, doing only one thing at a time, than to understand situations where many things occur simultaneously. Furthermore, we are limited by our main communication mechanisms with others, spoken or written language, which are inherently sequential. These convey information in parallel through the voice tone, facial and body expressions, writing style, etc., but we are often unaware of it. Thus, while we are ‘parallel processors’, and we leave in a world where multiple things happen at the same time, we usually reason by reduction to a sequential world.

The same happens in computing. It is much easier to reason about a sequential program, than about one in which operations are executed concurrently.

The grand challenge. For more than fifty years, one of the most daunting challenges in information science and technology lies in mastering concurrency. Concurrency, once a specialized discipline for experts, is forcing itself onto the entire IT community because of two disruptive phenomena: the development of networking communications, and the end of the ability to increase processors speed at an exponential rate. Increases in performance can only come through concurrency, as in multicore architectures. Concurrency is also critical to achieve fault-tolerant, distributed available services, as in distributed databases and cloud computing. Yet, software support for these advances lags, mired in concepts from the 1960s such as semaphores. The problem is compounded by the inherently nondeterministic nature of concurrent programs: even minor timing variations may generate completely different behavior. Sometimes tricky forms of concurrency faults can appear, such as data races (where even though two concurrent threads handle a shared data item in a way that is correct from each thread’s perspective, a particular run-time interleaving produces inconsistent results), and others, such as deadlocks (situation where some threads still have computations to execute, while none of them can proceed as each is waiting for another one to proceed), improper scheduling of threads or processes, priority inversions (where some processes do not proceed because the resources they need are unduly taken away by others) and various kinds of failures of the processes and communication mechanisms. The result is that it is very difficult to develop concurrent applications. Concurrency is also the means to achieve high performance computing, but in this paper we are not concerned with such applications.

A classic synchronization difficulty. Let us consider the following classical illustration of the concurrency difficulties in software engineering. A bank account is shared by a group of people. The rule is that if the balance drops below a certain threshold, $L$, some high interest will be charged. Thus, each time a member of the group wants to withdraw some amount of money, $x$, she first needs to send a message to the bank to make sure the balance is greater than or equal to $L + x$. Only then she will send a message asking to withdraw $x$ from the account. Without any synchronization, it is impossible to maintain the invariant that the balance of the account is always at least $L$, unless of course no withdrawals are ever done. Even assuming that the participants can directly access the account, synchronization is needed.
Namely, suppose members of the group can issue `read()` operations, that directly return the current balance in the account, and execute `withdraw(x)` operations that reduce the balance by $x$. If Alice asks for the balance and gets back a value $z > L + x$, she cannot then issue a `withdraw(x)` operation, because she might be a bit slower than Bob, who could very fast issue `read()` and then `withdraw(x)`, just after of Alice invoked `read()` but before she invokes `withdraw(y)`.

**What does concurrent computing through sequential thinking mean?** Instead of trying to reason directly about concurrent computations, the idea is to transform problems in the concurrent domain into simpler problems in the sequential domain, yielding benefits for specifying, implementing, and verifying concurrent programs. It is a two-sided strategy, together with a bridge connecting them:

- Sequential specifications for concurrent programs.
- Concurrent implementations.
- Consistency conditions relating concurrent implementations to sequential specifications.

Although a program is concurrent, the specification of the object (or service) that is implementing is usually through a *sequential specification*, stating the desired behavior only in executions where the processes execute one after the other, and often through familiar paradigms from sequential computing (such as queues, stacks and lists). In the previous example, when we state the rule that if the balance drops below a certain threshold, $L$, some high interest will be charged, we are thinking of an account which is always in an *atomic* state, i.e., a state where the balance is well defined. This makes it easy to understand the object being implemented, as opposed to a truly concurrent specification which would be hard or unnatural. Thus, instead of trying to modify the well-understood notion of say, a queue, we stay with the usual sequential specification, and move to another level of the system the meaning of a concurrent implementation of a queue.

The second part of the strategy is to provide *implementation techniques* for efficient, scalable, and fault-tolerant concurrent objects. Additionally, bridging techniques show how to obtain concurrent executions that appear to the processes as if the operations invoked on the object where executed atomically, in some sequential interleaving. This is captured by the notion of a *consistency* condition, which defines the way concurrent invocations to the operations of an object correspond to a sequential interleaving, which can then be tested against the sequential specification.

**A brief history.** The history of concurrency is long; a few milestones are in the Sidebar. The interested reader will find many more results in textbooks on shared memory [48, 58, 70], and message-passing systems [3, 48, 61]. We concentrate here only on a few significant examples of sequential reasoning used to master concurrency, highlighting fundamental notions of this approach (such as: sequential specifications, consistency (linearizability), progress conditions (availability), universal constructions, the need to solve consensus for fault-tolerance, strong shared objects as a way of solving consensus, and distributed ledgers). We describe several algorithms as a concrete illustration of the ideas. We tell the story through an evolution that starts with mutual exclusion, followed by implementing read/write registers on top of message passing systems, then implementing arbitrary objects, and finally doing so in a fault-tolerant way through powerful synchronization objects. We discuss the modern distributed ledger trends of doing so in a highly scalable, tempered-proof way.

We conclude with a discussion of the limitations of this approach: it is expensive to require atomicity (linearizability), and furthermore, there are inherently concurrent problems with no sequential specifications.
Sidebar 1: History of synchronization: a few important dates

1965
- Mutual exclusion from atomic read/write registers [16]

1971
- Semaphores [18]

1974
- Mutual exclusion from non-atomic read/write registers [39]

1977, 1983
- Concurrent reading and writing [40], [54]

1978
- Distributed state machine [41] (DA 2000)

1980, 1982
- Byzantine failures in synchronous systems [46, 52] (DA 2005)

1981
- Simplicity in mutex algorithms [53]

1983
- Asynchronous randomized Byzantine consensus [4, 55] (DA 2015)

1985
- Liveness (progress condition) [1] (DA 2018)
- Impossibility of asynchronous deterministic consensus in the presence of process crashes [22] (DA 2001)

1987
- Fast mutual exclusion [44]

1991
- Wait-free synchronization [31] (DA 2003)

1993, 1997
- Transactional memory [33, 68] (DA 2012)

1995
- Shared memory on top of asynchronous message-passing systems despite a minority of process crashes [2] (DA 2011)

1996
- Weakest information on failures to solve consensus in the presence of asynchrony and process crashes [12, 13] (DA 2010)

2008
- Scalability, accountability [50]

1982, 2010
- Distributed recursion [24, 45]

2011, 2016
- Distributed universality [2, 3, 51, 63]

Some of the previous papers were awarded the famous ACM-EATCS Dijkstra Award. Created in 2000, this award is given to outstanding papers on the principles of distributed computing, whose significance and impact on the theory and/or practice of distributed computing have been evident for at least a decade. In the history line, “[aa] DA b cde” means “paper(s) referenced [aa] received the Dijkstra Award in the year b cde”.

The interested reader will find recent textbooks on shared memory synchronization in [35, 58, 55, 70], and message-passing synchronization in [3, 8, 25, 38, 48, 58, 61, 64].
Concurrent computing began in 1961 with what was called *multiprogramming* in the Atlas computer, where concurrency was simulated – as we do when telling stories where things happen concurrently – interlacing the execution of sequential programs. Concurrency was born in order to make efficient use of a sequential computer, which can execute only one instruction at a time, giving users the illusion that their programs are all running simultaneously, through the operating system. A collection of early foundational articles on concurrent programming appears in [6].

As soon as the programs being run concurrently began to interact with each other, it was realized how difficult it is to think concurrently. By the end of the 1960s there was already talk of a crisis: programming was done without any conceptual foundation and lots of programs were riddled with subtle errors causing erratic behaviors. In 1965 Dijkstra discovered that the *mutual exclusion* of parts of code is a fundamental concept of programming, and opened the way for the first books of principles on concurrent programming which appeared at the beginning of the 1970s.

1970s, multi-processor computers were built, and in 1967 there were debates about their computing computing and what is known today as Amdahl’s Law. In the late 1970s a move occurred from multiprocessors with shared memory to multicomputers with distributed memory communicating by sending messages. In the 1990s, the importance of shared memory with multicores, returns, as it meets the barriers of energy expenditure, and the limits of making processors increasingly faster, emphasizing that the exponential growth prophesied by Moore’s Law refers to packaging more and more components on the same chip, that is more and more parallel computing. And now entering a new generation of distributed systems motivated by new distributed services and blockchain-like applications, where we are building huge distributed systems open and tolerant to arbitrarily malicious faults. Nevertheless, while both parallel computing and distributed computing involves concurrency, they are different address different computing worlds (see Sidebar 2).

As far as terminology is concerned we consider the following definitions (from [61]).

- **Parallel computing.** Parallel computing addresses concepts, methods, and strategies which allow us to benefit from parallelism (simultaneous execution of distinct threads or processes) when one has to implement a computation. The essence of parallel computing lies in the decomposition of the computation in independent computation units and exploit their independence to execute as many of them as possible in parallel (simultaneously) so that the resulting execution is time-efficient.

- **Distributed computing.** Distributed computing arises when one has to solve a problem involving geographically distributed entities (processors, nodes, sensors, peers, agents, etc.), such that each entity only has a partial knowledge of the many input parameters involved in the problem to be solved. Because their knowledge is partial, these computing entities must cooperate to solve the problem. They also must cope with their environment, which can be modeled as adversaries, such as asynchrony, failures, mobility, etc. These adversaries create an uncertainty on the state of the system, uncertainty that has to be understood and mastered if one wants to produce correct distributed software.

As we can see, parallel and distributed computing are in some sense dual: one consists in decomposing a computation into independent entities, while the other consists in allowing pre-existing entities – whose distribution is not under the control of the programmer – to cooperate in the presence of adversaries such as the net effect of asynchrony and process failures.

Sidebar 2: Distributed computing versus parallel computing: the two faces of concurrency
**Mutual exclusion.** A mutual exclusion algorithm consists of the code for two operations, \(\text{acquire}()\) and \(\text{release}()\), that a process invokes to bracket a section of code called a *critical section*. The usual environment in which a mutual exclusion algorithm is executed is *asynchronous*, where process speeds are arbitrary, independent from each other. The mutual exclusion algorithm should guarantee two conditions.

- Mutual exclusion. No two processes are simultaneously executing their critical section.
- Deadlock-freedom. if one or several processes invoke concurrently \(\text{acquire}()\), eventually one of them terminates its invocation, and consequently executes its critical section.

**Progress conditions.** When Dijkstra introduced mutual exclusion [16], he also introduced the previous progress condition, called *deadlock-freedom*. As observed by D.E. Knuth in [37], Deadlock-freedom does not prevent specific timing scenarios from occurring in which some processes can never enter their critical section. Hence, he proposed The stronger *starvation-freedom* progress condition, states that any process that invokes \(\text{acquire}()\) will terminate its invocation (and will consequently execute its critical section).

**On mutual exclusion algorithms from atomic read/write registers.** The first mutual exclusion algorithms were abstruse, difficult to understand and prove correct (some of them are collected in [57]). We describe here an elegant algorithm by Peterson [53]. The version presented in Algorithm 1 is for two processes, but can be easily generalized to \(n\) processes.

The two processes \(p_1\) and \(p_2\) share three read/write atomic registers, \(\text{FLAG}[1]\), \(\text{FLAG}[2]\), and \(\text{LAST}\). Initially \(\text{FLAG}[1]\), \(\text{FLAG}[2]\), are down, while \(\text{LAST}\) does not need to be initialized. Both processes can read all registers. Moreover, while \(\text{LAST}\) can be written by both processes, only \(p_i, i \in \{1, 2\}\), writes to \(\text{FLAG}[i]\). *Atomic* means that the read and write operations on the registers appear as if they have been executed sequentially (hence, the notion of “last writer” associated with \(\text{LAST}\) is well defined).

```
operation acquire() is % invoked by \(p_i, i \in \{1, 2\}\)
    \(\text{FLAG}[i] \leftarrow \text{up}; \text{LAST} \leftarrow i; \text{let } j = 3 - i;\)
    wait ((\(\text{FLAG}[j] = \text{down}\)) \lor (\text{LAST} \neq i));
    return()
end operation.

operation release() is \(\text{FLAG}[i] \leftarrow \text{down}; \text{return()}\) end operation.
```

Algorithm 1: Peterson’s algorithm for two processes

When process \(p_i\) invokes \(\text{acquire}()\), it first raises its flag, thereby indicating it is competing, and then writes its name in \(\text{LAST}\) indicating it is the last writer of this register. Next process \(p_j\) repeatedly reads \(\text{FLAG}[j]\) and \(\text{LAST}\) until it sees \(\text{FLAG}[j] = \text{down}\) or it is no longer the last writer of \(\text{LAST}\). When this occurs, \(p_i\) terminates its invocation. The operation \(\text{release()}\) consists in a simple lowering of the flag of the invoking process. The read and write operations on \(\text{FLAG}[1]\), \(\text{FLAG}[2]\), and \(\text{LAST}\) are totally ordered (atomicity), which facilitates the proof of the mutual exclusion and starvation-freedom properties.

Mutual exclusion was the first mechanism for mastering concurrent programming through sequential thinking, and lead to the identification of notions that began to give a scientific foundation to the approach, such as the concepts of *progress condition* and *atomicity*. 
Fast mutual exclusion and adaptive algorithms. The previous algorithm can be easily generalized to solve mutual exclusion in a set of $n \geq 2$ processes. Many $n$-process mutual exclusion algorithms have been proposed, in which each process must solve $(n - 1)$ conflicts to access the critical section. An algorithm in which the number of read and write accesses to shared registers is constant in contention-free scenarios appears in Lamport [44]. This article is the origin of research on adaptive algorithms, whose complexity depends on the concurrency pattern in which operations are invoked.

Atomicity from non-atomic read/write registers. The previous algorithms implements mutual exclusion using underlying atomic read/write registers. In fact, this hardware atomicity is not required, Lamport [39], showed that mutual exclusion can be achieved using only safe registers [43]. Several algorithms building atomic read/write registers from non-atomic read/write registers are described in e.g., 58 [70].

On the database side. The concept of a transaction was introduced in database as a computation unit (usually, an operation-based translation of a query expressed in a specific query language) [28]. The management of transactions introduced the notion of concurrency control, which gave rise to several approaches to ensure that transactions appear as if they had been executed sequentially [5] [51].

Transactional memory. The concept of transactional memory (TM) was introduced by M. Herlihy and J. Moss in 1993 [33], and then investigated from a pure software point of view (STM) by N. Shavit and D. Touitou in 1997 [68].

The aim of a TM/STM system is to discharge the programmers from the management of synchronization in multiprocess programs that access concurrent objects. To that end, an TM/STM system provides the programmer with the concept of a transaction. Basically, the job of the programmer is to design each process of the application as a sequence of transactional code and non-transactional code, where a transaction is any piece of code that accesses concurrent objects, but contains no explicit synchronization statement, and non-transactional code does not access concurrent objects. It is then the job of the underlying TM/STM system to provide the illusion that each transaction appears as being executed atomically (see Sidebar 3, where each read or write operation is replaced by a transaction). Executing each transaction in a critical section would solve the problem, but this would be inefficient. So, for efficiency, a TM/STM system must allow transactions to execute concurrently. The major parts of a TM/STM systems execute transaction in a speculative mode at the end of with a transaction is committed or aborted. According to the TM/STM system, the recovery of a transaction can be under the control of either the system or the invoking process. Examples of STM systems based on different underlying principles can be found in [9] [15].

As we can see, a TM/STM system allows the programmer to concentrate on the problem it has to solve and not on the way the required synchronization must be implemented. In this sense it provides the programmer with a higher abstraction level. It is important to see that a transaction can be any piece of code (and not a code obtained from a specific query language as in databases). TM/STM provides programmers with a tool from which they can see executions as sequences of transactional codes.

The important point here is that both concurrency control in database and transactional memory aim at providing an abstraction level at which the users see an execution as if it was produced by a sequential processor.
FROM RESOURCES TO OBJECTS

From physical resources to services. At the beginning, a critical section was encapsulating the use of a physical resource, which by its own nature, is sequentially specified (e.g., disk, printer, processor). Conceptually not very different, it was then used to protect concurrent accesses to preserve consistency of simple data (such as a file in the readers/writers problem [14]). However, when critical sections began to be used to encapsulate more general shared objects, new ideas were needed.

Data are not physical resources. A shared object is different from a physical object, in that it does not a priori require exclusive access; a process can read the data of a file while another process concurrently modifies it. The mutex-free (also called lock-free) approach (introduced by Lamport in [40]), makes possible to envisage implementations of purely digital objects in which operation executions are free from mutual exclusion and can overlap in time, none of them depending of the others to terminate [31] (see progress conditions defined below).

Consistency conditions. Wherever concurrent accesses to share data take place, a consistency condition is needed to define what does it mean to correctly execute concurrently operations, especially in the presence of buffers and memory caches (that are defined only in sequential executions, such as read/write operations). Instead of transforming a concurrent execution into sequential execution (as in mutual exclusion), the idea appears to enforce only virtual sequentiality, namely, from an external observer point of view, everything must appear as if the operations were executed sequentially, thereby reducing—at a higher abstraction layer—concurrent computing to sequential computing. When the total order on the operations is required to respect the order on non-overlapping operations, this virtual sequentiality is called atomicity [43] or linearizability [36] (these two terms are synonyms). This is illustrated in Sidebar 3 which describes an execution in which three processes access an atomic read/write register $R$.

A short historical perspective. Since early on in 1976, in the database context, serializability [51, 66] of transactions that aggregate many operations without locking and unlocking entities was generally accepted as the right notion of correctness: to require that transactions appear to have executed atomically. In the concurrent programming the equivalent notion of sequential consistency was used, but for individual operations [42]. Later on, realizing that this type of condition is not composable, linearizability [36] required additionally that this sequential order must also preserve the global ordering of non-overlapping operations. Linearizability may be preferred over sequential consistency, because a system made of linearizable implementations is linearizable.

The environment has an impact on computations: crash failures. Let us remark that mutual exclusion cannot work when one has to implement an object in the presence of asynchrony and process crashes (premature halting). If a process crashes inside its critical section, mutual exclusion will never be released, and no other process will be able to access the object. It follows that the use of mutual exclusion (locks) is limited in the presence of asynchrony and process crashes.

On progress conditions in the presence of crash failures. Three progress conditions have been proposed for the implementation of the operations of data objects in an environment where processes are asynchronous and may crash. They are the following ones, going from the stronger to the weaker (see Table I).

- The wait-freedom progress condition states that if a process invokes an object operation, and does not crash, it terminates its invocation [31]. This means that it terminates whatever the behavior of
An atomic (linearizable) execution of processes $p_1$, $p_2$, and $p_3$ on atomic register $R$. The read and write operations are denoted $R.\text{read}()$ and $R.\text{write}()$. From an external observer point of view, it appears as if the operations were executed sequentially.

Sidebar 3: An atomic execution of a read/write register

the other processes (e.g., some of them being crashed, and others being concurrently involved in object operations).

- The non-blocking progress condition states that if several processes concurrently invoke operations on the object, at least one of them terminates [36].

- The obstruction-freedom progress condition states that if a process invokes an operation, does not crash during this invocation, and all other processes stop accessing the internal representation of the object during a long enough period, then the process terminates its operation [32].

Let us remark that the wait-freedom and non-blocking progress conditions are independent of both the failure pattern and the concurrency pattern. They can be seen as the “corresponding” of starvation-freedom and deadlock-freedom in asynchronous crash-prone system. Differently, obstruction-freedom is dependent on the concurrency pattern.

| Lock-based implementations | Mutex-free implementations |
|---------------------------|---------------------------|
| Deadlock-freedom [16]     | Non-blocking [36]         |
| Starvation-freedom [37]   | Wait-freedom [32]         |

Table 1: Progress conditions for the implementation of concurrent objects

READ/WRITE REGISTERS ON TOP OF MESSAGE-PASSING SYSTEMS

The read/write shared register abstraction provides several advantages over message passing: a more natural transition from uniprocessors, and simplifies programming tasks. For this reason, concurrent systems that support shared memory are have wide acceptance in both research and commercial computing.

It is relatively easy to build atomic read/write registers on top of a reliable asynchronous message-passing system (e.g. [59]), but if processes may crash, more involved algorithms are needed. Two important results are presented by Attiya, Bar-Noy and Dolev in [2]:

- An algorithm that implements an atomic read/write register on top of a system of $n$ asynchronous message-passing processes, where at most $t < n/2$ of them may crash.
• A proof of the impossibility of building an atomic read/write register when \( t \geq n/2 \).

The section presents the algorithm, referred to as the ABD Algorithm, which illustrates the importance of the ideas of reducing concurrent thinking to sequential reasoning. A more detailed proof can be found in [2,3,61], as well as other algorithms.

**Design principles of ABD: each written value has an identity.** Each process is both a client and a server. Let \( REG \) be the multi-writer multi-reader (MWMR) register that is built (hence any process is allowed to read and write the register). On its client side a process \( p_i \) can invoke the operations \( REG\text{.}write(v) \) (to write a value \( v \) in \( REG \), and \( REG\text{.}read() \) to obtain its current value. On its server side, a process \( p_i \) manages two local variables: \( reg_i \) which locally implement \( REG \), and \( timestamp_i \) which contains a timestamp made up of a sequence number (which can be considered as a date) and a process identity \( j \). The timestamp \( timestamp_i \) constitutes the “identity” of the value \( v \) saved in \( reg_i \) (namely, this value was written by this process at this time). Any two timestamps \( \langle sn_i, i \rangle \) and \( \langle sn_j, j \rangle \) are totally ordered by their lexicographical order; namely, \( \langle sn_i, i \rangle < \langle sn_j, j \rangle \) means \( (sn_i < sn_j) \lor (sn_i = sn_j \land i < j) \).

**Design principles of ABD: intersecting quorums.** The basic mechanism on which ABD relies on a query/response message exchange pattern. A process \( p_i \) broadcasts a query to all the processes and waits for acknowledgments from a majority of them. Such a majority quorum set, has the following properties. As \( t < n/2 \), waiting for acknowledgments from a majority of processes can never block forever the invoking process. Moreover, the fact that any two quorums have a non-empty intersection implies the atomicity property of the read/write register \( REG \).

```
operation REG.write (v) issued by process \( p_i \) is
    build a new tag tag identifying this write operation;
    % Phase 1: acquire information on the system state %
    broadcast WRITE_REQ (tag);
    wait acknowledgments from a majority of processes,
    each carrying tag and a sequence number;
    % Phase 2 : update system state %
    ts ← \( \langle msn + 1, i \rangle \) where msn is
    the greatest sequence number previously received;
    broadcast WRITE (tag, v, ts);
    wait acknowledgments carrying tag from a majority of proc.;
    return().

when WRITE_REQ (tag) is received from \( p_j \), \( j \in \{1, \ldots, n\} \) do
    send to \( p_j \) an acknowledgment carrying tag, and
    the sequence number contained in timestamp_i.

when WRITE (tag, v, ts) is received from \( p_j \), \( j \in \{1, \ldots, n\} \) do
    if (timestamp_i < ts) then
        timestamp_i ← ts; reg_i ← v
    end if;
    send to \( p_j \) an acknowledgment carrying tag.
```

Algorithm 2: Operation \( REG\text{.}write (v) \): client and server behavior for a process \( p_i \)

**The operation \( REG\text{.}write (v) \).** This operation is implemented by Algorithm 2. When a process \( p_i \) invokes \( REG\text{.}write (v) \), it first creates a tag denoted \( \langle tag \rangle \) which will identify the query/response messages generated by this write invocation. Then (phase 1), it executes a first instance of the query/response exchange pattern to learn the highest sequence number saved in the local variables \( timestamp_j \) of a majority of processes \( p_j \). When this is done, \( p_i \) computes the timestamp \( ts \) which will be associated with the
value \(v\) it wants to write in \(REG\). Finally (phase 2), \(p_i\) starts a second query/response pattern in which it broadcasts the pair \((v, ts)\) to all the processes. When, it has received the associated acknowledgments from a quorum, \(p_i\) terminates the write operation.

On its server side, a process \(p_i\) that receives a \(WRITE\_REQ\) message sent by a process \(p_j\) during phase 1 of a write operation, sends it back an acknowledgment carrying the sequence number associated with the last value it saved in \(reg_i\). When it receives \(WRITE\_REQ\) message sent by a a process \(p_j\) during phase 2 of a write operation, it updates its local data \(reg_i\) implementing \(REG\) if the received timestamp is more recent (with respect to the total order on timestamps) than the one saved in \(timestamp_i\), and, in all cases, it sends back to \(p_j\) and acknowledgment (so \(p_j\) terminates its write).

It is easy to see that, due to the intersection property of quorums, the timestamp associated with a value \(v\) by the invoking process \(p_i\) is greater than the ones of the write operations that terminated before \(p_i\) issued its own write operation. Moreover, while concurrent write operations can associate the same sequence number with their values, these values have different (and ordered) timestamps.

**The operation \(REG.read()\).** Algorithm 3 implements operation operation \(REG.read()\), with a similar structure as the implementation of operation \(REG.write()\). Namely, it is made up of two phases, each one being an instance of the query/response communication pattern. In the first phase, the invoking process obtains a pair (value, associated timestamp) from a minority of processes, from which – thanks to the total order on timestamps – it can extract the most recent value, that it will return as the result of the read operation.

```
operation REG.read() is
    build a new tag tag identifying this read operation;
    % Phase 1: acquire information on the system state
    broadcast READ_REQ(tag);
    wait acknowledgments from a majority of processes,
    each carrying tag and a pair (value,timestamp);
    let ts be the greatest timestamp received,
    and v the value associated with this timestamp;
    % Phase 2 : update system state
    broadcast WRITE(tag, v, ts);
    wait ACK_WRITE(tag) from a majority of proc.;
    return (v).
```

**Algorithm 3:** Operation \(REG.read()\): client and server behavior for a process \(p_i\)

Notice that the following scenario can occur, which involves two read operations \(read1\) and \(read2\) on a register \(REG\) by the processes \(p_1\) and \(p_2\), respectively, and a concurrent write operation \(REG.write(v)\) issued by a process \(p_3\) (Fig. 1). Let \(ts(v)\) be the timestamp associated with \(v\) by \(p_3\).

It is possible that the phase 1 majority quorum obtained by \(p_1\) includes the pair \((v, ts(v))\), while the one obtained by \(p_2\) does not. If this occurs, the first read operation \(read1\) obtains a value more recent that the one obtained by the second \(read2\), which violates atomicity. This can be easily solved by directing each read operation to write the value it is about to return as a result. In this way, when \(read1\) terminates and returns \(v\), this value is known by a majority of processes despite asynchrony, concurrency, and a minority of process crashes. This phenomenon (called *new/old inversion*) is prevented by the phase 2 of a read operation.

The combination of intersecting quorums and timestamps allows for the implementation of atomic read/write registers in asynchronous message-passing systems where a minority of process may crash. Hence, sequential thinking on shared registers can be used at the upper abstraction level.
The phase 1 majority quorum obtained by \( p_1 \) contains the pair \((v, t\text{stamp}(v))\). The phase 1 majority quorum obtained by \( p_2 \) does not contain the pair \((v, t\text{stamp}(v))\).

Figure 1: New/old inversion scenario

THE WORLD OF CONCURRENT OBJECTS

**Objects defined by a sequential specification.** A read/write register is a special case of an immaterial object. In general, an object is defined by the set of operations that processes can invoke, and by an automaton, which specifies the behavior of the object when these operations are invoked sequentially. The automaton specifies, for each state, and each possible operation invocation, a response to that invocation, and a transition to a new state. A stack, for example, is easily specified in this way. The operations are \( \text{push}(v) \), to add \( v \) at the top of the stack; if the stack is full, it returns the control value \( \text{full} \). Similarly, if the stack is not empty, the operation \( \text{pop}() \) returns the value at the top of the stack and suppresses it from the stack; and it returns the control value \( \text{empty} \) if the stack is empty.

A concurrent stack can be implemented by executing the operations \( \text{pop}() \) and \( \text{push}() \) using mutual exclusion. As already indicated, this strategy to create a total order does not work if processes may crash. The state machine replication mechanism \[41\] is a general way of implementing an object by asynchronous crash-prone processes, that invoke operations on the object concurrently.

Implementing a state machine is easy if no process crash. This is no longer the case in crash-prone asynchronous systems, where the implementation of a state machine relies on the consensus object.

**Consensus.** At the core of many sequential reasoning for concurrent programming situations (including state machine replication) are agreement problems. A common underlying abstraction is the consensus object. It has a single operation denoted \( \text{propose}() \), that a process can invoke once. If a process invokes \( \text{propose}(v) \), the invocation eventually returns a value \( v' \). This sequential specification is defined by the following properties.

- **Validity.** If an invocation returns \( v \) then there is a \( \text{propose}(v) \).
- **Agreement.** No two different values are returned.
- **Termination.** If a process invokes \( \text{propose}() \) and does not crash, it returns a value.

Consensus objects are universal in the sense that (together with read/write registers), they can be used to implement, despite asynchrony and process crashes, any object defined by a sequential specification. The consensus-based state machine replication technique provides an illustration of this claim, as discussed below.

**All objects are not equal in a crash-prone environment.** It turns out that an object as simple as a concurrent stack cannot be implemented by asynchronous processes, which communicate using read/write registers only, if any operation invoked by a process that does not crash must return (independently of the speed or crashes of the other processes). Such an implementation of an object is said to be **wait-free** \[31\].

A way of measuring the synchronization power of an object in the presence of asynchrony and process crashes is by its consensus number \[31\]. The consensus number of an object \( O \) is the greatest
integer \( n \), such that it is possible to wait-free implement a consensus object for \( n \) processes from any number of objects \( O \) and atomic read/write registers. The consensus number of \( O \) is \( \infty \) is there is no such greatest integer. As an example, the consensus number of a Test&Set object or a stack object is 2, while consensus number of a Compare&Swap or LL/SC object is \( \infty \). The power and limits of shared memory systems is addressed in [34].

STATE MACHINE REPLICATION

The state machine replication mechanism [41] is the main approach to implement an object in a concurrent system, with asynchrony and process crash failures in message-passing systems [41, 67], and in multiprocessors where each processor has a local memory [58]. The idea is for the processes to agree on a sequential order of the concurrent invocations, and then each one to simulate the sequential specification automaton locally. We illustrate here the approach with a mechanism for reaching the required agreement: a total order broadcast abstraction.

Total order broadcast. The TO-broadcast abstraction [30, 61] is an important primitive in distributed computing, that ensures that all correct processes receive messages in the same order (we do not define them more formally here). It is used through two operations, \textsc{TO\_broadcast}(\( m \)) and \textsc{TO\_deliver}(\( m \)). A process invokes \textsc{TO\_broadcast}(\( m \)), to send a message \( m \) to all other processes. As a result, processes execute \textsc{TO\_deliver}(\( m \)) when they receive a (totally ordered) message. The TO-broadcast abstraction is defined by the following properties (the first three are safety, while the last two are liveness properties). It is assumed without loss of generality that all messages are different.

- \textbf{TO-validity}. If a process executes \textsc{TO\_deliver}(\( m \)) (i.e., to-delivers the a message \( m \)) , then a process executes \textsc{TO\_broadcast}(\( m \)).
- \textbf{TO-integrity}. If a process executes \textsc{TO\_deliver}(\( m \)) and \textsc{TO\_deliver}(\( m' \)), then \( m \neq m' \).
- \textbf{TO-order}. If a process executes \textsc{TO\_deliver}(\( m \)) and \textsc{TO\_deliver}(\( m' \)) in this order, then no process executes these operations in the reverse order.
- \textbf{TO-termination-1}. If a process executes \textsc{TO\_broadcast}(\( m \)) and does not crash, it eventually executes \textsc{TO\_deliver}(\( m \)).
- \textbf{TO-termination-2}. If a process executes \textsc{TO\_deliver}(\( m \)), then every process that does not crash executes \textsc{TO\_deliver}(\( m \)).

TO-broadcast illustrates one more general idea within the theory of mastering concurrent programming through sequential thinking: the identification of communication abstractions that facilitate building concurrent objects defined by a sequential specification.

State machine replication based on TO-broadcast. A concurrent implementation of object \( O \) is described in Algorithm [4]. It is a universal construction, as it works for any object \( O \) defined by a sequential specification. The object has operations \( \text{op}_{x}(\cdot) \), and a transition function \( \delta(\cdot) \) (assuming \( \delta \) is deterministic), where \( \delta(\text{state}, \text{op}_{x}(\text{param}_{x})) \) returns the pair \( \langle \text{state}', \text{res} \rangle \), where \text{state}' is the new state of the object and \text{res} the result of the operation.

Let \( p_{1}, \ldots, p_{n} \) be the set of asynchronous crash-prone processes. Each process \( p_{i} \) is both client (it can invoke operations on \( O \)) and server (it participates in the implementation of \( O \)). The idea of the construction is simple. Each process \( p_{i} \) has a copy \( \text{state}_i \) of the object, and the TO-broadcast abstraction is used to ensure that all the processes \( p_{i} \) apply the same sequence of operations to their local representation \( \text{state}_i \) of the object \( O \). When a process \( p_{i} \) invokes an operation it builds a message \( \text{sent\_msg} \) composed of two fields: \( \text{sent\_msg}\_\text{op} \) which contains the operation and \( \text{sent\_msg}\_\text{proc} \) which contains the identity of the invoking process. Then \( p_{i} \) to-broadcasts \( \text{sent\_msg} \) and waits until its
operation has been executed on its local copy of $O$. On its server side, a process $p_i$ executes an infinite loop in which it first waits for the next message to-delivery. Then, it computes the next state of the object $O$, and, if it is the process that invoked the operation, it writes its result into its local variable $\text{result}_i$ to allow the operation to terminate. The correction of this simple universal construction follows directly from the properties of the to-broadcast abstraction [30, 61].

### Implementing TO-broadcast from consensus

Algorithm 5 is a simple construction of TO-broadcast on top of an asynchronous system enriched with consensus objects [30].

Each process $p_i$ manages four local variables: a sequence number $sn_i$ initialized to 0, a set of message $\text{delivered}_i$ initialized to $\emptyset$, a queue $\text{to\_deliverable}_i$ initialized to the empty sequence $\epsilon$, and an auxiliary variable $\text{res}_i$. Let $\text{broadcast}(m)$ stand for “for each $j \in \{1, ..., n\}$ do send($m$) to $p_j$ end for”. If the invoking process does not crash during its invocation, all processes receive $m$; if it crashes an arbitrary subset of processes receive $m$. To simplify the presentation, it is assumed that a process can send a message to itself.

When $p_i$ invokes $\text{TO\_broadcast}(m)$ it sends the message to itself, which entails its broadcast, and only then $p_i$ adds $m$ to its local set $\text{delivered}_i$. When a process receives a message $m$ from another process for the first time, it does the same. It follows that when a process does not crash during its broadcast of a message $m$, all processes receive it. Hence, if a process $p_j$ adds $m$ to $\text{delivered}_j$, so
TO\_broadcast \((m)\) \hspace{1cm} \text{Application layer} \hspace{1cm} \text{TO\_deliver ()}

\[
\text{From a set to a sequence with the help of consensus objects}
\]

\[
\text{set delivered,}
\]

\[
\text{broadcast (m)} \hspace{1cm} \text{Underlying layer} \hspace{1cm} \text{reception of a message } m
\]

Figure 2: Structure of the consensus-based implementation of TO-broadcast

do at least all the processes that do not crash.

When, the queue \(\text{to\_deliverable}_i\) of a process \(p_i\) contains messages not yet locally to-delivered, \(p_i\) to-delivers them in the order in which they appear in \(\text{to\_deliverable}_i\).

The core of the algorithm is the background task \(T\). A consensus object \(SC[k]\) is associated with the iteration number \(k\). A process \(p_i\) waits until there are messages in the set \(\text{delivered}_i\) and not yet in the queue \(\text{to\_deliverable}_i\). When this occurs, process \(p_i\) computes this set of messages (seq) and order them. Then it proposes seq to the consensus instance \(SC[k]\). This instance returns a sequence saved in \(\text{res}_i\), which is added by \(p_i\) at the end of its local queue \(\text{to\_deliverable}_i\). The correctness of this algorithm relies on the properties of the consensus object. For any \(k \geq 1\), the consensus instance \(CS[k]\) returns the same sequence of messages to all the processes that invoke it. As processes execute instances in the same order, their queue \(\text{to\_deliverable}_i\) eventually contain the same sequence of messages. Formal proofs of this algorithms can be found in [13, 61].

While their styles are different, these two citations capture the universality issues encountered in asynchronous fault-tolerant distributed computing.

- In sequential systems, computability is understood through the Church-Turing Thesis: anything that can be computed, can be computed by a Turing Machine. In distributed systems, where computations require coordination among multiple participants, computability questions have a different flavor. Here, too, there are many problems which are not computable, but these limits to computability reflect the difficulty of making decisions in the face of ambiguity, and have little to do with the inherent computational power of individual participants.

Herlihy M., Rajsbaum S., and Raynal M., Power and limits of distributed computing shared memory models. Theoretical Computer Science, 509:3-24 (2013).

- A distributed system is one in which the failure of a computer you didn’t even know existed can render your own computer unusable.

L. Lamport, email Message-Id: <8705281923.AA09105@jumbo.dec.com>.

Sidebar 4: Two citations on universality
WHEN ARE UNIVERSAL CONSTRUCTIONS POSSIBLE?

An impossibility. A fundamental result in distributed computing is the impossibility to design a (deterministic) algorithm that solves consensus in the presence of asynchrony, even if only one process may crash, either in message-passing [22] or read/write shared memory systems [47]. Given that consensus and TO-broadcast are equivalent, the state machine replication algorithm presented above cannot be implemented in asynchronous systems where processes can crash.

Thus, sequential thinking for concurrent computing has studied properties about the underlying system that enable the approach to go through. There are several ways of considering computationally stronger (read/write or message-passing) models (see, e.g. [58, 61]), where state machine replication can be implemented. Some ways, mainly suited to message-passing systems, are presented in Sidebar 5.

We discuss next a different way, through powerful communication hardware.

The case of enriched read/write systems. Nearly all read/write systems usually provide processes with synchronization-oriented atomic operations such as Test&Set, Compare&Swap, or the pair of operations Load Link/Store Conditional (LL/SC in short). These operations have a consensus number greater than 1. More specifically, the consensus number of Test&Set is 2, while the consensus number of both Compare&Swap and the pair LL/SC, is $+\infty$. Namely, 2-process (but not a 3-process) consensus can be implemented from Test&Set, despite crash failures. Compare&Swap (or LL/SC) can implement consensus for any number of processes. Hence, for any $n$, any object can be implemented in an asynchronous $n$-process read/write system enriched with Compare&Swap (or LL/SC), despite up to $n-1$ process crashes. Furthermore, that are implementations that tolerate arbitrary, malicious failures [7, 61].

Ways of circumventing the consensus impossibility.

- The failure detector approach can [12] abstract away synchrony assumptions sufficient to distinguish between slow processes and dead processes.
- In eventually synchronous systems [19, 20] there is a time after which the processes run synchronously. The celebrated Paxos algorithm is an example [45].
- By using random coins [4, 55]. consensus is solvable with high probability.
- By using a synchronzation operation with consensus number is $+\infty$ if enriched read/systems.

In the first three cases, this means that the considered system is no longer fully asynchronous.

Sidebar 5: Circumventing consensus impossibility

Consensus from the pair LL/SC. The intuition of how the LL/SC operations work is as follows. Consider a memory location $M$ accessed only by the operations LL/SC. Assumed that if a process invokes $M.SC(v)$ it has previously invoked $M.LL()$. The operation $M.LL()$ is a simple read of $M$ which returns the current value of $M$. When a process $p_i$ invokes $M.SC(v)$ the value $v$ is written into $M$ if and only if no other process invoked $M.SC()$ since its ($p_i$) last invocation of $M.LL()$. If the write succeeds $M.SC()$ returns true, otherwise it returns false (see Sidebar 5).

Algorithm 6 is a simple implementation of consensus object from the pair of operations LL/SC, which tolerates any number of process crashes. The consensus object is represented by the memory location $M$ initialized to the default value $\bot$, which cannot be proposed). Each process manages a local variable $val_i$ and a Boolean $b_i$.

When a process $p_i$ invokes the operation propose($v$) it first reads the value of $M$ (first invocation of $M.LL()$) from which it obtains a value $val_i$. If $val_i \neq \bot$, it is the value decided by the consensus
Let $X$ and $Y$ be two different shared registers, and $p_i$, $p_j$, $p_k$ be three distinct processes. As there is no invocation of $Y.SC()$ between the invocations of $Y.LL()$ and $Y.SC()$ by $p_j$, its invocation of $Y.SC()$ succeeds. For the same reason, the invocation of for $X.SC()$ by $p_i$ succeeds. Differently, as there is an invocation of $X.SC()$ between the invocations of $X.LL()$ and $X.SC()$ by $p_k$, its invocation of $X.SC()$ does not succeed.

Sidebar 6: An execution of LL/SC operations

```algorithm
operation propose(v) is
    val_i ← M.LL();
    if (val_i ≠ ⊥) then return(val_i)
    else
        b_i ← M.SC(v);
        if b_i then return(v)
        else
            val_i ← M.LL(); return(val_i)
    end if
end if.
```

Algorithm 6: Consensus from the operations LL/SC

object and $p_i$ returns it. If $val_i = ⊥$, no value has yet been decided and possibly several processes are competing to impose their proposal as the decided value. Each of them invokes $M.SC()$. Due the semantics of the pair LL/SC one and only one of them succeeds. The winner returns its value, and the other competing processes read again the value of $M$ (second invocation of $M.LL()$) and return the value proposed by the winner.

A simple stacking-based universal construction. As consensus objects can be built from the pair of operations LL/SC (Algorithm 6) and TO-broadcast communication abstraction can be built on top of consensus objects (Algorithm 5), their stacking allows us to use the universal construction Algorithm 4 to obtain an implementation of any sequentially-defined object, which copes with the net effect of asynchrony and process failures. This construction can give the reader a feeling for the distributed ledgers discussed in the next section.

A direct universal construction Algorithm 7 (based on an algorithm introduced in [21], simplified in [60]) is a direct universal construction (does not use an intermediate layer of TO-broadcast) of an object $O$ with transition function $δ$, for $n$ processes.

The shared memory is composed of the two following data structures.

- An array on $n$ atomic single-writer multi-reader registers, $BOARD[1..n]$. While any process can read $BOARD[i]$, only process $p_i$ can write it. Each register $BOARD[i]$ is composed of two fields: $BOARD[i].op$ which contains the last object operation invoked by $p_i$ and $BOARD[i].sn$ which contains the associated local sequence number.
• An atomic register, $STATE$, accessed with the operations $LL()$ and $SC()$. It is made of three fields: $STATE.value$ contains the current state of the object under construction, $STATE.sn[1..n]$ is an array of local sequence number, and $STATE.res[1..n]$ which is an array of results. More precisely, $STATE.res[i]$ contains the result of the last object operation issued by $p_j$, and $STATE.sn[j]$ contains its sequence number.

![Algorithm 7: Universal construction for LL/SC-enriched shared memory systems (code for $p_i$)]

Each process $p_i$ manages a local sequence number $sn_i$ and two local variables, denoted $board_i$ and $state_i$, which will contain local copies of $BOARD$ and $STATE$, respectively.

When a process $p_i$ invokes an operation $op_x(param_x)$ on $O$, it informs all the processes of it by storing the pair $\langle op_x(param_x), sn_i \rangle$ in $BOARD[i]$. It executes then the internal procedure $apply()$ (which is the core of the construction). When it returns from $apply()$, it returns the result that has been deposited in $STATE.res[i]$. As there is no waiting statement in $apply()$, if the invoking process does not crash, it terminates its operation on $O$. Hence, the progress condition for object $O$ is wait-freedom.

When $p_i$ executes $apply()$, if first atomically reads the register $STATE$ (invocation of $STATE.LL()$), whose value is saved in its local variable $state_i$, reads the content of the array $BOARD$ and saves it in its local variable $board_i$. Let us remark that, while the the reading of each register $BOARD[j]$ is atomic, the array $BOARD$ is read asynchronously and consequently the reading of the whole array $BOARD$ is not at all atomic. When this is done, $p_i$ starts a speculative execution, which consists in a "for" loop, with one iteration per process $p_i$. If the last operation announced by $p_i$ is the next to be applied (according to its view of $p_i$’s local sequence numbers), $p_i$ applies $p_i$’s operation to its local view of the current state of $O$, namely $state_i$. When this has been done for each process $p_i$, $p_i$ tries to write the new resulting state in $STATE$ (this is done by the invocation of $STATE.SC(state_i)$). If $STATE.SC(state_i)$ returns $true$, the speculative execution succeeded: $p_i$’s operation has been executed, as have also been operations from other processes, and consequently $p_i$’s invocation of $apply()$ terminates. Otherwise, the speculative execution failed. In this case, process $p_i$ reads again $STATE$ (second invocation of $STATE.LL()$). If its operation has not been executed, $p_i$ speculatively executes it on $state_i$, and tries to commit it by invoking $STATE.SC(state_i)$. If this invocation returns $true$ its operation is taken into account. If it returns $false$, another process $p_k$ invoked successfully $STATE.SC(state_k)$ between the invocations of
STATE(LL()) and STATE.SC() by \( p_i \). But in this case, due to the fact that LL/SC are atomic operations, necessarily when \( p_k \) read \( BOARD[i] \) it was informed of \( p_i \)'s operation and consequently executed it. Hence, the result obtained by \( p_i \) from \( STATE.res[i] \) is the one associated with its last operation.

DISTRIBUTED LEDGERS

Since ancient times, ledgers have been at the heart of commerce, to represent concurrent transactions by a permanent list of individual records sequentialized by date (Fig. 3). Today we are beginning to see algorithms that enable the collaborative creation of digital distributed ledgers with properties and capabilities that go far beyond traditional physical ledgers. All participants within a network can have their own copy of the ledger. Any of them can append a record to the ledger, which is then reflected in all copies in minutes or even seconds. The records stored in the ledger can stay temper-proof, using cryptographic techniques.

---

**Ledgers as universal constructions.** Mostly known because of their use in cryptocurrencies, and due to its blockchain incarnation [50], from the perspective of this paper a distributed ledger is a byzantine fault-tolerant replicated implementation of a specific ledger object. The ledger object has two operations, read() and append(). Its sequential specification defines it as a list of blocks. A block \( X \) can be added at the end of the list with the operation append(\( X \)), while a read() returns the whole list. In the case of a cryptocurrency, \( X \) may contain a set of transactions.

Thus, a ledger object, as any other object, can be implemented in a distributed, fault-tolerant way, using the state machine replication technique. Furthermore, it can then be used as a universal construction of an object \( O \) defined by a state machine with a transition function \( \delta \). To do so, when a process invokes append(\( X \)), \( X \) consists of a transition to be applied to the state machine. The state of the object is obtained through a read() invocation, which returns the sequence of operations which have been sequentially appended to the ledger, and then locally applying them starting from the initial state of the object (see [61] for more details).

**Three remarkable properties.** The apparently innocent idea of a read() operation that returns the list of commands that have been applied to the state machine, opens the discussion of one of the remarkable points of distributed ledgers that has brought them to such wide attention. The possibility of guaranteeing a temper-proof list of commands. The blockchain implementation is by using cryptographic hashes that link each record to the previous one (although it actually has been known in cryptography community for years [49]).

The ledger implementation used in Bitcoin showed that it is possible to have a state machine replication tolerating Byzantine failures that scales to hundreds of thousands of processes. The cost is tem-
porality sacrificing consistency—forks can happen at the end of the blockchain, which means that the last few records in the blockchain may have to be withdrawn.

The third remarkable property brought to the public attention by distributed ledgers is the issue of who the participants can be. As opposed to classic algorithms for mastering concurrency through sequential thinking, the participants do not have to be a priori-known, can vary with time, and may even be anonymous. Anyone can append a block, and read the blockchain (although there are also permissioned versions where participants have to be registered, and even hybrid models). In a sense, a distributed ledger is an open distributed database, with no central authority, where the data itself is distributed among the participants.

**Agreement in dynamic systems.** Bitcoin’s distributed ledger implementation is relatively simple to explain in the framework of state machine replication. Conceptually it builds on randomized consensus (something that had already been carefully studied in traditional approaches, e.g. Sidebar[5], through the following ingenious technique to implement it. Whenever several processes want to concurrently append a block, they participate in a lottery. Each process selects a random number (by solving cryptographic puzzles) between 0 and some large integer $K$, and the one that gets a number smaller than $k << K$, wins, and has the right to append its desired block. The implementation details of the lottery (by a procedure called **proof of work**) are not important for this paper; what is important here, is that processes cannot cheat by biasing the random number they get. Thus, with high probability only one wins. However, from time to time, more than one process wins and a **fork** happens, with more than one block being appended at the end of the blockchain. Again, for the purpose of this paper, it suffices to say that only one branch eventually pervades (in Bitcoin this is achieved by always appending to the longest branch). This introduces a new interesting idea into the paradigm of mastering concurrency through sequential thinking: a tradeoff between faster state machine replication, and temporary loss of consistency. In other words, the $x$ operations at the very end of the blockchain, for some constant $x$ (which depends on the assumptions about the environment) cannot yet be considered committed. To be sure (with high probability) that an operation has permanently been applied to the blockchain, a process has to wait until it is at a depth greater than $x$ in the list of blocks.

**ON THE LIMIT OF THE APPROACH**

It is intuitively clear, and it has been formally proved since a long time that linearizability is an expensive requirement. Recent papers in the context of shared memory programming, argue that it is often possible to improve performance of concurrent data structures by relaxing their semantics (see, e.g. [10, 29, 65, 69, 71]). In the context of distributed systems, eventual consistency is widely deployed to achieve high availability by guaranteeing that if no new updates are made to a given data item, eventually all accesses to that item will return the last updated value [72]. Eventual consistency (also called optimistic replication), which is deployed in some distributed systems, has origins in early mobile computing. A system that has achieved eventual consistency is often said to have converged. In the case of distributed ledgers, we have seen the benefit that can be gained by relaxing the sequential approach to mastering concurrency: branches at the end of the blockchain (such as Bitcoin) temporarily violate a consistent view of the ledger. Still, blockchains suffer from a performance bottleneck due to the requirement of ordering all transactions in a single list, which has prompted the exploration of partially ordered ledgers, based on directed acyclic graphs such as those based on Iota, Tangle, or Hedera Hashgraph systems. The benefit is scalability to thousands of processes, that instead of communicating with each other to decide on a single leader that will append a block, they avoid communication altogether, using random numbers.

The **CAP Theorem** formalizes a fundamental limitation of the approach of mastering concurrency through sequential reasoning: at most two of the following three properties are achievable, Consistency
(linearizability), Availability, Partition tolerance \[26,27\]. This may give an intuition of why distributed ledgers implementations have temporary forks. An alternative is a cost in availability, and postpone the property that every non-failing participant returns a response for all operations in a reasonable amount of time. We have already seen in the ABD algorithm that the system continues to function and upholds its consistency guarantees, provided that only a minority of processes may fail.

Finally, another fundamental limitation to the approach of mastering concurrency through sequential reasoning is that not all concurrent problems of interest have sequential specifications. Many examples are discussed in [11], where a generalization of linearizability to arbitrary concurrent specifications is proposed.

CONCLUSION

The aim of this article was to show how does the theme of reducing concurrent programming to sequential reasoning weaves through history since the early days and along different domains (shared memory, databases, distributed systems, cryptocurrencies, etc), to build complex concurrent systems. The thread brings in a scientific foundation through common conceptual tools, such as sequential specifications, progress and consistency conditions, synchronization abstractions like consensus, communication mechanisms such as broadcast and gossiping, fault-tolerance techniques, etc. It evolves from concrete resource-oriented mutual exclusion in a failure free-context, through immaterial objects and failures, to universal constructions of replicated state machines, to current trends on dynamic, temper-proof distributed ledgers. The deep continuity lasting more than fifty years, is now exploring its frontiers, looking for roundabouts to the inherent limitations of the approach.

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