CScript: A distributed programming language for building mixed-consistency applications

Kevin De Porre a,∗, Florian Myter a, Christophe Scholliers b, Elisa Gonzalez Boix a

a Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussel, Belgium
b Ghent University, Sint Pietersnieuwstraat 33, Ghent, Belgium

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Current programming models only provide abstractions for sharing data under a homogeneous consistency model. It is, however, not uncommon for a distributed application to provide strong consistency for one part of the shared data and eventual consistency for another part. Because mixing consistency models is not supported by current programming models, writing such applications is extremely difficult. In this paper we propose CScript, a distributed object-oriented programming language with built-in support for data replication. At its core are consistent and available replicated objects. CScript regulates the interactions between these objects to avoid subtle inconsistencies that arise when mixing consistency models. Our evaluation compares a collaborative text editor built atop CScript with a state-of-the-art implementation. The results show that our approach is flexible and more memory efficient.

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1. Introduction

According to the CAP theorem [6] a distributed system cannot remain both available and consistent under network partitions. This forces programmers to choose between availability (AP) and consistency (CP) in the event of a partition. This choice can be made for each piece of shared data [7]. We call applications that share multiple pieces of data with different guarantees mixed-consistency applications. When developing such applications, programmers face two major problems. First, distributed programming languages lack abstractions to share data under AP/CP guarantees. This forces programmers to manually synchronize replicas. As a result, programmers often make mistakes against consistency models [20]. Second, many AP approaches such as [8,25,26] develop common data types with hardcoded conflict resolution semantics. Unfortunately, programmers cannot compose these data types to design custom ones. Going beyond the current portfolio of available replicated data types (RDTs) requires programmers to manually engineer the RDT using ad hoc conflict resolution strategies. This has shown to be error-prone and results in brittle systems [1,15,25].

To help programmers develop mixed-consistency applications, we argue that distributed programming languages should have (1) built-in RDTs for writing AP and CP functionality and (2) built-in defence mechanisms that prevent programmers from making mistakes when mixing data with different consistency guarantees. In this paper, we propose CScript, a novel distributed programming language with native support for availability and consistency. CScript extends JavaScript with first-class replicas and services. Replicas are objects that encode their availability and consistency guarantees, and can be composed into services which are distributed over the network. CScript supports two families of AP replicated data types guaranteeing strong eventual consistency [25] (SEC): conflict-free replicated data types (CRDTs) and strong eventually consistent replicated objects (SECROs). CRDTs are a subset of the RDTs for which all operations commute. SECROs use semantic information provided by the programmer to reorder conflicting operations such that they do not need to commute. This approach is based on the idea that conflict detection and resolution naturally depend on the semantics of the application [29]. When the operations of an RDT do not commute and conflicts can be solved by reordering operations, CScript programmers can use SECROs to build the RDT. All replicas of this RDT are guaranteed to converge to the same state.

This paper complements our previous exposition of SECROs in [10] by proving convergence and showing that progress depends on the data type itself. Hence, we formulate a necessary condition for SECRO data types which enables us to give a general proof of progress.

The remainder of this paper is organised as follows. Section 2 discusses related work that is necessary to understand this paper. Section 3 introduces our motivating example.
for mixed-consistency. Section 4 describes CScript’s architecture and programming model. Section 5 describes our novel SECRO data type which is part of CScript. We then work out our motivating example in Section 6 using CScript. Section 8 evaluates CScript by benchmarking a collaborative text editing application. Finally, we discuss related work in Section 10 and close with final conclusions in Section 11.

2. Background

In this section we introduce background knowledge on the CAP theorem, its implications, and the consistency models on which the paper builds.

The CAP theorem [6,12] describes the interactions between consistency (C), availability (A) and partition tolerance (P) in a distributed system consisting of nodes that can write to a conceptually shared memory. A system is consistent if all reads return the latest write. A system is available when all nodes are able to read from and write to the shared memory at any point in time. The system is partition tolerant if it is able to maintain its consistency or availability guarantees in the face of network partitions. The CAP theorem proves that a distributed system cannot remain both available and consistent under network partitions. This led to a multitude of consistency models (mainly weak consistency models1) being developed [31]. Eventual consistency [32] for instance, states that when updates stop, all replicas will eventually converge to the same state.

Strong eventual consistency (SEC) [25] is a variation on eventual consistency [32] that imposes an additional strong convergence requirement: correct replicas that received the same updates (possibly in a different order) must be in the same state. Strong convergence thus defines when replicas converge, something that is not specified by traditional eventual consistency.

Today’s only implementation of the SEC model is the conflict-free replicated data type (CRDT) [25]. CRDTs come in two flavours which have been proven equivalent: state-based CRDTs (abbreviated CvRDTs) and operation-based CRDTs (abbreviated CmRDTs). CvRDTs require replicated state to form a join-semilattice. As such, two states can always be merged deterministically by computing their least upper bound. On the other hand, CmRDTs require all operations to commute and as such guarantee strong convergence by design.

Imposing all operations to commute (or the equivalent requirement for state to form a join-semilattice) hurts the applicability of CRDTs. For this reason the literature describes only a limited portfolio of CRDTs. Furthermore, CRDTs cannot be composed out of the box. Some research [15,19] seeks to improve the composability of CRDTs, however, none of these composition mechanisms is general enough to allow arbitrary compositions for all CRDTs. JSON CRDTs [15] for instance only let programmers compose linked lists and maps. Hence, programmers often need to engineer their own CRDTs from scratch (if possible) or rely on manual conflict resolution which is error-prone and results in brittle systems [1,15,25].

3. Motivation: A mixed-consistency application

This section introduces a grocery list application which acts as a motivating example of mixed-consistency throughout this paper. Users of the application can create shared grocery lists to which they can add and delete items. Users can also request more pieces of an item or mark a certain quantity of an item as bought.

The application must meet the following consistency requirements:

1 Consistency models weaker than sequential consistency.
4.2. Programming model

We now describe CScript’s programming model which is centred around the concepts of replicas and services. We then illustrate how these concepts facilitate the development of collaborative mixed-consistency applications.

4.2.1. Replicas

CScript introduces first-class replicated objects, called replicas. Like regular objects, replicas contain state in the form of fields and behaviour in the form of methods. State can be primitive data or JavaScript objects. Programmers can invoke methods of a replica but cannot access state directly. The state of a replica is automatically kept consistent by its consistency model.

CScript supports two types of replicas: available and consistent replicas. The former guarantee SEC [28] and thus favour availability over consistency. The latter guarantee sequential consistency [28] and thus favour correctness over availability.

4.2.2. Services

When building mixed-consistency applications, replicas alone are not enough. Programmers need a way to compose replicas – possibly with different consistency guarantees – into a bigger unit that provides specific functionality. To this end, CScript provides first-class services.

Services encapsulate state (primitive data, objects, and replicas) and implement some methods which form the service’s API. The methods use the state and coordinate between the replicas to provide specific functionality. Programmers must use the service’s API as they cannot access a service’s state directly.

4.2.3. Publications and subscriptions

CScript lets programmers implement replicas and bundle them into services. To share services between instances of an application running on different devices, CScript features a topic-based publish–subscribe mechanism [11]. This mechanism lets application instances share services with one another without knowing each other beforehand, making the underlying network transparent to the application. Fig. 2 shows how CScript instances can publish services on the network and discover published services. When one instance discovers a service published by another instance, it acquires a copy of the service. The replicas encapsulated by the service are automatically managed by the CScript runtime such that they uphold their consistency guarantees.

4.2.4. The interplay between consistent and available replicas

Mixed-consistency applications share several pieces of data with different consistency guarantees. When building such applications, programmers must be careful not to break these guarantees. Ideally, the programming model enforces consistency models using a strict set of rules:

1. Each replica implements one specific consistency model.
2. Programmers can only interact with replicas through their public interface, i.e. programmers cannot access or modify a replica’s internal state directly.
3. Replicas are self-contained since they are replicated over the network.
4. Replicas may not leak references to their internal state as this would allow programmers to access internal state directly, thereby breaking rule 2.
5. Data that is replicated under a certain consistency model should not flow to replicas that enforce a stronger consistency model as it would break the stronger guarantees.

We now discuss how CScript enforces the aforementioned rules. Even though CScript provides consistent and available replicas, programmers can only nest replicas that guarantee the same level of consistency. Otherwise, one replica could provide different (possibly conflicting) consistency levels, thereby breaking rule 1. Hence, consistent replicas may embed other consistent replicas but not available replicas, and vice-versa. Replicas are black boxes and do not allow programmers to access or modify internal state directly (rule 2).

CScript deep copies the arguments that are passed to the methods of replicas as well as the return values. Deep copying the arguments ensures that the replica remains self-contained (rule 3). Deep copying the return value avoids leaking references to internal state (rule 4).

Regarding data flows (rule 5), CScript does not yet prohibit data obtained from available replicas to be passed as argument to a method of a consistent replica. We foresee a statically typed version of the CScript language that encodes the consistency model of data as part of its type and rejects illegal information flows at compile time.

5. Strong Eventually Consistent Replicated Objects (SECROs)

We now focus on CScript’s support for available replicas: strong eventually consistent replicated objects (SECROs), a novel RDT that addresses the applicability issues of CRDTs discussed in Section 2. SECROs use semantic information provided by the programmer to guarantee SEC without requiring operations to commute. This makes SECROs generally applicable.

5.1. SECRO data type

Like regular objects, SECROs contain state in the form of fields, and behaviour in the form of methods. The methods define the SECRO’s public interface which cannot be circumvented. Methods can be further categorised in accessors (i.e. methods querying internal state) and mutators (i.e. methods updating the internal state).

SECROs differ from regular objects in that programmers can enforce application-specific invariants by associating concurrent preconditions and postconditions to the mutators. We say that pre and postconditions are state validators. State validators are used by the SECRO to order concurrent operations in a way that does not violate any invariant.

5.2. State validators

State validators associate rules to mutators. Those rules express invariants over the state of the object which need to uphold in the presence of concurrent operations.2 Behind the scenes, SECRO’s replication protocol may interleave concurrent operations. From the programmer’s perspective the only guarantee is that these invariants are upheld. State validators come in two forms:

Preconditions specify invariants that must hold prior to the execution of their associated operation. As such, preconditions approve or reject the state before applying the actual update. In case of a rejection, the operation is aborted and a different ordering of the operations will be tried.

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2 From now on, we use the terms operation and mutator interchangeably, as well as the terms update and mutation.
Postconditions specify invariants that must hold after the execution of their associated operation. A postcondition does not execute immediately after applying an operation. Instead, it executes after all concurrent operations complete. As such, postconditions approve or reject the state that results from a group of concurrent, potentially conflicting operations. In case of a rejection a different ordering of the operations is tried.

5.3. SECRO's replication protocol in a Nutshell

Recall that SECROs guarantee SEC (eventual consistency and strong convergence). To provide this guarantee SECROs implement a dedicated optimistic replication protocol. We now briefly discuss this protocol, a detailed explanation including pseudo code is given in Section 7.

SECRO's replication protocol asynchronously propagates update operations to all replicas. In contrast to CRDTs, the operations of a SECRO do not necessarily commute. Therefore, the replication protocol totally orders the operations at all replicas. This order respects causality and all pre and postconditions.

Replicas maintain their initial state and a sequence of operations called the operation history. Each time a replica receives an operation, it is added to the replica’s history, which may require reordering parts of the history. Reordering the history boils down to finding an ordering of the operations that fulfills two requirements. First, the order must respect the causality of operations. Second, applying all the operations in the given order may not violate any of the concurrent pre or postconditions. An ordering which adheres to these requirements is called a valid execution. As soon as a valid execution is found each replica resets its state to the initial one and executes the operations in-order. Reordering the history is a deterministic process, hence, replicas that received the same operations find the same valid execution.

We now illustrate CScript’s programming model by implementing a grocery application that fulfils the requirements outlined in Section 3.

6.1. The grocery service

We model the grocery application as a CScript service, which is shown in Listing 1. On Line 1 we define the GroceryService using the service keyword. Similarly to class definitions in ES6,3 services have a constructor method to initialise the service (Lines 4 to 7). The GroceryService’s constructor defines two fields: the grocery list’s name and author (Lines 5 and 6). Additionally, the service encapsulates two replicas, groceryList and inventory, which are defined using the rep keyword (Lines 2 and 3). The former is the grocery list (an available replica) whereas the latter is the inventory containing all the items marked as bought (a consistent replica). Syntactically there is no difference between the eventually consistent groceryList replica and the sequentially consistent inventory replica because the consistency guarantees depend on the type of the replica. Finally, the service defines functionality to add, delete, and buy grocery items. This functionality is exposed through the GroceryService’s API which consists of the add, delete, and buy methods (Lines 8 to 14). The implementation of the buy method is discussed in Section 6.2.

Listing 1: Implementation of the grocery service.

```
1 service GroceryService { 
2 rep groceryList = new GroceryList(); 
3 rep inventory = new Inventory(); 
4 constructor(name, author) 
5 this.name = name; 
6 this.author = author; 
7 } 
8 add(item) { 
9 return this.groceryList.add(item); 
10 } 
11 delete(itemName) { 
12 return this.groceryList.delete(itemName); 
13 } 
14 buy(itemName, buyingQuantity) { /* ... */ } 
15 }
```

ECMAScript 6.

Fig. 2. Exchanging a GroceryService containing two replicas (list and inventory) between CScript instances.
6.2. The sequentially consistent inventory of purchases

Listing 2 shows the implementation of the Inventory class, which keeps a map to track how many pieces of each item were marked as bought (Line 3), this is called the “stock”. The inventory defines an approve method which is called before marking a certain quantity of an item as bought (Lines 5 to 15). This method first checks that the user’s view on the stock is equal to the actual stock for that item (Lines 8 and 9), thereby rejecting concurrent purchases of the same item. If the check succeeds, the inventory approves the buy request and updates its stock for that item (Lines 10 and 11).

By default, CScript replicas are sequentially consistent unless the data type implements SEC. CScript guarantees sequential consistency by serialising all operations on a single (remote) copy of the replica which resides at the creator of the (grocery) service, as depicted in Fig. 3. This means that there is no central server hosting the inventory, instead, the inventory is hosted by the device that created it. Interactions with consistent replicas may therefore involve network communication. For this reason, property accesses and method invocations on consistent replicas are asynchronous and return a promise.

Listing 3 shows the implementation of the grocery service’s buy method. The method first fetches the user’s local view on the stock from the eventually consistent grocery list, which may thus be outdated (Line 3). Then, it asynchronously sends a request to the inventory by calling the approve method (Line 6). If the request is approved, it informs the local grocery list replica (Line 9) which then marks the given quantity of that item as bought in the UI. This method shows that services may have to interact with replicas that exhibit different consistency guarantees in order to provide the required functionality.

6.3. The eventually consistent grocery list

We now discuss the implementation of the GroceryList, which is an available replica providing functionality to fetch the items of a list, add items to a list, and mark (a certain quantity
of) items as bought. To this end, we implemented the grocery list using our SECRO data type, presented in Section 5.

Listing 4 shows the implementation of the GroceryList which extends the SECRO interface. Its public interface consists of one accessor (get) and three mutators: add, bought, and delete. It also associates a precondition to the bought method and a postcondition to the add method, using the pre and post keywords respectively (Lines 15 and 16). The side-effect free method get is annotated with @accessor, otherwise, CScript treats it as a mutator.4 The toJson and fromJson methods serve to (de)serialize the object as it will be replicated over the network. In order for the receiver to know the GroceryList class, this SECRO must be registered at the CScript factory (Line 21).

Listing 4: Structure of the grocery list.

```java
1  class GroceryList extends SECRO {
2      constructor(items = []) {
3          this.items = new Map();
4          items.forEach((item) => (this.items.set(item.name, item)));
5      }
6      @Accessor
7      get() { /* ... */ }
8      // operations to manipulate the list
9      add(item) { /* ... */ }
10     bought(itemName, quantity) { /* ... */ }
11     delete(itemName) { /* ... */ }
12     // SECRO’s state validators
13     post add(originalState, state, args, res) {
14       /* ... */
15     }
16     pre bought(state, args) { /* ... */ }
17     // serialization methods
18     toJson() { /* ... */ }
19     static fromJson(items) { /* ... */ }
20  }
21  Factory.registerAvailableType(GroceryList);
```

Listing 5: Adding items to a grocery list.

Let us now take a look at the implementation of the add, bought, and delete mutators and their associated pre and postconditions.

```java
1  add(item) {
2      const description = this.items.getOrDefault(item.name, 0);
3      description.requested += item.requested;
4      this.items.set(item.name, description);
5  }
6  bought(itemName, quantity) {
7      this.items.getOrDefault(itemName, 0) += quantity;
8  }
9  delete(itemName) {
10     this.items.delete(itemName);
11  }
```

Listing 6: Marking items as bought and deleting items from the grocery list.

Having discussed the implementation of the add, bought, and delete operations, we now describe which operations can be generated by the users in a given state s. We call this the set of valid updates and denote it \( V_s \).

\[
\begin{align*}
\langle \text{name, req, bought} \rangle \in s & \quad \text{req} \in \mathbb{N}^+ \quad \text{bought} \in \mathbb{N}_0 \\
\text{add(item)} & \in V_s \\
\langle \text{name, qty} \rangle \in V_s & \quad \langle \text{name, req, bought} \rangle \in V_s
\end{align*}
\]  

The first rule states that users can always add well-formed items to the grocery list, independent of the application’s state. The second rule states that users can only buy a positive quantity of an existing item. The third rule states that users can only delete existing items.

6.4. Sharing grocery services between users

Users of our grocery application can create new grocery lists at will. Each grocery list must be shared between all instances (users) of the grocery application. To this end, we use CScript’s publish–subscribe mechanism.

Every time the user creates a new grocery list the create–Grocery function from Listing 7 is invoked. This function first creates a grocery service representing the list (Line 4), then publishes the newly created service under the Grocery type tag using the publish <service> as <typetag> construct (Line 5). The typetag is the topic of publication and is defined using the deftype keyword on Line 1. Afterwards, the function calls processService which installs the necessary callbacks on the service, such that the application can react to incoming updates, e.g. when another user adds an item to the shared grocery list. Reacting to updates will be discussed further in this section.

Listing 8 shows how to subscribe to services of the Grocery type using the subscribe <typetag> with <callback> construct (Line 2). The provided callback is parametrised with the

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4 When a mutator is invoked, the operation is propagated to all replicas.
5 Postconditions receive four arguments: the state before applying the operation, the state after applying all concurrent operations, the operation’s arguments and return value.
6 Preconditions receive the state before applying the operation and the arguments.
Alice’s
Grocery List

Bob’s
Grocery List

Alice's
Grocery List

Fig. 4. Alice adds one lasagna while concurrently Bob deletes the lasagnas from the grocery list. After propagating the operations the resulting list contains one lasagna because Bob was not aware of Alice’s addition at the time of his deletion.

def type Grocery
1 function createGrocery(name, author) {
2  const gservice =
3  new GroceryService(name, author);
4  publish gservice as Grocery;
5  processService(gservice);
6  return gservice;
7 }

Listing 7: Exporting grocery services on the network.

Listing 8: Subscribing to grocery services.

In order to make services self-contained, they do not have access to enclosing lexical scopes, much like isolates in AmbientTalk [30] or spores in Scala [21].

6.4.1. Reacting to updates of the grocery list

When a user modifies a shared grocery list all replicas will eventually observe the update and in turn update the user interface. To this end, CScript replicas emit two events to which applications can react: RemoteUpdate and Update. The former is triggered when a replica receives an update from a remote replica. The latter is triggered when a replica applies an update.

Fig. 5 shows how updates are propagated between two users. Alice adds an item to her grocery list (m₁) and the operation is sent to bob (m₂). Update events are triggered on both devices (m₃ and m₄) which causes the user interfaces to be refreshed (m₅ and m₆).

7. SECRO’s replication protocol

Having introduced the CScript language and our SECRO data type, we now turn our attention to the replication algorithm behind SECROS. The detailed algorithm is explained in [10]. This paper provides the correctness proofs and presents only the parts of the algorithm that are relevant to the proofs.

7.1. Algorithm

The algorithm described in this section assumes a reliable causal order broadcasting mechanism without loss of generality, i.e. a communication medium in which messages arrive in an order that is consistent with the happened-before relation [16]. It also assumes that reading the state of a replica happens side-effect free and that mutators solely affect the replica’s state (i.e. the side effects are confined to the replica itself).

A SECRO replica r is a tuple ⟨vᵢ, s₀, sᵦ, h, id⟩ consisting of the replica’s version number vᵢ, its initial state s₀, its current state sᵦ, its operation history h, and the globally unique identifier of the latest commit operation id. Reading the value of the replica simply returns its latest local state sᵦ. A mutator m is represented as a tuple ⟨o, p, a⟩ consisting of the update operation o, precondition p, and postcondition a. When a mutator is applied to a replica a mutate message is broadcast to all replicas. Such a message is an extension of the mutator ⟨o, args, p, a, c, id⟩ which additionally contains the arguments args passed to the operation o, the node’s logical clock time c, and a globally unique identifier id. We denote that a mutation m₁ happened before m₂ using m₁ ≫ m₂. Similarly, we denote that two mutations happened concurrently using m₁ ≃ m₂. Both relations are based on the clocks carried by the mutate messages [14].

Algorithm 1 governs the replicas’ behaviour to guarantee SEC by ensuring that all replicas execute operations in the same order. In particular, algorithm 1 delivers a list of mutate messages l to a replica r which optionally returns the updated replica r’, denoted l ⊪ r = Some r’ or l ⊪ r = None. The algorithm consists of two parts. First, it appends the list of mutate messages to the operation history, sorts the history according to the total order, and generates all linear extensions of the replica’s sorted history (see Lines 1 and 3). We say that m₁ = ⟨o₁, args₁, p₁, a₁, c₁, id₁⟩ ≃ m₂ = ⟨o₂, args₂, p₂, a₂, c₂, id₂⟩ iff id₁ > id₂, however, this could be any total order. The generated linear extensions are all the permutations of h that respect the partial order defined by the operations’ causal relations. Since replicas deterministically compute linear extensions and start from the same sorted operation history, all replicas generate the same sequence of permutations.

Second, the algorithm searches for the first valid permutation. For each operation within such a permutation it computes the transitive closure of concurrent operations7 and checks that their pre (Lines 11 to 17) and postconditions (Lines 18 to 24) hold.

7 The transitive closure of a mutate message m with respect to an operation history h is denoted TC(m, h) and is the set of all operations that are directly or transitively concurrent with m, including m itself. A formal definition is provided in Appendix C.
Postconditions are checked only after all concurrent operations of the transitive closure executed since they happened independently and may thus conflict. The algorithm returns the replica's updated state as soon as a valid execution is found, i.e., $r = \langle v_i, s_0, s_i, h, s_i' \rangle$. If no valid execution exists the algorithm fails, i.e., $r = \langle v_i, s_0, s_i, h, s_i' \rangle = \langle \rangle$.

Besides reading and mutating replicas, it is possible to commit a replica. Commit clears the replica’s operation history $h$, increments the replica’s version and replaces the initial state $s_0$ by the current state $s_i$. This avoids unbounded growth of operation histories, but operations concurrent with the commit will be discarded.\footnote{Since commit may drop operations, one can argue that SECROs are similar to last-writer-wins (LWW) strategies. However, SECROs guarantee invariant preservation, which is not the case with CRDTs.} Commit operations commute in order not to compromise availability. The detailed commit algorithm and its explanation can be found in [10].

7.2. Convergence and progress properties

As mentioned before, SECROs guarantee strong eventual consistency (SEC). This means that the replication algorithm ensures two properties: strong convergence and progress [25]. The former states that replicas which received the same operations must be in equivalent states. The latter states that if some replica generates a valid operation, applying that operation on another replica may not lead to an error state [13].

The SECRO algorithm guarantees strong convergence by deterministically reordering the operations at all replicas. Recall from the previous section that all replicas execute all operations in the same order and thus converge to the same state. Appendix A provides the complete proof of convergence.

The main advantage of SECROs over CRDTs lies in the fact that it is a general-purpose RDT. Programmers explicitly specify preconditions and postconditions that constrain the data type’s behaviour under concurrent operations. Depending on these pre and postconditions a replica may or may not end up in an error state. Hence, we cannot provide a general proof of progress that holds for all SECROs. Instead, we require the SECRO’s pre and postconditions to accept at least one causal serialisation\footnote{An ordering of the operations that respects the causality of the operations.} of the operations (see Lemma 1).

**Lemma 1.** Given an initial state $s$ and a set of valid updates $V$\footnote{The set of valid updates $V$ is defined as the set of all operations that can be generated by the application while being in state $s$.}, there exists an ordering of the updates that respects causality and all pre and postconditions.

Appendix B provides a proof that SECROs whose pre and postconditions meet Lemma 1 guarantee progress. It is up to the programmer to prove Lemma 1 when designing custom SECROs.

8. Evaluation

To evaluate CScript we built several applications, including the grocery list application and a collaborative text editing application. The text editor is built on top of SECROs, one of CScript’s core abstractions, which makes the application highly available and partition tolerant (AP). We compare the application to a state-of-the-art implementation on top of JSON CRDTs [15]. To this end, we perform various experiments which quantify the memory usage and execution time of both implementations.
JSON CRDTs are closely related to SECRos because they allow programmers to build custom CRDTs by nesting linked lists and maps, without having to worry about conflicts. However, the extensibility of JSON CRDTs is limited to the composition of lists and maps, and conflict resolution cannot be customised because it is hardcoded by the implementation of lists and maps.

Note that SECRos are designed to ease the development of custom RDTs guaranteeing SEC. Hence, our goal is not to outperform JSON CRDTs, but rather to evaluate the practical feasibility of SECRos. The results show that SECRos are memory efficient but induce a linear time overhead on top of the operations. Overall, SECRos can be made practical by committing regularly.

### 8.1. A text editing application

The collaborative text editor lets users share text documents and work on them simultaneously. A naive version of this application stores text documents as a linked list of characters. An improvement would be to store documents as a balanced tree of characters, allowing for logarithmic time lookups, insertions, and deletions. We implemented both versions of the text editor using SECRos in CScript. The tree version uses a third party AVL tree and extends it with pre and postconditions to turn it into a SECRo that can freely be replicated. The implementation is publicly available at [9] and is detailed in [10].

Since JSON CRDTs only let programmers nest linked lists and maps, it is not possible to implement a balanced tree data structure. Hence, using JSON CRDTs we were only able to implement the naive version of the text editor.

We compare to JSON CRDTs because they are designed to build custom CRDTs and are thus similar to SECRos which are meant to build custom RDTs. We did not compare CScript to other languages because performance benchmarks would be biased by the language.

### 8.2. Methodology

All experiments presented in this section were performed on a cluster consisting of 10 worker nodes which are interconnected through a 10 Gbit twinax connection. Each worker node has an Intel Xeon E3-1240 processor at 3.50 GHz and 32 GB of RAM. Depending on the experiment, the benchmark is either run on a single worker node or on all ten nodes. We specify this for each benchmark.

To get statistically sound results we repeat each benchmark at least 30 times, yielding a minimum of 30 samples per measurement. Each benchmark starts with a number of warmup rounds to minimise the effects of program initialisation. We also disable NodeJS’ just-in-time compiler optimisations.

We perform statistical analysis over our measurements as follows. We discard samples that are affected by garbage collection (e.g. the execution time benchmarks). For each measurement comprising at least 30 samples we compute the average value and the corresponding 95% confidence interval.

### 8.3. Memory usage

To compare the memory usage of the SECRo and JSON CRDT text editors, we perform an experiment in which 1000 operations are executed on each text editor. We continuously alternate between 100 character insertions followed by deletions of those 100 characters. We force garbage collection after each operation, and measure the heap usage. Fig. 6 shows the results. Green and red columns indicate character insertions and deletions respectively.

Fig. 6a confirms our expectation that the SECRo implementations are more memory efficient than the JSON CRDT one. The memory usage of the JSON CRDT text editor grows unbounded since CRDTs cannot delete characters but merely mark them as deleted using tombstones. Conversely, SECRos support true deletions by reorganising concurrent operations in a non-conflicting order. This results in lower memory usage, since all 100 inserted characters are deleted by the following 100 deletions.

Fig. 6b compares the memory usage of the list and tree-based implementations using SECRos. We conclude that the tree-based implementation consumes more memory than the list implementation because nodes of a tree maintain pointers to their children, whereas nodes of a singly linked list only maintain a single pointer to the next node. Interestingly, we observe a staircase pattern. This pattern indicates that memory usage grows when characters are inserted (green columns) and shrinks when characters are deleted (red columns). Overall, memory usage increases linearly with the number of executed operations, even though we delete the inserted characters and commit the replica after each operation. Hence, SECRos cause a small memory overhead for each executed operation, as shown by the dashed regression lines.

### 8.4. Execution time

In this section we discuss several aspects of the execution time of SECRos. First, we analyse the effect of committing the SECRo’s operation history on the execution time of operations. Then, we compare the SECRo list implementation of the text editor to a state-of-the-art implementation with JSON CRDTs.

#### 8.4.1. The effect of commit on the execution time

We now present two benchmarks related to the commit operation. The first quantifies the performance overhead of SECRos that results from reordering the operation history. The second illustrates the effect of commit on the execution time of the collaborative text editor and how commit improves its performance.

To quantify the performance overhead of SECRos we measure the execution times of 500 constant time operations, for different commit intervals. Each operation computes 10 000 tangents and has no associated pre or postcondition. Hence, the results reflect the best-case performance of SECRos.

Fig. 7a depicts the execution time of the aforementioned constant time operation. If we do not commit the replica (red curve), the operation’s execution time increases linearly with the number of operations. Hence, SECRos induce a linear overhead. This results from the fact that the replica’s operation history grows with every operation. Each operation requires the replica to reorganise the history. To this end, the replica generates linear extensions of the history until a valid ordering of the operations is found (see Algorithm 1 in Section 7.1). Since we defined no preconditions or postconditions, every order is valid and the replica generates exactly one linear extension and validates it. To validate the ordering, the replica executes each operation. Therefore, the operation’s execution time is linear to the size of the operation history.

Note that commit implies a trade-off between concurrency and performance. Small commit intervals lead to better performance but less concurrency, whereas large commit intervals

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11 Forcing garbage collection is needed to get the real-time memory usage. Otherwise, the memory usage keeps growing until garbage collection is triggered.

12 Tombstones are a trick to make the insert and delete operations commute.
Fig. 6. Memory usage benchmarks. Error bars represent the 95% confidence interval for the average taken from 30 samples. The experiments are performed on a single worker node. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 7. Execution time of SECROs for different commit intervals, performed on a single worker node of the cluster. Error bands represent the 95% confidence interval for the average taken from a minimum of 30 samples. Samples affected by garbage collection were discarded. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

support more concurrent operations at the cost of performance. Fig. 7a illustrates this trade-off. For a commit interval of 50 (blue curve), we observe a sawtooth pattern. The operation’s execution time increases until the replica is committed, whereafter it falls back to its initial execution time. This is because commit clears the operation history. When choosing a commit interval of 1 (green curve), the replica is committed after every operation. Hence, the history contains a single operation and does not need to be reorganised. This results in a constant execution time.

We now analyse the execution time of insert operations on the collaborative text editor. Fig. 7b shows the time it takes to append a character to a text document in function of the document’s length, for various commit intervals. If we do not commit the replica (red curve), append exhibits a quadratic execution time. This is because the SECRO induces a linear overhead and append is a linear operation. Hence, append’s execution time becomes quadratic. For a commit interval of 100 (blue curve) we again observe a sawtooth pattern. In contrast to Fig. 7a the peaks increase linearly with the size of the document because append is a linear operation. For a commit interval of 1 (green curve) we get a linear execution time. This results from the fact that we do not need to reorganise the replica’s history. Hence, we execute a single append operation.

From these results, we draw two conclusions. First, SECROs induce a linear overhead on the execution time of operations. Second, commit is a practical solution to keep the performance of SECROs within acceptable bounds.

8.4.2. SECRO vs. JSON CRDT text editor

We now compare the naive list implementation and the advanced tree implementation of the text editor to the JSON CRDT implementation. To this end, we measure the time it takes to append characters to a text document. Although this is not a realistic edition pattern, it showcases the worst case performance.

(a) Memory usage of the SECRO and JSON CRDT text editors.

(b) Memory usage of the list and tree implementations of the SECRO text editor.

(a) Execution time of a constant time operation in function of the number of executed operations.

(b) Time to append a character to the text document using the list implementation of the SECRO text editor.
From Fig. 8a we notice that the SECRO versions exhibit quadratic performance, whereas the JSON CRDT version exhibits linear performance. The reason for this is that reordering the SECRO’s history induces a linear overhead on top of the operations themselves (as explained in Section 8.4.1). Since insert is also a linear operation, the overall performance of the text editor’s insert operation is quadratic. To address this performance overhead the replica needs to be committed periodically.

Fig. 8a also shows that the SECRO implementation that uses a linked list is faster than its tree-based counterpart. To determine the cause of this countereintuitive observation, we measured the different parts that make up the total execution time in Appendix D. We found that the time overhead incurred by copying the document kills the speedup we gain from organising the document as a tree. This is because each insertion inserts only a single character but requires the entire document to be copied.

To validate this hypothesis, we re-execute the benchmark shown in Fig. 8a but insert 100 characters per operation. Fig. 8b shows the resulting execution times. As expected, the tree implementation now outperforms the list implementation. This means that the speedup obtained from 100 logarithmic insertions exceeds the copying overhead induced by the tree. In practice, this means that single character manipulations are too fine-grained. Manipulating entire words, sentences or even paragraphs is more beneficial for performance.

Overall, the execution time benchmarks show that deep copying the document induces a considerable overhead. We believe that this overhead is not inherent to SECROs, but to its implementation on top of mutable objects.

9. Guidelines for designing Replicated Data Types (RDTs)

We now provide some guidelines for designing replicated data types under (strong) eventual consistency. When designing available systems, programmers need to use existing RDTs or design their own. If a data type’s operations naturally commute then replicating it will guarantee strong eventual consistency out of the box, given that updates are eventually propagated to all replicas. This is for instance the case of a counter data type, whose increment and decrement operations commute.

When the data type’s operations do not naturally commute, one can browse the literature for an equivalent CRDT. A CRDT may exist that applies some clever tricks to make the operations commute (e.g. OR-Sets [24]).

If none of the above applies one can resort to SECROs to build their replicated data type without worrying about commutativity. SECROs are able to omit the commutativity requirement by (re)ordering operations deterministically. This naturally entails some performance cost, as shown in Section 8. Note that some conflicts may not be solvable solely by reordering operations and can thus not be tackled using SECROs. This is the case for mutually exclusive operations. When two mutually exclusive operations execute concurrently, a conflict will arise that can only be solved by discarding at least one of the operations. In those cases, the programmer may resort to synchronising the mutually exclusive operations, similarly to [3,4], or implement an ad-hoc conflict resolution scheme.

Finally, we draw the relation between CmRDTs (operation-based CRDTs, see Section 2) and SECROs. Both data types ensure SEC, but CmRDTs require all concurrent operations to commute. As such, all valid serialisations of the operations – those respecting causality – yield the same valid state. Interestingly, SECROs guarantee that all replicas agree on one valid serialisation (without having to synchronise with one another). Pre and post-conditions are used to confine the set of serialisations from which to pick one, e.g. to ensure that the given serialisation guarantees a certain conflict resolution strategy. Since all serialisations of a CmRDT are equivalent, any CmRDT can be implemented as a SECRO that associates no pre or postconditions to the operations. We thus conclude that CmRDTs are a subset of SECROs.

10. Related work

We now describe work that is closely related to the ideas presented in this paper. We distinguish between two research areas. First, we discuss programming languages and abstractions that like CScript help programmers trade off consistency for availability and vice-versa. Second, we discuss research on (strong) eventual consistency that is related to the SECRO data type.

Programming languages. CAPtain [22] is a programming model with two types of replicated objects: consistent and available. The former guarantee strong consistency whereas the latter guarantee availability but only eventual consistency. These two types of objects are completely separated and form CAPtain’s unit of distribution. In contrast to CAPtain, CScript bundles replicas into services which can be partly consistent and partly available, and distributes those services over the network. Each service exposes specific functionality through its API by coordinating between consistent and available replicas.

Geo [5] is an actor system for geo-replication that combines caching with replication techniques to hide latency and benefit from data locality where possible. Geo supports “single-instance” and “multi-instance” caching policies for actors across clusters. The single-instance caching policy is similar to consistent replicas in CScript, as it ensures a single instance of the actor that serialises all updates. The multi-instance caching policy replicates the actor to every cluster. These actors can be kept strongly consistent using Geo’s distributed cache coherence protocol, or eventually consistent using Geo’s Versioned API.

The MixT programming language [20] proposes mixed-consistency transactions to manipulate data with different consistency levels within a single database transaction. Using information flow analysis, MixT can break down mixed-consistency transactions into subtransactions for each consistency level and still guarantee atomicity. MixT works on top of existing databases whereas CScript’s programming model integrates replication at the object-level.

Lasp [19] is the first programming language where CRDTs are first-class citizens. New CRDTs are defined through functional transformations over existing ones. In contrast, CScript provides SECROs, general-purpose RDTs which are not limited to a portfolio of built-in data types. Existing data structures can be turned into SECROs by associating state validators to the operations. Eventual consistency. Central to SECROs is the idea of using application-specific information to reorder conflicting operations. Bayou [29] was the first system to use application-level semantics for conflict resolution by means of user-defined merge procedures. However, our work does not require manual conflict resolution; programmers instead specify the invariants the application must uphold in the face of concurrent updates, and the underlying update algorithm deterministically orders operations as to respect these invariants.

IPA [2] is closely related to SECROs as it preserves application invariants without coordinating operations. IPA extends the operations of traditional CRDTs with effects that guarantee the preservation of invariants in the face of concurrent updates. IPA differs from SECROs in that they modify operations whereas SECROs reorder concurrent operations.
JSON CRDTs [15] ease the construction of CRDTs by hiding the commutativity restriction that traditionally applies to the operations. Programmers can build new CRDTs by nesting lists and maps in arbitrary ways. The major shortcoming is that nesting lists and maps does not suffice to implement arbitrary RDTs. Moreover, programmers cannot customise conflict resolution because it is hardcoded by the implementation of lists and maps. Hence, JSON CRDTs are not truly general-purpose as opposed to SECRos.

Cloud types [8] are RDTs that like SECRos do not impose restrictions on the operations of the data type. However, cloud types hardcode how to merge updates coming from different replicas of the same type. As such, programmers have no means to customise the merge procedure of cloud types to fit the application’s semantics. Instead, they are bound to implement a new cloud type and the accompanying merge procedure that fits the application. Hence, conflict resolution needs to be manually dealt with.

Some work has considered a hybrid approach offering SEC for commutative operations, and requiring strong consistency for non-commutative ones [3,4]. There are some similarities to SECRos as they employ application-specific invariants to classify operations as safe or unsafe under concurrent execution. These hybrid approaches synchronise unsafe operations, whereas SECRos reorder them as to avoid conflicts without giving up on availability. Partial Order-Restrictions (PoR) consistency [18] uses application-specific restrictions over operations but cannot guarantee convergence nor invariant preservation since these properties depend on the restrictions over the operations specified by the programmer.

11. Conclusion

In this work we propose CScript, a distributed programming language featuring consistent and available replicas. Consistent replicas guarantee strong consistency but are not available under network partitions. On the other hand, programmers can always execute operations on available replicas but they only guarantee strong eventual consistency (SEC) [25]. CScript lets programmers bundle replicas into larger components called services. Services can mix available and consistent replicas which eases the development of mixed-consistency applications. The CScript runtime manages all replicas automatically, thereby freeing the programmer from manually synchronising them.

CScript supports two types of available replicas: conflict-free replicated data types (CRDTs) [25] and strong eventually consistent replicated objects (SECRos). Several CRDTs are built-in and programmers can implement custom ones. When CRDTs are not applicable, programmers can use our general-purpose SECRO data type. A SECRO is an RDT that guarantees SEC without imposing restrictions on the data type’s operations. Upon concurrent operations, SECRos compute a global total order of the operations that is conflict-free, without synchronising the replicas. To this end, SECRos use state validators: application-specific invariants that determine the object’s behaviour in the face of concurrency. By specifying state validators arbitrary data types can thus be turned into available replicas.

To the best of our knowledge, SECRos are the first approach to support truly general-purpose RDTs while still guaranteeing SEC. In this paper, we prove that SECROs guarantee convergence and we formulate a necessary condition for SECRO data types which is sufficient to then prove progress.

To evaluate our work, we implemented a collaborative text editing application using SECRos in CScript and compared it to a state-of-the-art implementation that uses JSON CRDTs. The memory usage benchmarks reveal that SECRos are more memory efficient than JSON CRDTs. The time complexity benchmarks reveal that SECRos induce a linear time overhead which is proportional to the size of the operation history. Performance wise, SECRos can be competitive to state-of-the-art solutions if committed regularly.

Fig. 8. Execution time of character insertions in the collaborative text editors. Replicas are never committed. Error bars represent the 95% confidence interval for the average taken from a minimum of 30 samples. Samples affected by garbage collection are discarded.
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. General proof of convergence for SECROs

In this appendix we prove that the SECRO data type guarantees strong convergence. In other words, we prove that SECRO replicas which received the same updates are in equivalent states.

In what follows we consider the SECRO implementation without commits and can therefore simplify the representation of SECRO replicas to a tuple \( r = (s, h) \) consisting of the replica’s initial state \( s \) and its history \( h \).

**Definition A.1.** Assume a replica \( r_1 \) with initial state \( s_1 \) and history \( h_1 \), and a replica \( r_2 \) with initial state \( s_2 \) and history \( h_2 \). We say that \( r_1 \) is equivalent to \( r_2 \) iff they have the same initial state and the same operation history: \( \forall u \in V_r \exists \) \( l \) such that \( l \downarrow r \) to deliver a list of updates \( l \) to a replica \( r \) which optionally yields the updated replica. We denote the set of permutations of a list \( l \) by \( \text{Perm}(l) \).

**Theorem A.1.** Replicas that received the same updates (possibly in a different order) are in equivalent states: \( \forall r_1, r_2 \in \text{Perm}(r) \), \( l_1, l_2 \) such that \( r_1 = (s_1, h_1) \land r_2 = (s_2, h_2) \land s_1 = s_2 \land h_1 \equiv h_2 \).

**Proof.** When we deliver the updates \( l_1 \) to the replica \( r_1 \), Algorithm 1 appends the incoming updates to the history on Line 1: \( h_1 = h_1 \uplus l_1 \). Similarly, when we deliver the updates \( l_2 \) to replica \( r_2 \), we add the updates to the history: \( h_2 = h_2 \uplus l_2 \). Since \( h'_1 \) and \( h'_2 \) are permutations of one another, sorting them according to a total order \( \gg \) yields the same list of updates: \( l \equiv \text{sort}_\gg(h'_1) = \text{sort}_\gg(h'_2) \). Both replicas then deterministically generate the linear extensions of \( l \) on Line 3: \( \text{LE}(l) \) and search for the first extension that is valid (i.e. respects all pre and postconditions). Given that the pre and postconditions are deterministic, finding the first valid extension is also deterministic. Hence, either both replicas find the same ordering of operations \( h' \) and end up in equivalent states \( (s_1, h') \equiv (s_2, h') \), or, both replicas end up in an error state because no valid extension exists.

Appendix B. Proof of progress for SECROs

As argued in Section 7.2, we cannot provide a general proof of progress for SECROs because the pre and postconditions are defined by the programmers. Instead, we require the SECRO’s pre and postconditions to meet Lemma 1.

**Lemma 1.** Given an initial state \( s \) and a set of valid updates \( V_r \), there exists an ordering of the updates that respects causality and all pre and postconditions.

Using Lemma 1 we define correctness of replicas.

**Definition B.1.** A replica \( r = (s, h) \) is correct iff the replica is an instance of a SECRO whose pre and postconditions meet Lemma 1 and all updates from its history \( h \) are valid.

We now prove that correct replicas guarantee progress.

**Theorem B.1.** For any correct replica \( r_1 = (s, h_1) \) and any valid update \( u \) issued by some other correct replica \( r_2 = (s, h_2) \), \( \exists u \in V \) such that \( u \downarrow r_1 \) does not fail:

\[
\forall r_1, r_2, u \in V_r : r_1 = (s, h_1) \land r_2 = (s, h_2) \land s = s \land h_1 \downarrow r_1 \land u \in V_r \implies (u \downarrow r_1 \land u \downarrow r_2).
\]

**Proof.** Let \( V \) be the set of valid updates observed by replica \( r_1 \), i.e. \( V \) contains all (and only those) updates from its history \( h_1 \). Upon delivering the update \( u \) at replica \( r_1 \), \( u \downarrow r_1 \), the algorithm generates all linear extensions of the updates in \( V \). Since there are no causality constraints on \( V \), \( u \downarrow r_1 \) is valid (cf. Lemma 1). The algorithm will find that linear extension and return the updated replica on Line 28, \( u \downarrow r_1 \) is Some \( r_1' \). Hence, delivering a valid update at a correct replica cannot fail.

Appendix C. Transitive closure of concurrent operations

Recall from Algorithm 1 in Section 7.1 that checking pre-conditions and postconditions requires computing the transitive closure of concurrent operations. We now formally define the transitive closure of concurrent operations.

**Definition C.1.** An operation \( m_1 = (a_1, p_1, o_1, c_1, d_1) \) happened before an operation \( m_2 = (a_2, p_2, o_2, c_2, d_2) \) iff the logical timestamp of \( m_1 \) happened before the logical timestamp of \( m_2 \): \( m_1 \prec m_2 \iff c_1 < c_2 \).

**Definition C.2.** Two operations \( m_1 \) and \( m_2 \) are concurrent iff neither one happened before the other \( [17] : m_1 \parallel m_2 \iff m_1 \not\prec m_2 \land m_2 \not\prec m_1 \).

**Definition C.3.** We define \( \parallel^+ \) as the transitive closure of \( \parallel \).

**Definition C.4.** The set of all operations that are transitively concurrent to an operation \( m \) with respect to a history \( h \) is defined as: \( TC(m, h) = \{ m' | m' \in h \land m' \parallel^+ m \} \).

Appendix D. Detailed execution time of the text editor

In Section 8.4.2 we found that the SECRO implementation that uses a linked list is faster than its tree-based counterpart. To determine the cause of this counterintuitive observation, we measure the different parts that make up the total execution time.
Execution time of operations  Total time spent on append operations.

Execution time of preconditions  Total time spent on preconditions.

Execution time of postconditions  Total time spent on postconditions.

Copy time  Due to the mutability of JavaScript objects our prototype implementation in CScript needs to copy the state before validating the potential history. The total time spent on copying objects (i.e. the document state) is the copy time.

Figs. D.9a and D.9b depict the detailed execution time for the list and tree implementations respectively. The results show that the total execution time is dominated by the copy time. We observe that the tree implementation spends more time on copying the document than the list implementation. The reason being that copying a tree entails a higher overhead than copying a linked list as more pointers need to be copied. Furthermore, the tree implementation spends considerably less time executing operations, preconditions and postconditions, than the list implementation. This results from the fact that the balanced tree provides logarithmic time operations.

Unfortunately, the time overhead incurred by copying the document kills the speedup we gain from organising the document as a tree. This is because each insertion inserts only a single character but requires the entire document to be copied.

Appendix E. Throughput of the text editor

The experiments presented in Section 8 focused on the execution time of sequential operations on a single replica. To measure the throughput of the text editors under high computational loads we also perform distributed benchmarks. To this end, we use 10 replicas (one on each node of the cluster) and let them simultaneously perform operations on the text editor. The operations are equally spread over the replicas. We measure the time to convergence, i.e. the time that is needed for all replicas to process all operations and reach a consistent state. Note that replicas reorder operations locally, hence, the throughput depends on the number of operations and is independent of the number of replicas.

Fig. E.10 depicts how the throughput of the list-based text editor varies in function of the load. We observe that the SECRO text editor scales up to 50 concurrent operations, at which point it reaches its maximal throughput. Afterwards, the throughput quickly degrades. On the other hand, the JSON CRDT implementation achieves a higher throughput than the SECRO version under high loads (100 concurrent operations and more). Hence, the JSON CRDT text editor scales better than the SECRO text editor. However, SECROs are truly general-purpose which allowed us to organise documents as balanced trees of characters, which is not possible using JSON CRDTs.

References
