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Master Thesis

Offline caching in web applications for AntidoteDB

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Abstract

Despite advancements in connectivity for user devices by service providers, such devices are subject to periods of disconnection. In order for the user to be able to interact with the application during periods of disconnectivity, the application must store its data on the client machine. Besides that, updates need to be maintained and delivered to the server once the connection is re-established. The demand for offline support has led to many ad-hoc solutions that often do not provide well-defined consistency guarantees.

In this thesis, we developed a WebCure, a framework for partial replication of data at client-side in web applications. It consists of a client-side data store that maintains both the data that has been received from the cloud storage server and the updates that have been executed by the client but have not been delivered to the cloud store, yet. A service worker acts as a proxy on client-side. While the client is offline, it forwards the requests to the client-side database. Finally, a cloud storage server maintains data shared between different clients. For this purpose, we chose AntidoteDB as the cloud storage server since it provides with conflict-free replicated data types (CRDTs) a well-defined semantics for concurrent updates. Updates that are executed while a client is offline are concurrent with all other updates happening between the last retrieval from the cloud storage and the next connection and synchronisation of the client. We developed the algorithms for WebCure and implemented a stable prototype of the framework. To evaluate its feasibility and performance, we additionally ported a calendar application that allows now for offline operations.

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Finally, I want to mention my friends, family and, particularly, **my parents** and **sister**. They did their very best to encourage and motivate me throughout the whole period of my study in Germany. Nothing of it would ever be possible without them. Thank you.

Ich versichere hiermit, dass ich die vorliegende Masterarbeit mit dem Thema „Offline caching in web applications for AntidoteDB“ selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel benutzt habe.
Die Stellen, die anderen Werken dem Wortlaut oder dem Sinn nach entnommen wurden, habe ich durch die Angabe der Quelle kenntlich gemacht.

Kaiserslautern, den 15. December 2018 Server Khalilov

Contents

1 Introduction

In this introductory chapter, we are going to discuss the motivation, research questions and the scope of this thesis.

1.1 Motivation

In modern days, with the speed the technology grows, the users always have their hopes high concerning having a more comfortable experience of working with web applications on their daily tasks. However, sometimes, even well-designed applications, which are expected to deliver better user experience, fail to do so and keep their users happy, due to the periods of disconnectivity that might occur. At such periods, for the matter of availability of the application, it should have its data on the client machine. That would allow users to maintain and perform different operations on their data while being offline or under poor network conditions. On the other hand, the updates performed offline at client side should be sent to the server, once the internet connection is back again. This is not an easy task, as, typically, one server could serve for multiple users. These users might deliver updates to the server at different times, so, the whole system should provide well-defined consistency[1] guarantees to make the offline support possible, which many ad-hoc solutions could not do to this day.

In this thesis, we designed and implemented a framework for web applications, which we named **WebCure**. The problem we introduced above requires having the data to be partially replicated at the client side. With WebCure, we offer an approach of having a data store on a client. However, its purpose is not only to have the application available, when there is no internet connection. The client data store will be able to maintain the data coming from both sources: firstly, the data received from the server; and, secondly, the updates performed by the client, but which have not been delivered back to the server, yet.

Additionally, for the web application to work offline and online, we are

[1]This and other concepts used in the introductory chapter will be defined in **Chapter 2**.

using a service worker. It serves as a programmable network proxy[1], allowing to manage how the network requests from the client are handled. When a client is offline, a service worker will redirect the requests coming from the client to its local storage. In the other situation, when a client has a connection, all the outgoing requests will proceed their way to a server side. This feature alone is a major positive regarding user experience, as it increases the availability of the application.

On the other side, the server maintains cloud storage, based on AntidoteDB. We chose this database as our cloud storage server for the reason that it uses Conflict-Free replicated data types (CRDTs), which provide well-defined semantics for concurrent updates. We consider the next updates to be concurrent: the operations that are executed while a client is offline and the operations that are happening in the period between the last retrieval from the cloud storage server and the next connection and synchronisation to it.

To sum it up, we developed the algorithms for WebCure and implemented a stable prototype of the framework. Apart from that, to evaluate WebCure's feasibility and performance, we ported a calendar application that allows for offline operations and demonstrates the advantages of our approach.

1.2 Research questions

Going through this thesis, our reader will find answers to the following research questions:

- *RQ1.* What could be a scalable solution for the transmission of CRDTs between a client and AntidoteDB-based server?
- *RQ2.* What are the methods and technics available to implement web applications that would be able to work offline and in the conditions of poor network connections?
- *RQ3.* How efficient is it to use a web-client with cache rather than without it?

The research questions mentioned above are essential. Sometimes, there are some creative solutions to different problems that work, but just for one particular case. Therefore, it is always important to look for a solution, which can be scaled to different levels. On this matter, we are going to discuss the problem of transmission of CRDTs between a client and the server it interacts with. As CRDTs offer two ways of replicating data, a state-based approach and an operation-based approach, we are going to argue for the second one. The reason is that it has the benefits which are especially valuable for the system we are going to design, which will be explained later. Throughout this thesis, we are going to present the technique for implementing a web application, which is functional offline. However, even though our way to implement the offline work has advantages, there are also some other methods, which we are going to discuss in **Chapter 7**. Regarding the last research question, as was already mentioned, in **Chapter 6** we will present the calendar application, which was extended with a feature of a client-side storage. There, we are going to share our thoughts on working with an app that has improved its functionality.

1.3 Structure of Thesis

In this section, we are going to give a summary of the structure of this thesis.

We started with the introduction in **Chapter 1**, where we described the motivation of the thesis in **Section 1.1** and then the research questions, which we specified in **Section 1.2**.

Next, in **Chapter 2**, we are going to talk about the fundamentals required to comprehend the idea of the paper: in **Section 2.1** we are discussing the main theoretical concepts related to the distributed databases, while in **Section 2.2** we introduce the cloud storage we are going to use for the server – AntidoteDB, and in **Section 2.3** we cover CRDTs in general. Additionally, there we describe the datatypes we used in our work.

Afterwards, in **Section 3.1** and **Section 3.2** we will talk about the requirements and assumptions we make for the system that we are going to design. Later, in **Section 3.3** we will show in details how we came up with the protocol of the system.

Then, there is **Chapter 4**, where we are going to discuss the technologies, which we used to implement the described protocol. Mainly, we will talk about the client side of the system there.

Having explained all the previous topics, in **Chapter 5**, we will go in details through the implementation of the system, starting discussing the main components of the system in **Section 5.1**.

Furthermore, in **Chapter 6** we will cover the topic on how we evaluated the system, where we will also show WebCure running in a Calendar application. Finally, in **Chapter 7** we discuss other methods and technics that inspired us for this work. Then, in **Chapter 8** we will summarise the work of this thesis and in **Section 8.2** we will talk about any future improvements and possible solutions that can be done over the current design of the system.

2 Theoretical background

In this chapter, we are going to make an introduction for our reader to the theoretical concepts, which represent a prerequisite to have an understanding of this thesis.

2.1 Main concepts

Distributed database is "a collection of multiple, logically interrelated databases distributed over a computer network"[2]. A *geo-distributed database*, in its turn, is a database, which is spread across two or more geographically distinct locations and runs without experiencing performance delays. The maintaining of such databases brings its challenges. As the database is spread across several locations, there should be a replication process in order to ensure that replicas of that database synchronise and have the latest state of the data. This replication process should be fast, because if there are two replicas of the database, then whenever there is some information written to the first replica, it should be accessible to users, who use the second one. That is the problem of the availability, but before the information at replicas becomes available, it first should be checked over the consistency, as the states of the replicas should be equal. That is a complex task to solve.

Working with such a distributed database, whenever the data is needed to be read or changed in any way, a transaction should be started, executed and closed. A *transaction* is a basic unit of computing, which consists of a sequence of operations that are applied atomically on a database. Transactions transform a consistent database state to another consistent database state. A transaction is considered to be *correct* if it obeys the rules, specified on the database. As long as each transaction is correct, a database guarantees that concurrent execution of user transactions will not violate database consistency [2]. *Consistency* requires transactions to change the data only according to the specified rules. An example of consistency rule can be the following: let us say that in a bank database the bank account number should only consist of integer numbers. If an employee tries to create an account that contains something other than integer numbers in it, then the database consistency rule will disallow it. Consistency rules are important as they control the incoming data and reject the information, which does not fit.

Sequential consistency and *linearizability* are two consistency conditions that are well-known. Sequential consistency requires that all of the data operations appear to have executed atomically (i.e. independently), in some sequential order. When this order must also preserve the global ordering of non-overlapping operations, this consistency is called linearizability[3]. Linearizability guarantees that the same operations are applied in the same order to every replica of the data item[4]. Serializability is a guarantee about transactions, that they are executed serially (i.e. without overlapping in time) on every set of the data items[4]. Serializability is more strict than sequential consistency, as the granularity of sequential consistency is a single operation, while for serializability it is a transaction. As a result, when serializability is satisfied, the sequential consistency is also satisfied, but not vice versa.

Now, let us introduce different consistency models and the one we will follow in the designing part of WebCure.

As stated by Shapiro [5], "*strong consistency* model could be described in the following way: whenever the update is performed, everyone knows about it". It means that there is a total order of updates, and reads are guaranteed to return the latest data, regardless of which replica is the source of the response. The advantage of strong consistency is that the database is always in a consistent state and to disadvantages, we can add low latency, as there is a delay for making sure that all the replicas are in a consistent state before any other read / write requests could be processed. The latency point is a huge drawback for the performance, especially if a strong consistency model is considered to be used as a solution for the web, where users usually expect high responsiveness and availability.

The main point of replicating data is to improve such aspects as reliability, availability, performance and latency. However, according to CAP Theorem[6], a distributed database can only have two of the three properties: consistency, availability and partition tolerance. This theorem is fundamental, as it makes people think towards the trade-off between those three properties for a specific use case. There are some weaker consistency models, where the results of requests can alter depending on the replica[7]. In this thesis, we will stick with partial *causal consistency*. As it is stated in Zawirski et al. [8], causal consistency is "the strongest available and convergent model". They continue their statement saying that "under causal consistency, every process observes a monotonically non-decreasing set of updates that includes its updates, in an order that

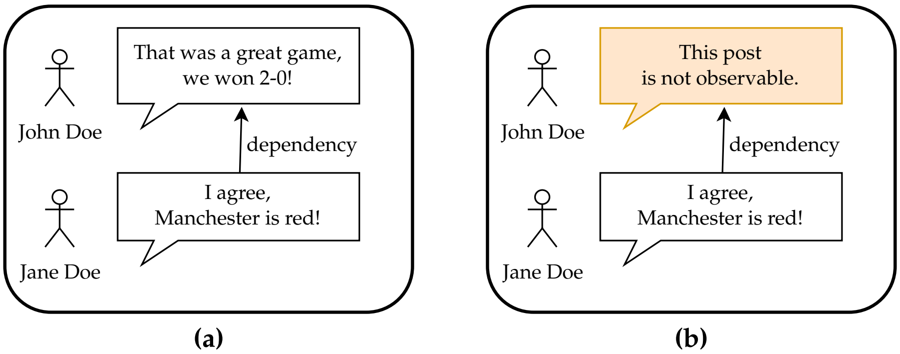


Figure 2.1: An example of how a causally consistent behaviour (a) and the one that is not (b) could work in a social network.

respects the causality between operations". As the causal ordering is respected, it makes it easier for programmers to reason, as it gives the guarantee that related events are visible in the order of occurrence, while the events, which have no relation to each other, can be in a different order in different replicas. Let us consider an example of an application for some of social networks. There, a reply to a wall post happens after the original post is published. Thus, users should not see the reply before the original post is observable. This type of guarantees is provided by causal consistency. Looking at **Figure 2.1** we can see that on the left subfigure, the user can see the original wall post as well as the reply, while on the right subfigure, without causal consistency, the user sees only the reply, while the original wall post is missing.

2.2 AntidoteDB

For this thesis, one of the core parts of the architecture of WebCure belongs to the database called AntidoteDB[9]. It helps programmers to write correct applications and has the same performance and horizontal scalability as AP / NoSQL[10], while it also:

- is geo-distributed, which means that the datacenters of AntidoteDB could be spread across anywhere in the world;
- groups operations into atomic transactions[11, 12];
- delivers updates in a causal order and merges concurrent operations.

Merging concurrent operations is possible because of CRDTs[13], which are used in AntidoteDB. It supports counters, sets, maps, multi-value registers and other types of data that are designed to work correctly in the presence of concurrent updates and failures. The usage of CRDTs allows the programmer to avoid problems that are common for other databases like NoSQL, which are fast and available, but hard to program against[12]. We will cover the topic of CRDTs later in this chapter.

Apart from that, to replicate the data AntidoteDB implements the *Cure*[12] protocol. It is a highly scalable protocol, which provides causal consistency.

To ensure the guarantees it offers, AntidoteDB uses timestamps, indicating the time after the transaction. Timestamps are considered to be unique, totally ordered, and consistent with causal order, which means that if *operation 1* happened before *operation 2*, then the timestamp related to the *operation 2* is greater than the one related to the *operation 1*[13].Whenever the update operation has to be applied, it is also possible to provide a minimum time from what that update should be performed. This information is useful when a client is working with a server, which is based on AntidoteDB. In such cases, when one data centre stops working, the client can reconnect to another one. As a client can remember the latest timestamp for the data it has worked on, the failover to another data centre is possible without any additional efforts, as the timestamp information will help the client to request only the data, which have timestamps greater than the one, which is already stored at the client.

2.3 CRDTs

As it is stated in the work of Preguiça et al. [14], a CRDT is an abstract datatype, which is designed for a possibility to be replicated at multiple processes and possesses the following properties:

- The data at any replica can be modified independently of other replicas;
- Replicas deterministically converge to the same state when they received the same updates.

Replication is a fundamental concept of distributed systems, well studied by the distributed algorithms community[13]. There are two models of replication that are considered: state-based and operation-based. We are going to describe both of them below.

Operation-based replication approach

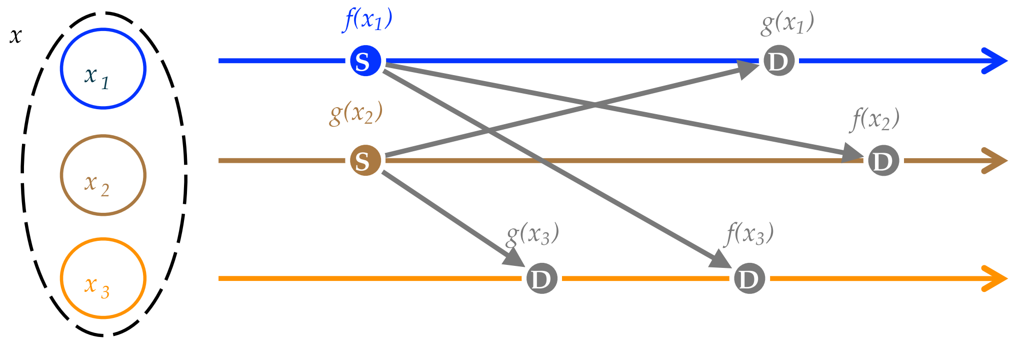


Figure 2.2: Operation-based approach[13]. «S» stands for source replicas and «D» for downstream replicas.

In this thesis, we are going to use the operation-based replication approach, where replicas converge by propagating operations to every other replica[14]. Once an operation is received in a replica, it is applied locally. Afterwards, all replicas would possess all of the updates. In **Figure** 2.2, we can see that firstly operations $f(x_i)$, $g(x_i)$ applied locally at source replicas x_i, and then the operations are conveyed to all the other replicas. The second part of this process is named *downstream* execution.

This replication approach infers that replicas do not exchange full states with each other, which is a positive concerning efficiency. Not always, though, as it depends on the task. Sometimes, applying multiple operations at every replica could be costly, and this is where state-based replication approach is beneficial.

State-based replication approach

The idea of this approach is kind of opposite to the operation-based one. Here, every replica, when it receives an update, first applies it locally. Afterwards, it sends its updated state to other replicas. Following this way, every replica sends its current full state to other replicas. Afterwards, the merge function is applied between a local state and a received state, and every update eventually is going to appear at every other replica in the system. We can see this it in the **Figure** 2.3, where x_i stands for replicas, $f(x_i)$, $g(x_i)$ stands for the functions that apply updates locally at source

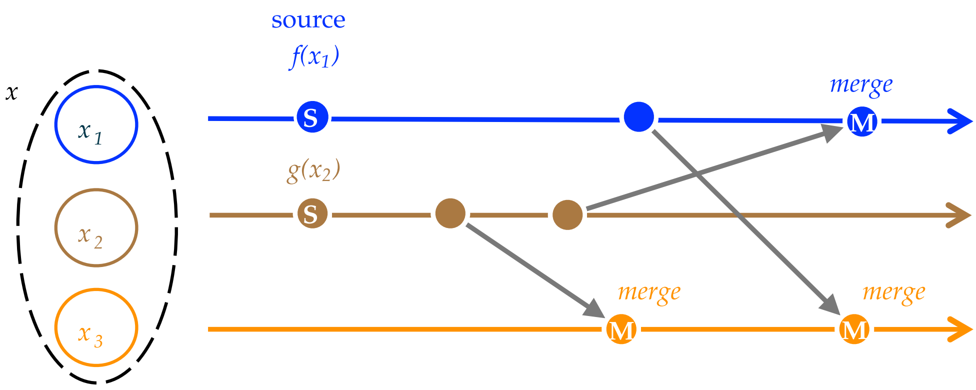


Figure 2.3: State-based approach[13]. «S» stands for source replicas and «M» for merging stages.

replicas before sending a new full state for a follow-up merges to other replicas in the system.

There are different types of CRDTs, yet, we will consider three of them: counters, sets and multi-value registers. We will give a brief description to each of the mentioned datatypes below.

Counter

Counter is a datatype, which keeps track on its state, which is an integer number. The value of the Counter could be modified by the operations *inc* and *dec* that increases or decreases the state by one unit, accordingly[14]. The concurrency semantics for this datatype is that a final state of the object reflects all the performed operations on it. In other words, to calculate the state of the Counter, it is needed to count the number of increments and subtract the number of decrements.

Add-wins Set

Add-wins Set[2] datatype represents a collection of objects with a specific handling of concurrent updates performed over them. In case of concurrent updates on the same object, *add* operations in Set win against *remove* operations. If, for example, there is an empty set and two concurrent operations applied to it – *add a* and *remove a*, then the result is going to be *{a}*,

[2]For the simplicity of reading, later it goes as Set.

as *add* operation wins. A *remove* operation will “overwrite” an *add* operation only when it happens after it[14].

Multi-value Register

This datatype maintains a value and provides a *write* operation of updating that value. The exciting part about multi-value Registers is their concurrency semantics. In the case of two or more updates happening at the same time, all values are kept. Thus, the state of the register will consist of all the concurrently written updates for further processing. However, any additional single *write* operation will overwrite the previous state of the register, even if it consisted of multiple values[15].

3 Design

In this chapter, we are going to, firstly, introduce the requirements and assumptions we make for the design of WebCure. Having set them, afterwards, we will in detail describe the design of the system.

3.1 Requirements

We listed the functional requirements of WebCure in **Table** 3.1 and non-functional requirements in **Table** 3.2.

First of all, looking at the first three functional requirements, *R1–R3*, we see that for the implementation were selected such CRDTs as counter, set and multi-value Register. The reason for that is that these data types cover the most operations on CRDTs and, if our design works for them, it will work for the rest as well. The requirement *R4* makes the user able to get the data from the server at different timestamps and compare it. Next, talking about the requirement *R5*, even though it is possible to request data at different timestamps, it is vital for the client to store in cache only the latest available at the server data. The reason for it is to make it possible to continue working on the most relevant data, while offline. The requirement *R6* is due to one of the limitations AntidoteDB possesses and is related to one of the assumptions we make in the following section. Requirements *R7–R9* specify what kind of actions the user can perform on a client when offline, as well as their synchronisation with the server. Finally, the requirements *R10* and *R11* guarantee that the changes performed offline at the client, as well as changes at the server side, are synchronised in a way satisfying causal consistency model.

Next, there are non-functional requirements: *NFR1* and *NFR2*. Basically, both of them support our claim that a client can work offline, as well as under uncertain network conditions.

Table 3.1: Functional requirements.

R1	Retrieval, increment and decrement of the counter CRDT should be possible.
R2	Retrieval, adding and removing elements from the set CRDT should be possible.
R3	Retrieval, assigning and resetting the multi-Value Register CRDT should be possible.
R4	Retrieval elements of any supported CRDTs should be possible according to the passed timestamp.
R5	The client should cache only the latest data available at server's side.
R6	It should not be possible to create elements of different CRDTs with the same name (due to limitations of AntidoteDB).
R7	When offline, it should be possible to make read/write operations on supported CRDTs.
R8	The user should be able to remove from the client any stored data element.
R9	Any operations performed offline, once the connection is restored, should be sent to the server immediately.
R10	The execution model of offline operations at the client should be sequential (updates are ordered).
R11	When the connection is re-established after having data changes in offline mode, the client storage should be updated appropriately (with a consideration of the client's offline changes and possible changes on the server).

Table 3.2: Non-functional requirements.

NFR1	The system should be available online and offline (except for the functionality with timestamp-related updates).
NFR2	The system should be available with a poor network connection.

3.2 Assumptions

In this section, we are going to give a list of assumptions we make for WebCure.

1. **Timestamps**. Firstly, the database storage used for the server's side should have the concept of timestamps (like in AntidoteDB, described in **Section 2.2**), in order for the protocol we are going to describe in **Section 3.3** to work correctly.

2. **Cache is persistent**. For WebCure to work online and, especially, offline, we believe that the browser's cache is safe from automatic clearing. Contrarily, if the cache could be cleared automatically depending on the browser's behaviour, it makes it impossible to support the claim that the application can work offline. To guarantee this assumption, a Persistent Storage API described in **Section 4.4** can be used.

3. **Name duplicates**. We limit the creation of different CRDT elements with the same name in the system due to limitations of AntidoteDB, as the requirement *R7* describes it in the **Table 3.1**. As AntidoteDB is in the process of ongoing development, currently the database crashes when there is an attempt to create elements of different CRDTs with the same name. Thus, this condition has to be fulfilled.

4. **Server's database is always on**. We assume that the server's database is not going to be reset and lose all its data. The client entirely relies on the server's storage for the synchronisation and only sends back operations performed offline on client's side. Therefore, it will be impossible to restore the server's database from the client's storage, even if it was up-to-date before the server's data loss. With additional changes to the current protocol, it might be possible, though, but that is not the topic we cover in this thesis. However, even in such a situation, the client will be able to continue the offline work.

As we specified the requirements, we can go further into and design the protocol of the system.

3.3 Protocol

The fundamental part of WebCure will be its protocol design. We are going to describe it in an event-based way in the form of pseudo-code in the following sections.

3.3.1 Data transmission

As we already remember from **Chapter 2**, because AntidoteDB is using CRDT datatypes, the following options are possible to update the database: state-based and operation-based. This thesis will consider only the operation-based approach, as it has such an advantage over the state-based approach as less transferred data in most situations. Therefore, whenever a client needs to update the database, it will send to the server a list of operations. However, whenever it needs to read the value, it will receive the current state of the object from the database. For this thesis, we are going to use such datatypes as counters, sets and multi-Value Registers, to which the reader was introduced in **Section 2.3**.

3.3.2 Description

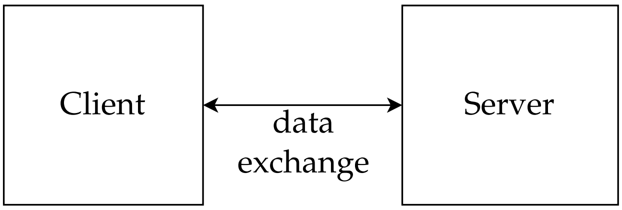


Figure 3.1: An overview of the communication protocol.

Firstly, as we would like to focus on the communication part between a server and a client, let us for now keep both of them as black boxes[3], as they are represented in **Figure 3.1**. Next, we will go through different stages of their communication and describe, how we handled these processes.

Graphics notations

Let us explain the notations, which are going to be used for a further protocol description. In **Figure 3.2 (a)**, we can see a notation for the timeline. Timelines will be used for the matter of showing the sequence of events happening. In **Figure 3.2 (b)**, the arrow shows the transmission of data between a subsystem A and subsystem B, as well as its direction and a

[3]In software engineering, a black box is a system, which can be viewed in terms of its inputs and outputs, without the understanding of its internal workings.[16]

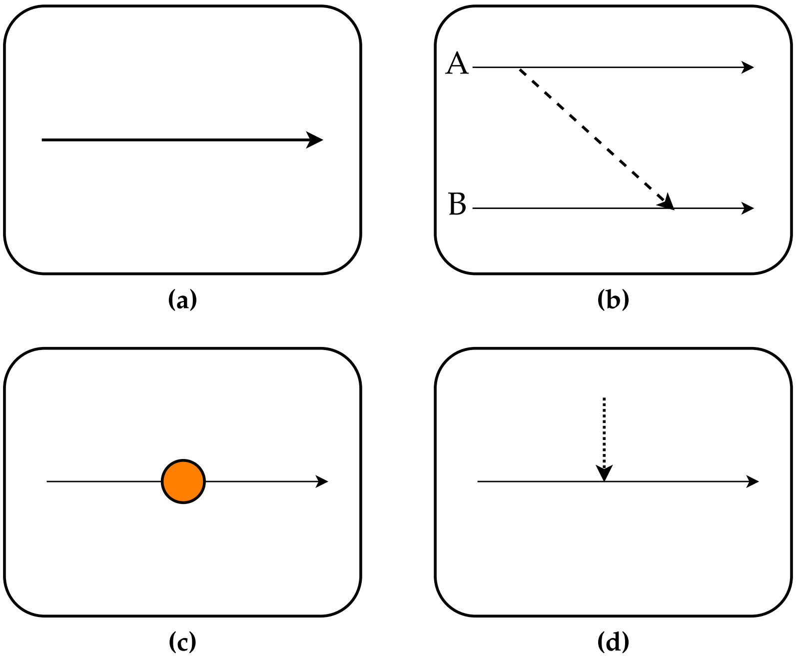


Figure 3.2: An overview of notations used in the following chapters for the protocol explanation.

command. **Figure** 3.2 **(c)** represents the state of the data on a system's side, while **Figure** 3.2 **(d)** points to a timestamp, at which an operation that changes the system's storage was applied.

Next, as we already mentioned, we will explain the protocol in an event-based way.

A client receives an update from the server

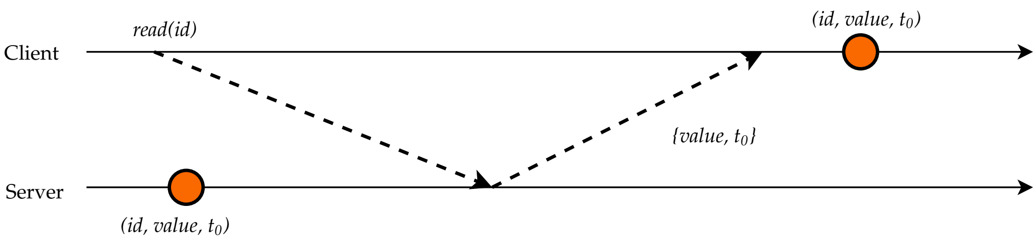


Figure 3.3: The communication between a client and a server for the read function.

Let us assume that a client initiates its work with empty storage. Then, a user might want to request the actual data from the server. In this case, as can be seen in **Figure** 3.3, a user has to pass to the server an *id* of the data to *read*. If the request is successful, the server is going to *respond* with a *value* for the requested *id* and the timestamp of the last write – t_0, so the client will store this information in its own storage.

Listing 3.1 Pseudocode for requesting the data: client.

```
// Read function that pulls database changes
// @param id: the id of the object, for which the update was
    requested;

function read(id) {
  GetHttpRequest( // send an http-request to get the data
      from the server by id
    id,
    function onSuccess(value, timestamp) { // get the value
        and timestamp from the server

      // create an object that maintains all necessary data
      var item = {
        id: id, // id of an data item
        operations: [], // operations performed offline
        sentOperations: [], // operations performed offline
            and already sent to the server
        state: value, // a state received from the server
        type: 'set' // a type of CRDT
      };

      storeInCache(item); // cache an item created earleir
      storeInCache(timestamp); // cache the timestamp
    },
    function onFail() {
      getFromCache(id); // get the object from cache by id
    }
  );
}
```

The pseudocode of the logic for this *read* functionality can be seen in

Listing 3.1. At the *line 5*, an asynchonous function *GetHttpRequest* has two callbacks – *onSuccess*, in case a request proceeds successfully, and *onFail* in case of a failure.

In case of success, the value and the timestamp associated with passed *id* are going to be fetched from the server. After that, at the *line 10* we create an element *item*, which has the following properties: *id* for the id of a data item, *state* for the actual state of the data item on the server, *type* for the type of CRDT, *operations* for the operations performed at the client's side while offline, *sentOperations* for the operations performed at the client's side while offline, but which are already sent to the server. Next, a function *storeInCache* is called twice at the lines *18 and 19*. Firstly, to store in cache an object *item* for the offline use. Secondly, to store in cache a *timestamp* received from the server. A client will always receive either the data associated with the latest timestamp from the server or, if a client chooses to specify the timestamp, it will receive the data associated with that timestamp.

In case of failure, however, the method *getFromCache* is going to be called with an argument *id*, as can be seen at the *line* 22. If *id* exists at client's cache, then it will be returned.

Now, let us say, that after receiving an element *id* from the server, the client wants to change it and send it back to the server.

A client sends an update to the server

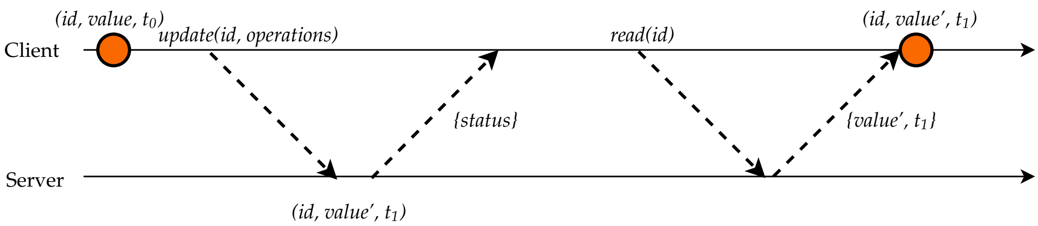


Figure 3.4: The communication between a client and a server for the update function.

Looking at **Figure 3.4**, in the case of writing the information to the server, a client has to send an *id* with an operation to perform. After that, the server is going to apply the received operation on its side and, in case of success, the new state of the data will receive a timestamp t_1, and an acknowledgement of the successful commit will be sent back to the client. What happens in case of unsuccessful acknowledgement will be explained below.

So, once the client is notified that the update was applied on the server successfully, a user can get the latest changes to the client's side now. Thus, when the read request for *id* is sent again, the server will send back the new value – *value'* and a new timestamp – t_1, for the element *id*.

Listing 3.2 Pseudocode for making a request to change the data: client.

```
1  // Update function that processes user-made update
2  // @param id: an id for the object that should be updated;
3  // @param op: operation performed on the object for the
       specified id

5  function update(id, op) {
6    PostHttpRequest(
7      // send an http-request to update the data on the server
8      { id, op },
9      function onSuccess(result) {
10       // no actions performed
11     },
12     function onFail() {
13       var item = getFromCache(id); // get the object from
             cache by id
14       item.operations.push(op); // store the operation on a
             client's side in order to try sending it again later
15       storeInCache(item); // cache an updated item
16     }
17   );
18 }
```

However, let us look at the pseudocode placed in **Listing 3.2**. There we can see the function *update*, which has to have an access to the parameters *id* and *op*. There is an attempt to send the operation *op* for the element *id* to the server, by using *PostHttpRequest*. It is asynchronous and has two callbacks – *onSuccess* and *onFail*, just as before it was explained for the *read* function. If the request succeeds, then the client gets notified about it, and no further actions are taken. However, in the case of failure, as we can see at the *line 13*, firstly we are getting the object from the cache by *id*. If it exists, then we add the operation *op* to that object into its property *operations*, and, afterwards, store an updated object in cache again using *storeInCache* at the *line 15*. That makes the update available while the user is offline and gives an opportunity to send the operation again when the connection is back.

Next, let us say that a client loses its network connection, so any updates made from that point onwards will be stored locally.

Offline behaviour

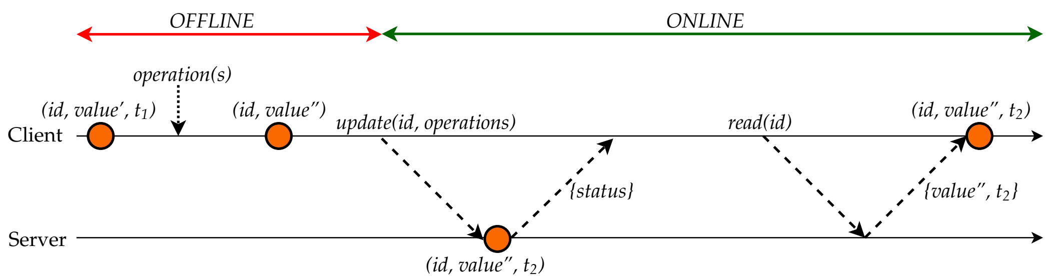


Figure 3.5: The communication between a client and a server while offline with a transition to online.

Have a look at **Figure** 3.5, where appropriate markings can clearly distinguish periods when the client was offline and online. The client has an element *id* with a value *value′* at timestamp t_1 and then makes a local change applying some operation, which changes the previous value to a new one – *value″*. Pay attention that a new value does not receive a timestamp assigned to it, while locally: to support the causal consistency claims, the server should take responsibility for assigning timestamps. Then, after some time, the connection gets back, and the client sends an immediate update message to the server with *id* of an element, the applied operation and a timestamp t_1. The server's side, as was already described above, applies that operation on a t_1 to back up the causality claims, and returns an acknowledgement of success. Eventually, the client sends a *read* message and gets back the *value″* as well as the assigned to it timestamp t_2.

Listing 3.3 Pseudocode for sending offline performed operations to the server: client.

```
// Update function that processes user-made updates performed
    offline when the connection is restored
// @param offlineOperations: an array that contains all the
    operations performed on a client's side offline
function synchronise(offlineOperations) {
  if (ONLINE) {
    offlineOperations.forEach(operation => {
      send(operation);
    });
  }
}
```

The logic described above can be seen in **Listing 3.3**, which has the function named *synchronise* that should be triggered at the time when the client's side restored a network connection. There, we can see that every operation performed offline is sent once at a time to the server. For causality, the array should be sorted in the order the operations were performed initially.

Now, let us move to the point when more than one client interacts with a server, in order to see how scalable the described protocol is.

Two clients interact with a server.

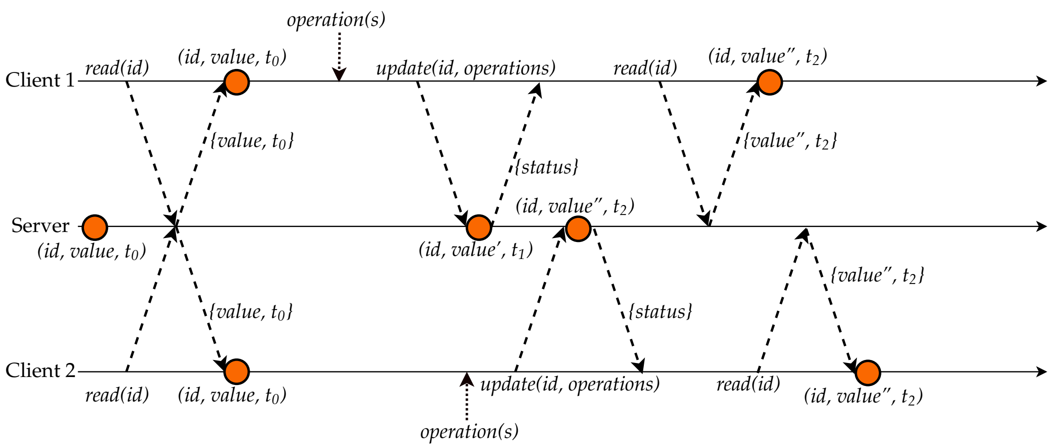


Figure 3.6: The communication between two clients and a server.

Let us assume that, initially, as can be seen in **Figure 3.6**, the server has a stored element *(id, value)* at the timestamp t_0. Therefore, when both clients request to read the data from the server, they get that data and store it locally. At the representation above, a *Client 1* is acting first and sends an update to the server changing the value of an element *id* to *value'* at t_1. Observe that *Client 1* does not request the latest data from the server and still only has its local changes. In parallel, a *Client 2* makes the change later at time t_2, and an element *id* is now set to *value"*. Then, both clients request the updated data from the server and both receive the actual value of the element *id* at the timestamp t_2, which is *value"*. We would like to stress the point that all systems - the server and both clients end up having the same data.

Now we would like to give a brief overview of the next two chapters: firstly, in **Chapter 4** we will give a proper introduction into the technologies we used to implement the described protocol and, then, in **Chapter 5** we will go through its development.

4 Technologies

In this chapter, we describe the technologies we used to implement the design we introduced in **Chapter 3**. To give an overview, the implementation of the design for WebCure demands the following components:

- A service worker, in order to manage requests coming from the client;
- A Cache API to store HTML, CSS, JavaScript files, and any static files[17] to make the application available offline;
- A database to store the data locally;
- Background Sync for deferring the actions conducted offline until the connection is stable.

4.1 Service Worker

Service worker[18] is a web worker[4], which is a JavaScript file, which lies in the middle, between the web application and network requests. Service worker runs independently from the web-page and has the following characteristics:

- It does not have access to the DOM[5], however, it has the control over pages (not just a specific one);
- When the application is not running, a service worker still can receive push-notifications from the server[1], which let us improve the user experience of the application and makes it "closer" to native mobile applications;

[4]Web Workers make it possible to run a script operation in a background thread separate from the main execution thread of a web application[19].

[5]DOM, or **D**ocument **O**bject **M**odel of the page defines HTML elements as objects, as well as their properties, methods, and events.

- It runs over HTTPS, as for the projects using a service worker, the "man-in-the-middle"[6] attacks could represent a real threat;

- It offers a possibility to intercept requests as the browser makes them and has the following options:
  - to let requests go to the network as usual;
  - to skip the network and redirect requests to get the data from the cache;
  - to perform any combination of the above.

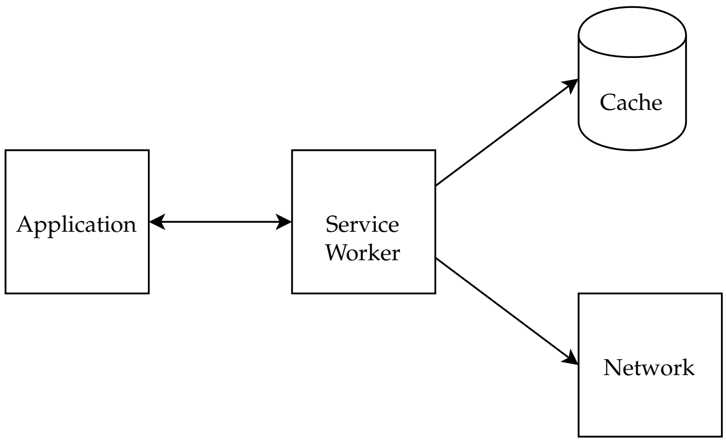


Figure 4.1: An overview of the service worker being able to provide the application experience of both online and offline modes.

We are going to use a service worker in order to intercept the network traffic. For example, as can be seen at **Figure 4.1**, in circumstances when problems are happening with a network when a request is in processing, we will get the data from the cache. At times, when the internet connection could not be established, the cache content can be easily displayed without forcing a user to wait, which dramatically improves performance and user experience. Also, when the internet connection is present, the data can be received from the actual network.

[6] In computer security, this is a type of attack, where a third party secretly alters the communication between two parties, while they believe they are directly "talking" to each other[20].

4.1.1 Service worker lifecycle

In this subsection, we will introduce the steps through which a service worker goes. These steps are registration, installation, and activation. All of them we are going to describe below in more details.

Registration

Before one can use service worker features, a developer has to register the corresponding script in the JavaScript code. The registration helps the browser to find a service worker and, afterwards, start its installation in the environment.

Listing 4.1 Code, which demonstrates how to register a service worker[1].

```
1 if ('serviceWorker' in navigator) {
2   navigator.serviceWorker.register('/service-worker.js')
3   .then(function(registration) {
4     console.log('Registration successful, scope is:',
        registration.scope);
5   })
6   .catch(function(error) {
7     console.log('Service worker registration failed, error:',
        error);
8   });
9 }
```

Looking at the *line 1* of code in **Listing 4.1**, we see that, firstly, it is necessary to check, whether the browser supports service workers by observing the property *serviceWorker* of *navigator*[7]. If so, the service worker is going to be registered then, as can be seen at the *line 2*, where the location of the service worker is stated as well. The *navigator.serviceWorker.register* returns a promise[8], which resolves when the registration was successful. Afterwards, the scope of the service worker is logged with *registration.scope*.

[7] The navigator object contains information about the browser[21].
[8] JavaScript Promise is an object, which represents the eventual completion or failure of an asynchronous operation[22].

Not every browser supports the functionality of service workers. Nowadays, the latest versions of such browsers as Chrome, Edge (partially) and Firefox support it. However, it is still only partially supported in Opera and Safari, and not at all in the Internet Explorer[23] – that is something developers should keep in mind.

The scope of the service workers is quite significant: it defines the paths, from which it can intercept network requests. By default, the scope of the service worker is the location, where the service worker file is stored, including all the sub-directories. For example, if the scope is the root directory, then the service worker is going to regulate the requests for all files at the domain.

Listing 4.2 Code, which demonstrates how to set a custom scope when registering a service worker[1].

```
navigator.serviceWorker.register('/service-worker.js', {
  scope: '/app/'
});
```

When registering, it is also possible to use a custom scope. **Listing 4.2** demonstrates that the service worker is going to have a scope of */app/*. It indicates that it will control requests from all the pages like */app/* and deeper. When the service worker is already installed, *navigator.serviceWorker.register* returns the object of the currently active service worker.

Installation

After the registration, the browser might attempt installation of a service worker, if it is considered as a new one, which happens in the following situations:

- when the site does not have a registered service worker yet;
- when there is a difference between the previously installed service worker and the new one;

Listing 4.3 Code, which demonstrates a listener for the *install* service worker's event[1].

```
// Listen for install event, set callback
self.addEventListener('install', function(event) {
    // Perform some task
});
```

Installation triggers service worker's *install* event. There is a probability of having a listener for it in order to assign a specific task (depends on the use case), which follows the installation on success. The way to set up this listener is shown in **Listing** 4.3.

Activation

After the installation, a service worker has to be activated. In case there are open pages, which are controlled by the previous version of a service worker, then the recently installed service worker will be waiting. The activation of a new service worker takes place only when there are no other pages, controlled by the old version of a service worker. That provides a guarantee that only one version of service worker manages the pages of its scope at any time.

Listing 4.4 Code, which demonstrates a listener for the *activation* service worker's event[1].

```
self.addEventListener('activate', function(event) {
  // Perform some task
});
```

Similar to the installation, the activation phase also has its event that gets triggered once the service worker is activating, as we can see in **Listing** 4.4. For example, at this point, it might be a good idea to clean the previously stored old cached data.

4.2 Cache API

For the best offline experience, the web application should store somewhere HTML, CSS, JavaScript code, as well as images, fonts. There is a place for all of it called Cache API, which we are going to use for WebCure. With Cache API it is possible to store network requests associated with corresponding requests.

Listing 4.5 Code, which demonstrates how one can create cache storage called *my-cache*[24].

```
caches.open('my-cache').then((cache) => {
  // do something with cache...
});
```

In **Listing 4.5** we see an example code of how a cache with a name *my-cache* is created. If the operation is performed successfully, then a promise resolves, and one is going to get access either to a newly created cache or to the one, which existed before the call of *open* method.

That covers the main functionality of the API. After creating a cache, it is possible to manipulate it in many ways.

Let us now introduce one of the operations – adding elements to the cache. A developer can provide a string for the URL that will be fetched and stored in a cache object. Whenever the data is received from the cache, the browser will return a particular object according to the URL that was stored in the cache. More details on how long the data could be stored in the cache are given in **Section 4.4**.

Apart from adding to the cache object, it is also possible to remove stored URLs, check the current list of cached requests, delete a cache object, and other operations.

4.3 IndexedDB

As the protocol we introduced in **Chapter 3** clearly describes that there is a necessity to have a client-side storage system, we are going to use for that purpose IndexedDB[25]. It is a large-scale, NoSQL database, which lets us store any data in the user's browser. Apart from that, it supports transactions and achieves a high-performance search due to the usage of indexes.

4.3.1 IndexedDB terms

In order to properly understand how IndexedDB works, it is quite useful to understand the concepts that are used in the database. First of all, each *IndexedDB database* contains *Object stores*. Those object stores, in its turn, are similar to tables in traditional databases. Usually, the practice is to have one object store for each type of data. This data could be anything: custom objects, strings, numbers, arrays, and other. It is possible to create more than one database, which could contain various object stores, but normally it is one database per application, which should have one object store for each type of data stored. To expedite the way of identifying objects in object stores, the latter have *primary keys*, which must be unique in the particular object stores. Primary keys are defined by the developer and are very useful regarding searching the data.

All read and write operations in IndexedDB should be wrapped into a *transaction*, which guarantees the database integrity. The critical point is that if one operation within a transaction fails, then none of the other operations are going to be applied.

4.3.2 IndexedDB Promised

Listing 4.6 Code, which demonstrates how one can check the support for IndexedDB API[25].

```
if (!('indexedDB' in window)) {
  console.log('This browser doesn\'t support IndexedDB');
  return;
}
```

As IndexedDB is relatively a new API, it is not supported by all the web browsers yet. Therefore, the support for it should be checked before any further development, as it is shown in **Listing** 4.6. However, all the recent versions of the major web browsers are compatible with it.

Nevertheless, one of the most significant problems with IndexedDB is using it in the development. It has an asynchronous API, which is using events. That makes developers produce a complex code, which is hard to maintain. Therefore, in the design of WebCure, we are going to use a wrapper over the IndexedDB API – IndexedDB Promised[26, 27]. It is a tiny library, written by Jake Archibald from Google, which makes the use of JavaScript promises and simplifies the development process with IndexedDB while keeping its functionality.

4.4 Persistent Storage

Both Cache API and IndexedDB database mentioned in **Section 4.2** and **Section 4.3** are taking place at the local machine. However, when the local machine is running out of storage space, user agents will clear it automatically on an LRU policy[9][28]. This is not something that suits an application, which promises to provide offline experience. Moreover, in the worst case scenario, if the data was not synced with the server, it is going to be lost. The solution to this problem is to use a Persistent Storage API[29, 30], which guarantees that cached data is not going to be cleared if the browser comes under pressure.

4.5 Background Sync

The reality is that it is not always possible to be online all the time, even if someone wanted to. Sometimes, there is no network connection at all, or it could be that abysmal that it could be hard to do anything under such conditions. Therefore, the scenario when someone could do his or her work offline and then, when the connection is re-established again, this work will go online, is useful. Nowadays, thanks to *Background Sync*[31] from Google it is possible to do in web applications.

Listing 4.7 Code, which demonstrates how to register sync (*myFirstSync* here) event for the service worker[31].

```
// Register the service worker:
navigator.serviceWorker.register('/sw.js');
```

[9]In the systems with LRU or least recently used caching policy, the least frequently used data will be cleared first.

```
// Then later, request a one-off sync:
navigator.serviceWorker.ready.then(function(swRegistration) {
  return swRegistration.sync.register('myFirstSync');
});
```

For this feature to work, the web application has to use a service worker. First of all, it should be registered and, afterwards, a unique tag should be registered as well, which is going to be responsible for the background call of the method. Let us show an example: in **Listing 4.7**, we can see how a synchronisation tag *myFirstSync* is registered.

Listing 4.8 Code, which demonstates that a function *doSomeStuff* called, when the *sync* event happened[31].

```
self.addEventListener('sync', function(event) {
  if (event.tag == 'myFirstSync') {
    event.waitUntil(doSomeStuff());
  }
});
```

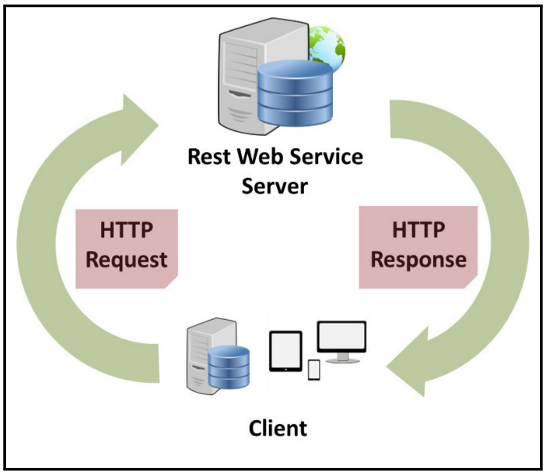
Afterwards, when a page controlled by the service worker is going back online (which is when the user agent has established a network connection[32]), a *sync* event is triggered. There, it is possible to perform a distinct action, depending on the registered earlier tag. For instance, in **Listing 4.8** we can see that a function *doSomeStuff* is called once the connection is back, after a *sync* event occurred. This function has to return a promise, which could be successful or not. In the latter case, another sync will be scheduled to try when there is a connectivity[31].

Background synchronisation is an advantageous feature, which can be used in different scenarios. It could be, for example, sending the e-mails or any other type of messages, after having failed to send it when the connection was poor. However, in our case, in WebCure we are going to use it for sending the operations conducted offline back to the AntidoteDB server for further synchronisation. Moreover, if there was a use case with a requirement to get the most recent data from the server after the re-connection to the network, it is possible to implement it using the background synchronisation feature.

5 Implementation

In this chapter, we are going to describe the way we solved the obstacles that we faced during the development stage.

In **Chapter 4** we already named the key frameworks and techniques that we used in the implementation for the client. The server is going to provide to the client a RESTful[10] interface for the use cases, which we will describe below.



Source: https://cdn-images-1.medium.com/max/660/1*EbBD6IXvf3o-YegUvRB_IA.jpeg

Figure 5.1: A server-client architecture with a RESTful interface.

To demonstrate the functionality of WebCure, we implemented three different types of CRDTs used in AntidoteDB: a counter, a set and a multi-value register. We support each of these data types on the server and the client as well. We will use a Set CRDT as an example for code listings introduced further.

[10]REST or Representational State Transfer is a set of design principles, which make the network communication more flexible and scalable[33].

5.1 Main components of the system

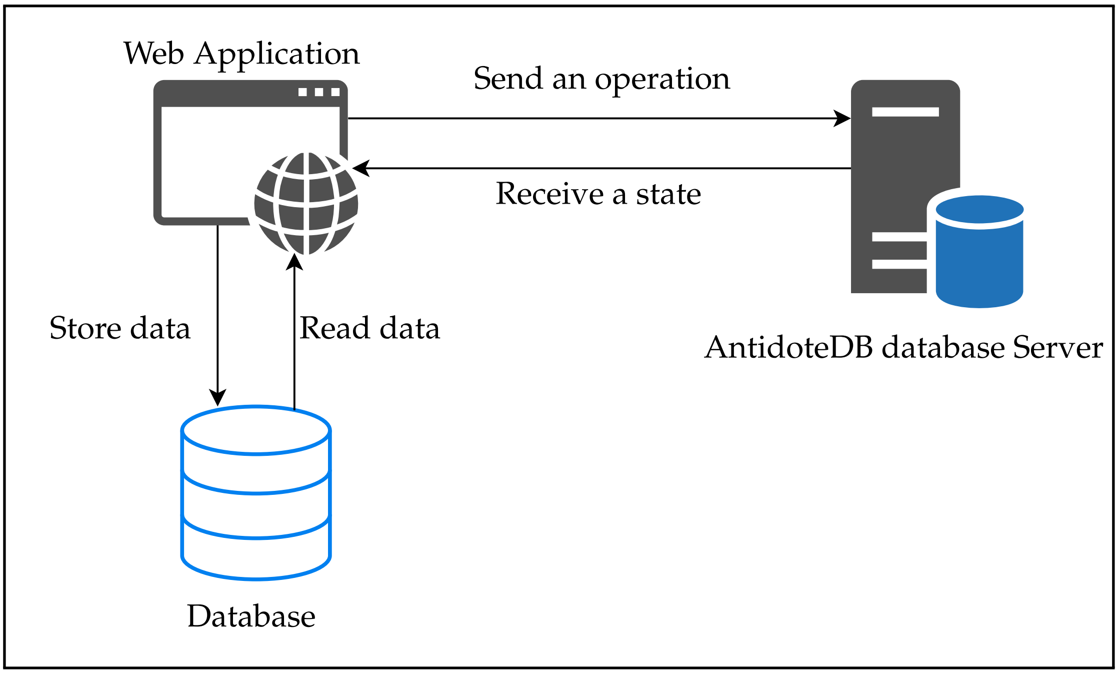


Figure 5.2: A top-level view of the system's design.

In **Chapter 3**, we introduced a client and a server as black boxes, without really explaining their internal structure. However, we have a clear picture of what the system and its main components will look like. As we can see in **Figure 5.2**, the client part of the system, which we introduced before, contains a web application that has a database on its side for reading and storing the data locally. The server, on the other hand, is controlling an AntidoteDB database and, apart from that, can exchange messages with clients. A service worker controls the communication with the server on a client side. It serves as a proxy and gets the data either from cache or from the server, depending on the use case. Regarding the exchanging of the data, the client can send to the server the operations performed offline, while the server is sending back to the client the current states of CRDT data.

We are going to design WebCure using a 3-tier architecture[34]. Its principal distinction is that it has a clear separation between the presentation, application, and data layers, as we can spot in **Figure 5.3**, where we also sketch how each JavaScript file of WebCure relates to these layers. Each

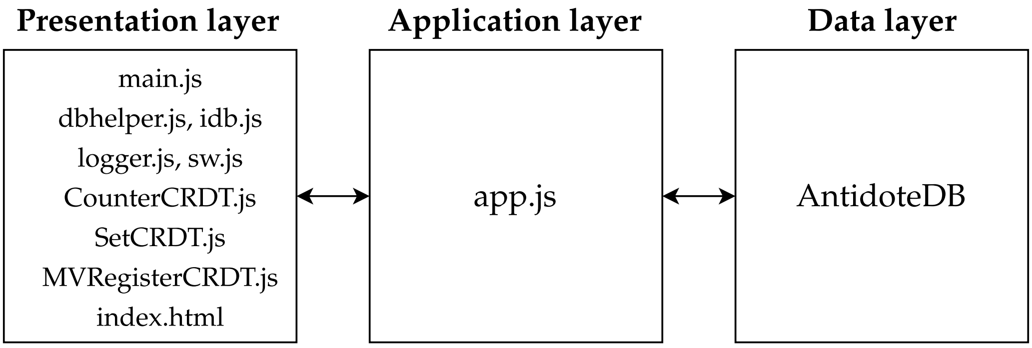


Figure 5.3: 3-Tier architecture.

layer is responsible for its tasks. Let us now briefly characterise them. A *presentation layer* is implemented on a client side and is responsible for presenting the information to the users, while it can also accept requests from them. An *application layer* is based on a server's side, implements the algorithmic part of the system and answers the operations requested by the client. The last one, a *data layer*, manages and implements the data sources of the system. The advantages of a 3-tier architecture style are the scalability and portability it provides. However, a disadvantage could be a communication overhead between the layers[35].

In the next subsections, we are going to describe the implementation of the system.

5.1.1 Database

This layer includes an AntidoteDB database, which is used to store and handle CRDT-objects. To be able to work with the database, we are going to use a JavaScript Client for AntidoteDB[11], which suits the stack of the technologies we are using for WebCure. The database itself will be running on a Docker[12] container created from an image of the Antidote data store. For this thesis, however, specific changes were applied to the docker image of Antidote and the JavaScript Client for Antidote as well. In order to read and to apply changes to the data at a specific timestamp, the Antidote image for docker should be running with certification checks disabled, while also there is a flag, which was added to the Antidote JavaScript client to make sure that the client supports the possibility of comitting updates at specific timestamps. Apart from that, the database was

[11]https://antidotedb.github.io/antidote_ts_client/
[12]https://www.docker.com/

also changed to support this functionality.

5.1.2 Server

The server side of WebCure is fundamental, as it provides the interface to the client and manages the communication with the database layer. To implement a server we used a Node.js[13] framework called Express[14]. Taking Set CRDT as an example, we will now discuss the methods the server implements:

- Sending back either the latest state of a Set CRDT or, if a timestamp was provided, then the state at a specific timestamp;
- Adding/removing elements from a Set CRDT;
- Applying a list of operations, which were performed at the client while offline.

Sending the data back

In this section, we will describe how we implemented the functionality of the server to send the data back, as requested by the client.

Listing 5.1 Code for sending back to the client the requested data.

```
apiRouter.route('/set/:set_id/timestamp').post(async function
    (req, res, next) {
    /// ...

    var setId = req.params.set_id;
    var timestamp = req.body.timestamp;

    setTimestamp(timestamp,..);

    let tx = await atdClient.startTransaction();
    let set = tx.set(setId);
```

[13]Node.js is a JavaScript run-time environment, which let us execute JavaScript code outside the web browser. More details can be found here: https://nodejs.org/en/.
[14]Express is a Nodej.s framework for web and mobile applications that provides such features as robust routing, HTTP helpers and others. More details can be found here: https://expressjs.com/.

```
11     let val = await set.read();

13     await tx.commit();

15     // ...
16     res.json({
17       status: 'OK',
18       cont: val,
19       lastCommitTimestamp: atdClient.getLastCommitTimestamp()
           .toBase64()
20     });
21    // ...
22 });
```

Have a look at **Listing 5.1**, where at the *line 1* there is an object *apiRouter* from Express framework introduced above, which adds an HTTP Post route to listen for. As a response to that request, starting from *line 4*, we can observe the logic of the function. There, firstly, we assign the passed parameters to variables. The id of the requested Set CRDT – *req.params.set_id*, is assigned to the variable *setId* and an optional timestamp – *req.body.timestamp*, is assigned to the variable *timetamp*, which is used in the function *setTimestamp* to set the current timestamp of the database. For this operation, the timestamp parameter is optional, though.

At *line 9* we use the asynchronous method *startTransaction* of object *atdClient*, which represents the Antidote JavaScript Client. From that point, a reference of the Antidote Object associated with *setId* is assigned to the variable *set* and afterwards its value is read and assigned to *val*. Then, at the *line 13* the transaction is committed and, afterwards, a JSON object containing the status of the request, the value of requested Set CRDT and the timestamp of the transaction (as the timestamp is an object representing a type of ByteBuffer[15], for a successful transmission in a JSON format, it is converted to Base64[16] at *line 19*. That eases the process of passing the timestamp information in a JSON format.) are sent back to the client.

[15]https://github.com/dcodeIO/bytebuffer.js

[16]Base64 – a group of similar binary-to-text encoding schemes that represent binary data in an ASCII string format by translating it into a radix-64 representation[36].

Adding / removing elements

As operations of adding and removing elements from the Set CRDT do not differ regarding implementation, we will use the operation of adding elements as an example for further explanation.

Listing 5.2 Code for applying an *add* operation to a Set CRDT.

```
1  apiRouter
2    .route('/set/:set_id')
3    .put(async function(req, res, next) {
4       /// ...

6        var setId = req.params.set_id;
7        var value = req.body.value;

9        let tx = await atdClient.startTransaction();
10       let set = tx.set(setId);
11       await tx.update(set.add(value));
12       await tx.commit();

14     // ...
15       res.json({
16         status: 'OK'
17         // ...
18       });
19     // ...
20   })
```

As we can see in **Listing 5.2**, this code looks very similar to what we have already seen before, with some small differences. At the *line 7*, for example, we receive an element (the one, which has to be added to the Set CRDT identified as *id*) passed by a client and assign it to the variable *value*. Afterwards, we start a transaction and at the *line 10* assign to the variable *set* an Antidote Object associated with *setId*. Later, we call an operation *update* of the transaction object *tx*, which let us update the value in the database. We passed it as a parameter a method call *add(value)* of the object *set*. Finally, we commit the transaction and send back to the client the status of the request. Additionally, even though it is not the case for the code we presented in the above scenarios, the same transaction in

AntidoteDB can mix read and update methods on different objects.

Applying the operations performed offline

Now, let us have a look at the server's logic when it comes to synchronising operations, which were performed at the client offline and were sent to the server when the internet connection was re-established.

Listing 5.3 Code for applying an *add* operation to a Set CRDT.

```
apiRouter.route('/set_sync/:set_id').post(async function(req,
    res, next) {
    // ...
    var setId = req.params.set_id;
    var lastCommitTimestamp = req.body.lastCommitTimestamp;
    var updates = req.body.updates;

    setTimestamp(lastCommitTimestamp, false);
    let tx = await atdClient.startTransaction();
    let set = tx.set(setId);

    var antidoteUpdates = [];
    updates.forEach(element => {
      if (element.type === 'add') {
        antidoteUpdates.push(set.add(element.value));
      } else if (element.type === 'remove') {
        antidoteUpdates.push(set.remove(element.value));
      }
    });

    await tx.update(antidoteUpdates);
    await tx.commit();

    // ...

    res.json({
      status: 'OK'
    });
   // ...
});
```

In **Listing 5.3**, we can see the server's implementation for this case. The most, we are interested in a part, which starts at the *line 11*. There, we create an empty array named *antidoteUpdates*, where we are going to store the updates from the client in the order in what they were received. To do that, we start iterating over the elements of the array *update* using the loop *forEach*. The array *updates* was received through the POST request from the client. The format of *updates* array allows to distinguish between the operations applied on the Set CRDT – it is either *add* or *remove*. We can see it inside the loop between the lines *13* and *17*. Afterwards, we have the array, consisting of Antidote-compatible updates. Then, the important point is to apply these updates at the timestamp, which the client had on its side, as there could be other updates coming from different clients which could have been online at that time. For this reason, at the *line 4*, we store a timestamp coming from the client, which is the latest it received from the server before going offline. Thus, we apply the updates on that timestamp, to satisfy causal consistency guarantees.

5.1.3 Client

In order for the user to communicate with an AntidoteDB server, we are going to have a running web application that serves as a client. It runs in the web-browser, supports various commands from the user and sits on top of the local database layer.

For each of the supported CRDTs, there are different commands available. In **Figure 5.4**, we can observe the commands that are available for a Set CRDT in our demonstration application. For the explanation of the functionality, there are three inputs available to the user. The first input labelled *Set Id*, is responsible for the names of the elements stored in the local cache and the AntidoteDB. The second input, *Element*, is there for the user to enter a list of elements to add or remove from the Set CRDT. The last input gives an opportunity to provide a specific timestamp, in order to be able to get the data at that timestamp or, in the other case, to apply a selected operation at that timestamp. Apart from the inputs, there are four buttons, which perform specific operations on a set CRDTs – *getting the value by id*, *adding and removing elements*, *removing element by id from the cache*.

However, for all this functionality to work as intended in both modes – offline and online – at first, a service worker has to be set up.

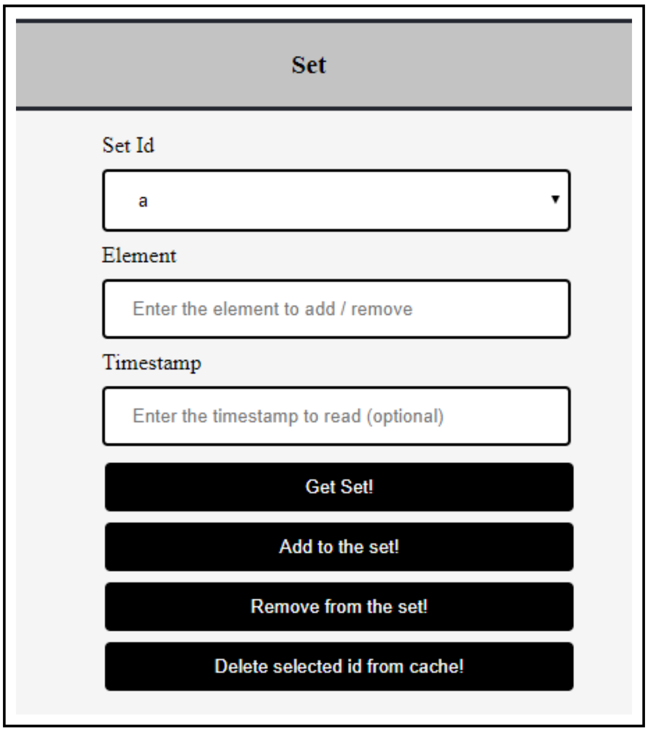


Figure 5.4: A Set CRDT part of the demonstration application, based on WebCure.

Setting up a service worker

Our service worker is located in the root directory of the application under the file *sw.js*. With its help, the application can maintain its main features such as support the offline work and synchronising the changes performed offline with the primary database. As explained in **Chapter** 4, we registered the service worker on *load* event of the application. Then, we added two listeners to the service worker for the events *install* and *fetch*, which we are going to explain further.

Listing 5.4 Code for caching necessary data for the client.

```
self.addEventListener('install', function(event) {
  // Mention URLS that need to be cached
  // It is required in order for the application to work
      offline
```

```
4  var urlsToCache = [
5    // root
6    '/',
7    '/index.html',
8    // js
9    '/logger.js',
10   '/main.js',
11   '/dbhelper.js',
12   '/idb.js',
13   // js CRDTs
14   '/CRDTs/CounterCRDT.js',
15   '/CRDTs/SetCRDT.js',
16   '/CRDTs/MVRegisterCRDT.js',
17   // css
18   '/styles.css',
19   // images
20   'img/icon-192.png',
21   'img/icon-512.png',
22   'img/favicon.ico',
23   // manifest
24   'manifest.json'
25 ];

27 event.waitUntil(
28   caches.open(CACHES_NAME).then(function(cache) {
29     // Add all mentioned urls to the cache, so the app
          could work without the internet
30     return cache.addAll(urlsToCache);
31   })
32 );
33 });
```

In **Listing 5.4**, we can see that the array *urlsToCache* consists of elements of type JavaScript strings, which are all the required frameworks, libraries, HTML pages, CSS styles and images needed for the application to work. This array is later used at the *line 28* to create a cache storage *CACHES_NAME*, where the responses to stored URLs from the array *urlsToCache* are going to be stored. All this work is performed when the installation of the service worker for the page is triggered, which in our case is the start of the application.

Listing 5.5 Code for maintaining the requests of the application.

```
1 self.addEventListener('fetch', function(event) {
2   event.respondWith(
3     caches.match(event.request).then(function(response) {
4       // Respond the data from the cache, if it was found
            there. Otherwise, fetch from the network.
5       return response || fetch(event.request);
6     })
7   );
8 });
```

Now, once we already have the cached data, we still need to make use of it to make our application work offline. If we look at **Listing 5.5**, we can see that whenever there is a request going to the network, at *line 3* we are trying to match that request with the ones we have in cache: if it is the case, then the cached object is returned or, otherwise, the fetching process from the network continues, as can be seen at the *line 5*. If the requested resource is not cached and, moreover, the client is offline, then the *fetch* request executes normally and will respond with an error, as the resource will not be loaded.

Apart from caching scripts and media files, necessary for the application to work, we will also need to set up a local database to store the data on the client side.

Setting up a local database

As explained in **Chapter 4**, in the file *js/dbhelper.js* we are setting up an IndexedDB database for the client side. There, we are going to create two object stores. The first one will consist of different CRDT data items, differentiated by their *id*. The other object store will keep track of the timestamp, which is associated with the latest data taken from the server. The point of having that timestamp is for the client to send it with the updates performed while offline, which will give an insight to the server, at what timestamp these updates should be applied.

Listing 5.6 Creating object stores in IndexedDB for CRDTs and timestamps.

```
// ...
var stateStore = upgradeDB.createObjectStore('crdt-states',
    {
  keyPath: 'id'
 });

var snapshotStore = upgradeDB.createObjectStore('crdt-
    timestamps',  {
  keyPath: 'id'
 });
// ...
```

We can observe the logic explained above in **Listing** 5.6, where there is an object store named *'crdt-states'* created for CRDTs and *'crdt-timestamps'* for the timestamp. A *keyPath* parameter for both of them is there in order to be able to query the data by *id*.

While it is clear why do we store the states of CRDTs, it might be not the case for why it is done for the timestamps. First of all, any updates a client makes when it loses the internet connection will be stored in the cache. However, when these updates are sent to the server, it needs to know how to apply them. To that point, the server might have already received updates from some other clients. Therefore, to make sure that the updates we send are applied at the version of the data we were dealing with locally, a client has to provide a timestamp to the server. Secondly, we store a timestamp in the cache for the persistence. While we could have turned to create a variable for this case, it would not have allowed us to use this information after closing the application. Caching solves this problem.

Implementation of abstract Set CRDT

Next, let us introduce our implementation of Set CRDTs abstraction for the client side, which helps to maintain the data received by the server.

Listing 5.7 A class *SetCRDT*, objects of which are going to be stored in the *'crdt-states'* object store.

```
class SetCRDT {
```

```
  constructor(id, values) {
    this.id = id;
    this.state = values ? new Set(values) : new Set();
    this.type = 'set';
    this.operations = [];
    this.sentOperations = [];
  }

  processSentOperations() {
    this.operations.forEach(operation => {
      this.sentOperations.push(operation);
    });
    this.operations = [];
  }

  materialize() {
    let values = [];

    this.sentOperations.forEach(operation => {
      if (operation.type === 'add') {
        this.state.add(operation.value);
      } else if (operation.type === 'remove') {
        this.state.delete(operation.value);
      }
    });

    this.operations.forEach(operation => {
      if (operation.type === 'add') {
        this.state.add(operation.value);
      } else if (operation.type === 'remove') {
        this.state.delete(operation.value);
      }
    });

    this.state.forEach(key => {
      values.push(key);
    });

    return values;
  }

  add(valueToAdd) {
    let operation = {
      type: 'add',
```

```
      value: valueToAdd
    };

    this.operations.push(operation);
  }

  remove(valueToRemove) {
    let operation = {
      type: 'remove',
      value: valueToRemove
    };

    this.operations.push(operation);
  }
}
```

First, let us have a look at the constructor of a *SetCRDT* class in **Listing 5.7**, which takes two parameters – an *id* and, optionally, an array of elements – *values*. The class has the following properties:

- *id* – a string corresponding to the id of the data element stored in the server's database;
- *state* – a JavaScript Set, which reflects the state of the *SetCRDT* object and behaves like sets;
- *type* – a string reflecting the datatype and is needed for the client to distinguish between different CRDTs;
- *operations* – an array, which consists of operations performed offline at the client;
- *sentOperations* – an array, which consists of operations performed offline, but which are already sent to the server;

Secondly, there are the methods, which ease the process of working with *Set CDRT* objects at the client:

- *processSentOperations()* – shifts offline performed operations to the *sentOperations* property in order to have a distinction for the operations, which are already sent to the client.
- *materialize()* – returns the current state of the CRDT Set, taking into account the operations performed offline.

- *add(valueToAdd)* – performs an offline operation of adding an element to the Set CRDT, takes *valueToAdd* as a parameter.
- *remove(valueToRemove)* – performs an offline operation of removing an element from the Set CRDT, takes *valueToRemove* as a parameter.

Listing 5.8 An example of a *SetCRDT* object, stored on a client side.

```
{
id: "a",
operations: [{type: "add", value: "c"}],
sentOperations: [],
state: Set(2) {"b", "d"},
type: "set"
}
```

Having now understood the structure of the data stored on a client side, as well as the way it is managed, let us look at **Listing 5.8**, where an example of a Set CRDT element with an id *a* is shown. As can be seen, it has a state received from the server of *{"b", "d"}*, while also having an offline operation *add(c)* performed on it, which is still about to be sent to the server, as an array *sentOperations* is empty at this example.

As we have already explained the server's side logic earlier, in the following sections, we will only touch the topic of a client's offline work and the logic happening at the client on a transition from offline to online modes. We believe that the part, which is related to the online work of the client is already apparent to the reader, as it comes down to the simple client-server communication through predefined requests and this part was already covered when explaining the server's side.

Read

One of the crucial aspects of the client working offline as intended is storing the CRDT states received from the server. Let us further explain the logic behind the implementation of it.

Listing 5.9 Storing CRDT states in the local database after a successful request from the server.

```
1 DBHelper.crdtDBPromise
2   .then(function(db) {
3   // ...

5     var tx = db.transaction('crdt-states', 'readwrite');
6     var store = tx.objectStore('crdt-states');

8     var item = new SetCRDT(id, value);

10    store.put(item);

12 // ...

14    return tx.complete;
15  })
16  .then(function() {
17    DBHelper.crdtDBPromise.then(function(db) {
18 // ...

20     var tx = db.transaction('crdt-timestamps', 'readwrite');
21     var store = tx.objectStore('crdt-timestamps');

23     store.put({ id: 0, data: lastCommitTimestamp });

25     return tx.complete;
26    });
27  });
```

In **Listing** 5.9, *DBHelper.crdtDBPromise* at the *line 1* gives us an access to the IndexedDB database consisting the object stores we created. There, we start a transaction on a *'crdt-states'* object store and at the *line 8* we create an element of *SetCRDT* class introduced above, passing it the *id* of the Set CRDT and its *value* that was just received from the server. Then we assign it to the variable *item* and add this *item* to the object store of CRDT states using the method *put* of *store* object. Next, we close the transaction using the method *complete* of the *tx* transaction object.

When we successfully stored the received state, there is another piece of information that has to be saved on the client as well. This time it is a timestamp associated with the update we received. Looking again at **Listing 5.9**, at *line 20* we refer to the *'crdt-timestamps'* object store this time. Similarly as before, as can be seen at the *line 25*, we store *lastCommitTimestamp*, which consists the timestamp received from the server. That happens each time we get a new update from the server and normally, there is no way to observe a new update without an updated timestamp as well.

Listing 5.10 Reading CRDT states from client's cache.

```
1  DBHelper.crdtDBPromise.then(function(db) {
2  // ...

4    var index = db.transaction('crdt-states').objectStore('crdt
        -states');

6    return index.get(id).then(function(state) {
7      if (state) {
8       Object.setPrototypeOf(state, SetCRDT.prototype);
9       log('[Offline] The value of ' + name.value + 'is: [ ' +
           state.materialize() + ']');
10     } else {
11      log('[Offline] Selected key is not available offline.');
12     }
13   });
14 });
```

Now comes the part regarding reading the states of the Set CRDTs from the cache. We can have a look at **Listing 5.10**, where the code already looks familiar to us. There, at the *line 6*, we use the method *get* of *index* to search by the property *id* of the object. Then, if an element with such *id* was found in the object store, we are going to have it in a *state* variable. As we do not store the class information in the client's database, we will have to "remind" the object we have in the *state* variable about its prototype. That is why a method *Object.setPrototypeOf* is used with *state* and *SetCRDT.prototype* as parameters. After that, the object *state* will have an access to the methods of a *SetCRDT* class. For the demonstration of the client's functionality, in this thesis we are using a JavaScript Logger[17] li-

[17] http://www.songho.ca/misc/logger/logger.html

brary, which we have an access to under the *log* variable at *lines 9 and 11*. It let us keep the track of neccessary information in a convinient manner. As can be seen, at the *line 9* we log the actual state of the Set CRDT using a *materialize()* method of *SetCRDT* class.

Add / Remove

Another functionality that a client covers, apart from reading and storing the values in the local database, it is performing the operations on CRDTs offline.

Listing 5.11 Performing an operation *add* on a Set CRDT while the client is offline.

```
DBHelper.crdtDBPromise
  .then(function(db) {
// ...

    var index = db.transaction('crdt-states').objectStore('
        crdt-states');

    return index.get(id).then(function(storedValue) {
      var tx = db.transaction('crdt-states', 'readwrite');
      var store = tx.objectStore('crdt-states');

      Object.setPrototypeOf(storedValue, SetCRDT.prototype);
      storedValue.add(value);
      store.put(storedValue);

      return tx.complete;
    });
  });
```

Looking at **Listing 5.11**, we can see that there is not so much of a difference with previous code that we have seen on performing the read operations from IndexedDB. Again, as we can see from the example, a transaction on a *'crdt-states'* object store is created and if an element with *id* is found in the object store, its value will be available under the variable *storedValue*. Then, similarly, the method *Object.setPrototypeOf* is used for the *storedValue*, in order for it to have an access to the *SetCRDT* class methods. Once it is done, at *line 12* we use the method *storedValue.add(value)*, where *value* variable is the value entered by the user. If we get back to **Listing 5.7**, we will recall that the method *add* will add an element to the array-type property *operations* of the object *storedValue*. Finally, we use *store.put(storedValue)* to put the update data item back to the client's database and afterwards complete the transaction. Similarly, the same happens when a user tries to remove elements from Set CRDTs.

A transition from offline to online

Next, we would like to discuss what happens when the client switches from offline mode back to online. For every offline operation performed on sets, we register a unique tag named *syncSetChanges*, as was explained in **Section 4.5**.

Listing 5.12 A function *pushSetChangesToServer*, triggered whenever a client reconnects to the network.

```
function pushSetChangesToServer() {
  // ...
  DBHelper.crdtDBPromise.then(function(db) {
    var index = db.transaction('crdt-states').objectStore('
        crdt-states');

    return index
      .getAll()
      .then(function(objects) {
        DBHelper.crdtDBPromise.then(function(db) {
          // ...
          var index = db.transaction('crdt-timestamps')
              .objectStore('crdt-timestamps');
          return index.get(0).then(function(timestamp) {
            if (objects) {
              objects.forEach(object => {
                if (object.operations.length > 0) {
                  fetch(`${DBHelper.SERVER_URL}/api/set_sync/
                      ${object.id}`, {
                    method: 'POST',
                    body: JSON.stringify({
                      lastCommitTimestamp: timestamp ?
                          timestamp : undefined,
```

```
                      updates: object.operations
                    }),
                    headers: {
                      'Content-Type': 'application/json;
                         charset=utf-8'
                    }
                  });
                }
              });
            }
          });
        });
      })
      .then(function() {
        return DBHelper.crdtDBPromise.then(function(db) {
          // ...

       var index = db.transaction('crdt-states').objectStore(
          'crdt-states');

       return index.getAll().then(function(objects) {
         var tx = db.transaction('crdt-states', 'readwrite');
         var store = tx.objectStore('crdt-states');
         if (objects) {
              objects.forEach(object => {
                if (object.type === 'set') {
                  Object.setPrototypeOf(object,
                     SetCRDT.prototype);
                  object.processSentOperations();
                  store.put(object);
                }
              });
            }
         return tx.complete;
          });
        });
      });
  });
}
```

Then, a *sync* event is going to be triggered inside the service worker. At the time it happens, we are going to check whether our tag *syncSetChanges* registered it. In this case, a function *pushSetChangesToServer* is called, which we can observe at **Listing 5.12**.

Let us have a closer look into it. At the *line 7*, we get all the elements stored in the object store of *'crdt-states'*. In this section, we are describing the implementation of maintaining only Set CRDTs. However, the object store *'crdt-states'* normally can contain any CRDTs. Once we got the states, at *line 12*, we are also getting the latest timestamp that was stored on a client side (we use *get(0)* here, as we store every new timestamp under the id *0*). This step is specifically needed for the causality of updates (more details are available in **Chapter 3**). Then, for every Set CRDT, we are creating a POST HTTP request, which contains the information about the timestamp at which these updates were performed, as well as operations themselves. We can see it at *lines 16–24*, where the timestamp is sent as *lastCommitTimestamp* and operations are sent as *object.operations*. In such a way, this information is sent to the server, which continues processing it on its side.

However, this is not it for the client yet. There is a reason why the client has to distinguish between offline operations that are already sent to the server and the ones that are not yet. First of all, in order to not send the same updates multiple times to the server. At the *line 46* of **Listing 5.12**, we see that the method *processSentOperations()* is called. We can look up its implementation again in **Listing 5.7**. As we remember, it shifts already sent operations to another array named *sentOperations*, which is also a property of the class *SetCRDT*. Our reader might also think about the possibility of just clearing these operations from the cache as soon as the internet connection at the client side is re-established again. That would not be a good idea. Let us imagine the following situation: a client works offline for some time, then the connection gets back, but before the client could request new updates from the server, the connection gets off again. What happens in such a scenario? First of all, the operations performed offline at the client side will be sent to the server immediately, but if we delete from the cache operations that are sent already, then we are risking losing the data at client side. As we did not yet receive the latest updates from the server, the client would not be able to continue working offline on its data. It was the second reason, why it is better to keep offline operations at client side in two separate collections, at least before the server sends back data updates, having already applied the operations, which the client sent. At that point, it will be safe to remove them.

Finally, we have covered so far every aspect of the implementation, and in the next chapter, we will evaluate our work.

6 Evaluation

In this chapter, we are going to evaluate the system we built, as well as present a running application based on WebCure.

6.1 Testing

To assure the correctness of our application, we covered it with test cases of different types.

Firstly, we did unit testing for the implemented CRDT classes, which purpose is to validate the correctness of their work according to the design specifications.

Listing 6.1 Simple unit test that checks the correct initialization of objects of a *SetCRDT* class.

```
it('Check the initialization of a SetCRDT Class', function(
    ) {
  var a = new SetCRDT('a', ['a', 'b', 'c']);
  var b = new SetCRDT('b');

  expect(a.id).toEqual('a');
  expect(a.state).toEqual(new Set(['a', 'b', 'c']));
  expect(a.type).toEqual('set');

  expect(b.state).toEqual(new Set([]));

  expect(a.operations).toEqual([]);
  expect(a.sentOperations).toEqual([]);
});
```

In **Listing 6.1**, we can observe a simple unit test, which helps to check the correctness of the initialisation of *SetCRDT* objects, written with the help of Jasmine framework[18]. At *lines 9 and 10* we can see that objects *a* and *b* are created using a constructor of *SetCRDT* with parameters. The first parameter, as we mentioned in **Section 5.1.3**, is referring to the *id* of the set, while the second one is referring to the elements, it contains initially. Later, step by step, every property is checked according to the expected values it should possess. This is just one of the unit tests, which serves as an example to demonstrate the way we wrote unit tests for the abstract CRDT classes, which we implemented for the client side.

Apart from that, we did system testing as well. To achieve that, we had to mimic the behaviour of WebCure in the testing environment. For that, we set up the server running with AntidoteDB configured in the same way we used it for the demonstration application. Then, we created test cases that reproduce the possible actions of the user and wrote system tests based on them. So, basically, for these tests, we had the whole system running.

Listing 6.2 Simple system test that checks different actions performed on *SetCRDT*.

```
var TestHelper = require('./TestHelper');
const type = 'set';

describe('Set', function() {
  it('Should check the get request for the set and initial value of [ ]', function(done) {
    TestHelper.checkGet(type, 'd', [], done);
  });

  it('Adding and removing the value from the set', function(done) {
    const key = 'e';
    TestHelper.checkPut(type, key, { value: 'a' }, function() {
      TestHelper.checkGet(type, key, ['a'], function() {
        TestHelper.checkDel(type, key, { value: 'a' }, function() {
          TestHelper.checkGet(type, key, [], done);
        });
      });
```

[18]https://jasmine.github.io/

```
17        });
18    });
19 });
```

The example of such a system test we can observe in **Listing 6.2**. There, we can see two test cases, wrapped up in *it* structure, which is a syntax of Jasmine. Normally, every *it* corresponds to a new test case. First of all, to perform system testing, we created our testing helper. It can be seen at *line 1*. Then, the first system test checks that a GET HTTP request to the server should return a Set CRDT, which does not contain any elements. For that, it calls the method *checkGet*, which takes four parameters. The first parameter is for the type of the CRDT (we declared ours at the top of the file), the second parameter is for *id*, the third one is of type array, which reflects the number of elements a Set CRDT should contain and is representing the values that are checked, while the fourth parameter is a callback, which is executed at the end of the *it* structure. The second system test is quite simple as well, as it checks that methods of adding/removing elements to the server database are working correctly. There, *checkPut* stands for sending a PUT HTTP request to update a SetCRDT by adding an element into it, and *checkDel* stands for a DEL HTTP request to update a Set CRDT by removing an element from it. The checks are happening again by the *checkGet* method of *TestHelper*.

6.2 Running the Calendar App based on WebCure

Now, after we designed, implemented and tested our system, it is time to demonstrate the applicability of WebCure. For that, we are going to take the Calender App designed and built in the work of Tim Dellmann [37]. To give an overview, in that work a calendar application was developed, which offers apart from basic calendar functionality, some conflict-management features. That is possible due to AntidoteDB, which is a database the Calendar App is built on. In the implementation of the Calendar App, the next types of CRDTs were used: maps, multi-Value registers and sets. Maps and multi-value registers were used for the point of managing the appointments, while sets were used to create and manage different users of the calendar. For this thesis, as we already showed in the previous chapters, one of the CRDTs we implemented are Sets. Therefore, we restructured the Calendar App, so the integration with WebCure would be possible. However, we have done that only with the part of the Calendar App, which works based on Sets (the functionality related to managing the users of it).

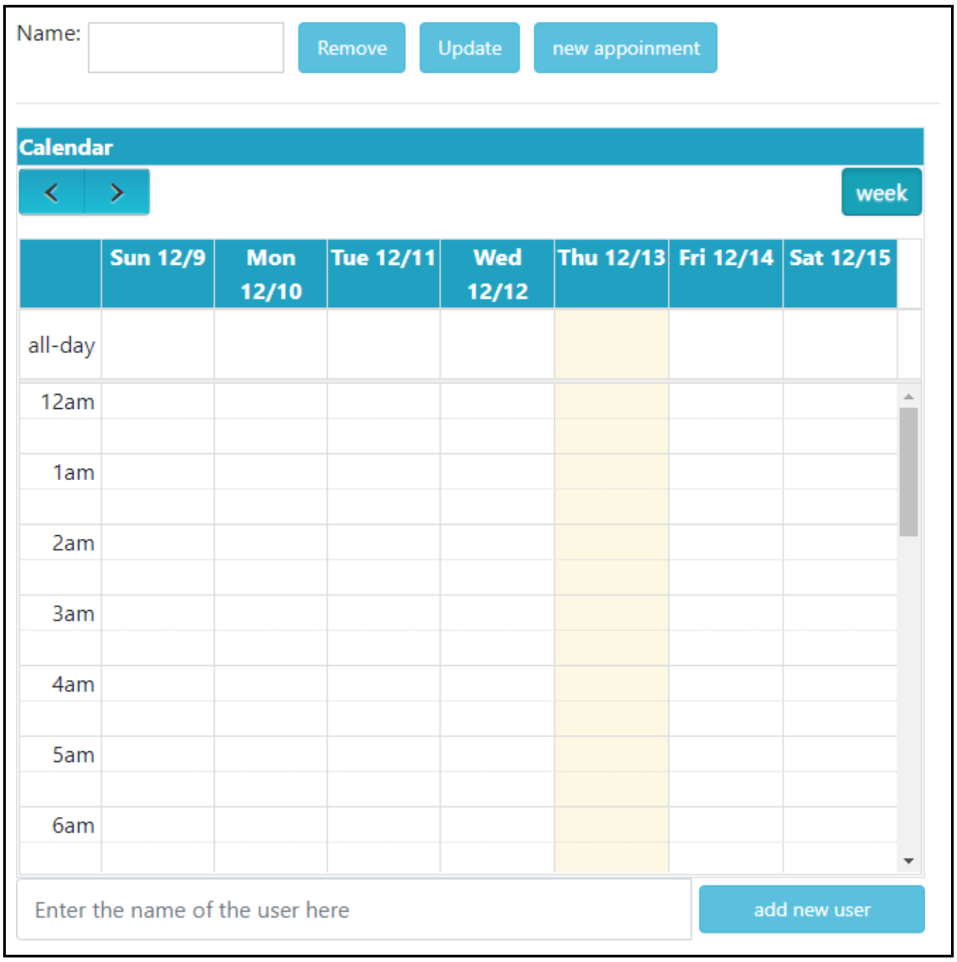


Figure 6.1: A view at the interface of the Calendar App.

We can see the interface of the Calendar App in **Figure 6.1**. As it was said, it provides the basic functionality, which every application of that sort should have: adding/removing users, creating appointments from their behalf and editing this data. At the top left corner of the figure, we can observe a label *Name:*, where there is a list of users on the right-hand side from it. Apart from that, there is a calendar view, which covers the most space of the interface in the middle. Additionally, the functionality is controlled by four buttons: *Remove* – for removing selected users from the list of users; *Update* – for updating the available list of users and appointments from the server; *new appointment* – to create a new appointment on behalf of the selected user; *add new participant* – to add a participant with a name specified in the input on the left side from the button.

Now, as we introduced our reader to the interface of the application and the functionality it has, we are going to demonstrate how a part of its functionality was integrated to work based on WebCure framework.

In the original Calendar App, the feature of having users was implemented with Set CRDTs. Therefore, we extended the application to have our abstract *SetCRDT* class on a client side, while also making the additional features of the application to work offline. For the demonstration purposes, we have the following setup: two separate Docker containers built on Antidote data store, interconnected for the mutual synchronisation; a configured server (according to the concepts introduced in WebCure) working with those two Antidote data stores; a web application that presents the view of two Calendar Apps simultaneously, while possessing all the offline features according to WebCure and a functionality to disconnect the link between two Antidote stores (mimicking network interruptions).

Listing 6.3 The state of the users object store at the first Calendar App.

```
{
id: "users",
operations: [],
sentOperations: [],
state: Set(2) {"John", "Jennie"},
type: "set",
}
```

Let us say, we added two users with names *John* and *Jennie* to the first Calendar App, as **Figure 6.2** shows. At this point, the first Calendar App will have its users stored under the *"users"* id, as it is shown in **Listing 6.3**. The second Calendar App, at this point, will have its storage empty at client side, even though its server storage synchronises with the server storage of the first Calendar. If the user of the second Calendar App requests the updates from its server by clicking the button *Update*, the client storage of the second Calendar App will reach the same state as the first

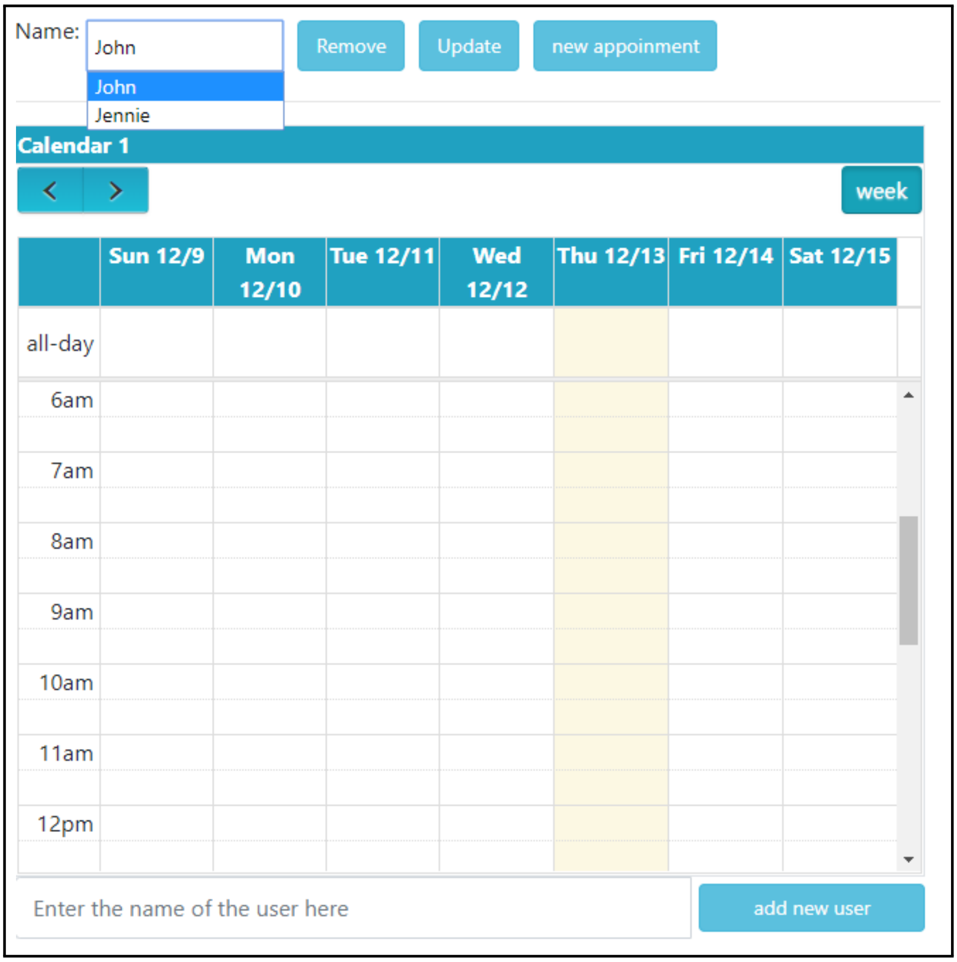


Figure 6.2: A view at the interface of the Calendar App.

Calendar App has. However, for now, we are postponing this step.

Next, let us say, that we turn off the network for both calendar applications. Then, we firstly locally remove the user *John* through the interface of the first Calendar App and, afterwards, we add a user *Wayne* at the second Calendar App.

Listing 6.4 The state of the users object store after offline changes at the first Calendar App.

```
{
```

```
id: "users",
operations: [0: {type: "remove", value: "John"}],
sentOperations: [],
state: Set(2) {"John", "Jennie"},
type: "set"
}
```

Listing 6.5 The state of the users object store after offline changes at the second Calendar App.

```
{
id: "users",
operations: [0: {type: "add", value: "Wayne"}],
sentOperations: [],
state: Set(0) {},
type: "set"
}
```

As we are working offline, the changes will be applied straight away, so the local stores of the calendars will look like they are represented in **Listing** 6.4 and **Listing** 6.5, respectively. As our reader observes, even though both applications are in offline mode, they are still available and functional.

Listing 6.6 The state of the users object store after the connection is enabled at the first Calendar App.

```
{
id: "users",
operations: [],
sentOperations: [0: {type: "remove", value: "John"}],
state: Set(2) {"John", "Jennie"},
type: "set"
}
```

Listing 6.7 The state of the users object store after the connection is enabled at the second Calendar App.

```
{
id: "users",
operations: [],
sentOperations: [0: {type: "add", value: "Wayne"}],
state: Set(0) {},
type: "set"
}
```

After we turn the connection back on, all the offline performed operations are sent to the server immediately. Therefore, now the data stores of the calendars will change again. Basically, as we remember, the operations performed offline will move to the array *sentOperations*. We can observe this behaviour in **Listing** 6.6 and **Listing** 6.7.

Listing 6.8 The state of the users object store for both calendars.

```
{
id: "users",
operations: [],
sentOperations: [],
state: Set(2) {"Wayne", "Jennie"},
type: "set"
}
```

Finally, if the users request updates from the respective servers, associated with their applications, both calendars will reach the same state, as the servers converged having applied all the provided operations. At this point, at client sides of both Calendar Apps the state of the users' local storage will look like it is shown in **Listing** 6.8.

As we can see, the user *John* was removed and the user *Wayne* was added for both calendars. Obviously, all the operations took their effect in the interface as well, the final state of which is shown in **Figure** 6.3.

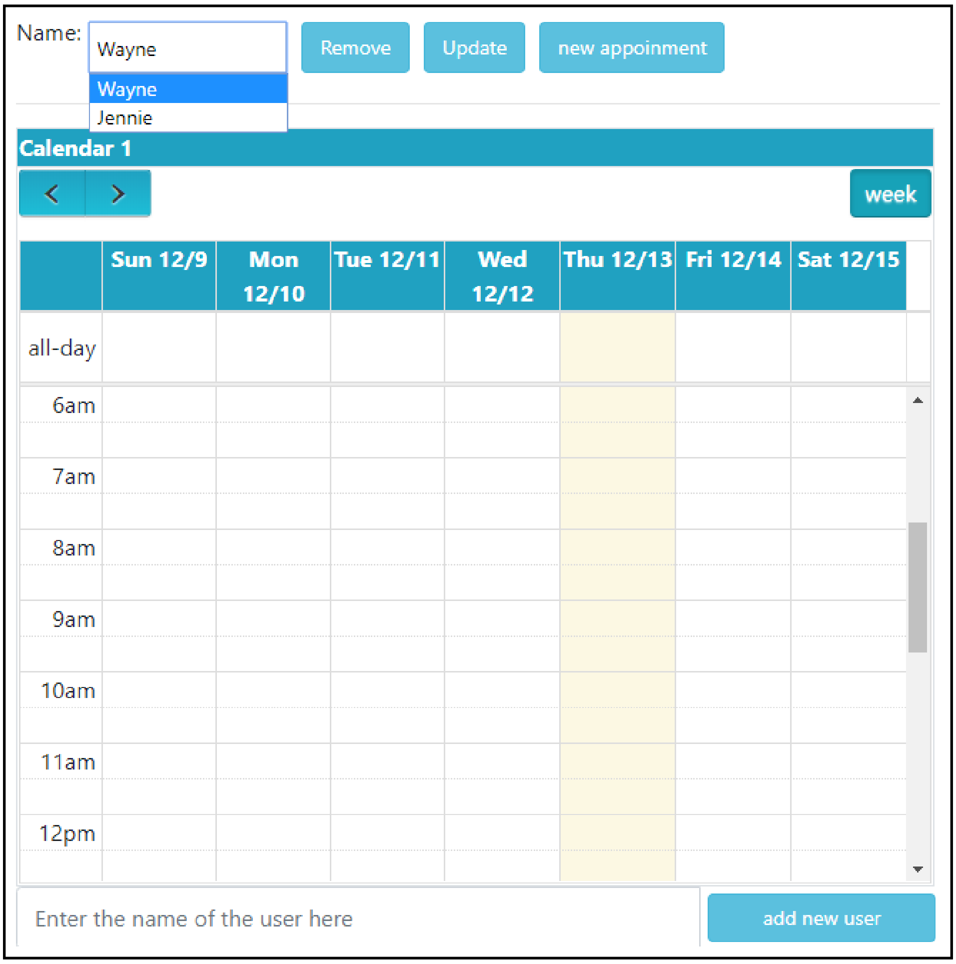


Figure 6.3: The final state of user list shown in the interface of the first Calendar (the same for the second one).

Summary

To summarise this chapter, we took a working Calendar application and extended its functionality using the design concepts, which we developed for WebCure.

First of all, let us compare the responsibility of both applications. To do that, we are going to measure the *Respose time*, which indicates the time needed till the main page of the application loads, as well as all the styles, images, and JavaScript libraries. For the *N=20*, where *N* – number of trials, the mean response time of the original application was *316.35ms*. For the extended version of the app, it was *2.06ms*, without taking into account the initial load (when all the files required for the application to work, are cached). As we can see, caching already makes a huge difference regarding the performance and, therefore, the user experience as well.

Apart from that, the extended version proved to be available and functional offline and online, while partially replicating the data at client side, which lets users continue working with their data. This example proves the point that WebCure allows to build web applications, which outperform their normal versions, while keeping their functionality and giving users the opportunity to work on their data while offline.

7 Related Work

In this chapter, we present some other approaches, which influenced our work.

7.1 SwiftCloud: a transactional system that brings geo-replication to the client

Geo-replication of data into several data centres (DC) across the world is used in cloud platforms in order to improve availability and latency[38]. This goal could be achieved even to a greater extent by storing some part of the data or even by replicating all of it at client machines. Thus, caching could be useful concerning the increasing availability of systems.

A system that integrates client- and server-side storage is called SwiftCloud, where the idea is to cache a subset of the objects from the DCs, and if the appropriate objects are in cache, then responsiveness is improved, and the operation without an internet connection is possible[39]. The authors of the SwiftCloud state that it improves latency and throughput if it is compared to general geo-replication techniques. That is possible due to availability during faults thanks to automatic switch of DCs when the current one does not respond. Apart from that, SwiftCloud distributed object database is the first to provide fast reads and writes via a causally-consistent client-side local cache backed by the cloud. To provide the convergence of the data, SwiftCloud relies on CRDTs, which have rich confluent semantics[8].

7.2 Legion: a framework, which enriches web applications

A framework named Legion shows another exciting approach on how to address availability and scalability issues by using the cache at the client-side. The idea is to avoid a concept of a centralised infrastructure for mediating user interactions, as it causes unnecessarily high latency and hinders fault-tolerance and scalability[40]. As an alternative, authors of Legion suggest client web applications to securely replicate data from servers and afterwards synchronise the data among the clients. This change makes the system less dependent on the server and, moreover, it reduces the latency of interactions among the clients. The guarantee of convergence between all of the replicas is possible due to CRDTs, introduced in **Chapter 2**.

7.3 Developing web and mobile applications with offline usage experience

Nowadays, applications with offline experience are becoming extremely popular. In this thesis, in **Chapter 4** we presented an approach of developing web applications with the help of service workers and background synchronisation (they also go by the name of Progressive Web Applications [PWA]). It is a universal approach to create a cross-platform application that would work in web and on mobile devices. However, there are also other ways how the offline experience could be achieved. Sometimes, the process could become easier if specific frameworks are used. In the following subsections, we are going to describe the tools and techniques that are useful in this context.

Polymer App Toolbox

Polymer is a JavaScript library from Google, which helps to build web applications with the use of Web Components. The former concept represents a set of web platform APIs, which allow creating custom HTML tags to use in web pages[41]. As web components are based on the latest web standards, and it eases the process of development. Polymer App Toolbox, in its turn, provides a collection of components to build PWAs with Polymer. However, the support of offline-experience is possible yet again due to Service Workers[42], which repeats the solution used in this thesis. Nevertheless, in contrast to the implementation offered in this thesis, working with Polymer App Toolbox requires additional knowledge of the Polymer framework. Currently, among the users of Polymer, apart from Google, there are such giants as Electronic Arts, IBM and Coca-Cola[43].

HTML5 Specification

The specification of HTML5 contains some features that offer a possibility to build web applications that work offline. The solution to address this problem is to use SQL-based database API in order to be able to store data locally and to use an offline application HTTP cache to make sure about the availability of the application when there is no internet connection. The latter makes possible the following advantages: offline browsing, flexibility and a fast load of resources from the hard drive[44]. However, from 2015 the application cache is considered to be deprecated and is recommended to be avoided[45] in favour of service workers. Thus, for the implementation of WebCure, we favoured the approach of using a combination of a service worker and a Cache API.

Hoodie

Hoodie is a framework, which eases the process of developing web and iOS applications. We will not cover all the features it offers and will only stop on it providing offline experience for applications that are developed using Hoodie. The documentation states that the framework is offline-first[46], which means that all the data is stored locally and any request the application makes, firstly will be tried to be proccessed by acquiring the cached data. It is possible due to PouchDB database, which performs this work in the background[47]. We will explore the process of how PouchDB works below.

localForage

localForage is a JavaScript library, which provides the possibility to improve the offline-experience of web applications regarding storing data on the client-side. It uses IndexedDB, localStorage or WebSQL with a simple API. localForage sits on top of the data store layer and provides a range of methods to control the data. One of the useful benefits of it is that the data is not required to be explicitly converted into JSON format, as localForage does that automatically[48]. localForage might be a useful library; however, as we already used IndexedDB Promised to work with IndexedDB database, we did not need to use anything heavier, such as localForage, primarily as it does not provide any fundamental differences in the approach.

PouchDB and CouchDB

PouchDB represents an open-source JavaScript database, which is designed to build applications, which work well online and offline. To put it in a nutshell, PouchDB enables web applications to store the data locally, and, apart from that, eases the process of synchronisation with CouchDB-compatible servers. CouchDB, in its turn, is a database that is supported by a replication approach, which allows synchronising two or more servers, based on CouchDB. As there is a replication approach, it has its way of dealing with conflicts, which we explain next by following the description of the protocol offered by Lehnardt [49].

Listing 7.1 A typical result of retrieving the item *document* stored in CouchDB.

```
{"_id":"document","_rev":"1-23202479633c2b380f79507a776743d5"
    ,"a":1}
```

For every item stored in CouchDB, the database will add two extra properties: *_id* and *_rev*, which can be seen in **Listing** 7.1 that shows the result of getting an element named *document* previously stored in the database. As we can see, the *_id* represents the name of the item, which is a custom name set by the user, while *_rev* represents the hash value, associated with the content. Afterwards, whenever we want to change the item *document*, the same *_id* and *_rev* should be used.

Listing 7.2 Updating the value of item *document* by adding *b* into it.

```
PUT /database/document
{"_id":"document","_rev":"1-23202479633c2b380f79507a776743d5"
    ,"a":1, "b":2}
```

For example, to change the value of *document* by adding *b* into it, a simple PUT HTTP-request should be sent, as **Listing** 7.2 shows.

Listing 7.3 The result of requesting the updated version of *document*

```
GET /database/document
{"_id":"document","_rev":"2-c5242a69558bf0c24dda59b585d1a52b"
    ,"a":1, "b":2}
```

The next retrieval of the *document* will get us the result shown in **Listing 7.3**.

As we can see, the *_rev* property got updated. In case the wrong revision is sent to update the document, the database will respond with an error.

Listing 7.4 Updating the value of item *document* by adding *d* into it.

```
PUT /database/document
{"_id":"document","_rev":"2-c5242a69558bf0c24dda59b585d1a52b"
    ,"a":1, "b":2, "d":4}
```

However, it is much more interesting, when we have more than one server. Let us assume that now we have two CouchDB servers. Imagine we try to update the *document* once again with the values shown in **Listing 7.4**.

Listing 7.5 The result of requesting the *document* from CouchDB-1.

```
GET /database/document
{"_id":"document","_rev":"3-2235fd4815b81b2da1b84159aba4006e"
    , "a":1, "b":2, "d":4}
```

For example, let us say that it gets written to the first CouchDB server, which gives the response shown in **Listing 7.5**.

Listing 7.6 The result of requesting the *document* from CouchDB-2.

```
GET /database/document
{"_id":"document","_rev":"2-c5242a69558bf0c24dda59b585d1a52b"
    ,"a":1, "b":2}
```

However, the second CouchDB server still has the old data, as we can see in **Listing** 7.6.

Ideally, the replication happens fastly, and both databases will synchronise and reach the same state. However, sometimes it might take a while. Moreover, if a client tries to update the document yet another time, there is a possibility that the update will go to the second server, which will reject the update, as *_rev* does not match any more.

Listing 7.7 Updating the value of item *document* by adding element *e* and removing previously added element *d*

```
PUT /database/document
{"_id":"document","_rev":"3-2235fd4815b81b2da1b84159aba4006e"
    , "a":1, "b":2, "e":5}
```

Listing 7.8 The demonstration of a conflict situation happening, when the *_rev* of sent operation and the one at the server do not match.

```
{"error":"conflict","reason":"Document update conflict."}
```

As we mentioned earlier, the response of the second CouchDB server for the operation shown in **Listing** 7.7 will look like the one in **Listing** 7.8.

Listing 7.9 Updating the value of item *document* by adding element *e* and removing previously added element *d* after receiving the new *_rev* from the second CouchDB server.

```
PUT /database/document
{"_id":"document","_rev":"2-c5242a69558bf0c24dda59b585d1a52b"
    , "a":1, "b":2, "e":5}
```

However, there is another option to perform this update. We might have a strategy of getting the latest *_rev* first, which was *"2-c5242a69558bf0c24dda59b585d1a52b"* at the second CouchDB server, and only then applying the update. So, the operation will look as it is in **Listing 7.9**.

In case this PUT request goes to the second CouchDB server, then this operation will be successful, and now both servers will have different states, which creates a conflict situation. However, it is still an undesirable situation. Thus, there are the limitations that should be given a thought in the development process, which indeed make the process of creating the product based on CouchDB more complicated:

- Making a change, do not request multiple GETs and POSTs;
- Do not update the *_rev* locally in the client without getting new data from the server before that.

Let us now summarise the advantages WebCure has due to using AntidoteDB and not CouchDB.

First of all, since CouchDB "blocks" the possibility of updating the server's database without knowing the latest revision *_rev*, it already adds extra-work in the design and implementation of the protocol. Moreover, as we believe, it struggles to provide the support of concurrent updates. AntidoteDB, on the other hand, uses the concept of timestamps, which allows supporting causal consistency guarantees and, as it is not creating such restrictions on making updates, it has a massive advantage with the support of concurrent updates.

Realm Mobile

Realm Mobile is a framework, which makes integration of a client-side database for iOS and Android with a server-side, which offers the following features: real-time synchronisation, conflict resolution and event handling. This framework eases the process of developing applications with offline experience. The concept we are interested here is conflict-handling. In AntidoteDB, for this purpose, CRDTs are used. Realm Mobile maintains a good user experience in offline mode due to the rules they described for conflict resolution. As they state, “at a very high level the rules are as follows:

- **Deletes always win.** If one side deletes an object, it will always stay deleted, even if the other side has made changes to it later on;
- **The last update wins.** If two sides update the same property, the value will end up as the last updated;
- **Inserts in lists are ordered by time.** If two items are inserted at the same position, the item that was inserted first will end up before the other item. It means that if both sides append items to the end of a list, they will end up in order of insertion time.”[50]

The authors of the framework state that “strong eventual consistency” guarantees are reached[50] with the approach mentioned above. Though, such way of conflict handling is not as flexible as CRDTs and has to be taken into account by the programmer at the stage of the development.

8 Conclusion

In this chapter, we will make a summary of our work and suggest some possibilities for future work.

8.1 Summary

The work of this thesis mostly concentrated on designing such a client-server system, which would let replicating the data on a client machine. That would allow the user for offline operation at times, when there is no internet connection available, or when it is poor. Moreover, there are requirements for the system such as the possibility to maintain the data at client side as well, and synchronise it with a cloud storage server, when the mode of the client switches from offline to online. Additionally, after the system was designed, it was needed to be implemented, and its feasibility and performance should have been evaluated.

This task was achieved in a framework, which we named WebCure. Firstly, we designed a stable protocol for the communication between a client and a server. Then, we made a research on available technologies, which would allow us to implement the system in a way it is intended to work. Next, we developed a presentation application, which demonstrates the work of WebCure on an example of a Set CRDT. After this step, we took a calendar application, which was already built based on AntidoteDB, and extended it to work with WebCure in order to evaluate the outcome. It turned out that, as expected, that the extended version of the calendar has a much shorter response time, better availability, while still keeping its original functionality and letting its users work both offline and online.

8.2 Future Work

Different circumstances create uncertainty with the current design of the application. In this section, we would like to discuss these situations, while keeping the answers to them open for future improvements.

Missing acknowledgement

In the current design of the WebCure, when a client is online and makes a request to the server with an update, the server sends back the acknowledgement, so the client knows that the requested operation was applied on the server side. However, there is a topic for discussion in this use case. Let us imagine that the server does not send back the acknowledgement. There are two possibilities:

- The update was applied on the server, but the connection failed when the acknowledgement was about to be sent back to the client;
- The update was not applied on the server, and the client did not receive the acknowledgement because of that.

However, the problem is that a client does not know, which of the above situations happened.

One of the solutions could be the following: it does not matter, whether the update was applied on the server or not. A client will send the update again, until it does not receive an acknowledgement, regardless of what happens on the server's side. Nevertheless, in this case, there should be a policy in order not to apply on the server the same update twice.

The other possibility is to have a double verification on the server side. Let us say, that a client sends an update to the server. After that, the server should send a message back that it received an update. Next, if a client received that message with acknowledgement, it sends another message to the server that it is possible to apply the update.

Though, the above information represents our thoughts on the problem, which is not necessarily a solution to it.

Automatic updates of data at a client

The current design of WebCure requires that after a client sends a request with an update to the server and receives an acknowledgement, it should then still send another read request in order to update the data on its side. However, this behaviour can be improved. For example, in some cases, it might be needed that a client acquires updates from the server automatically. To extend WebCure with such functionality, our suggestion would be to use Push Notifications feature[1] of a service worker. The service worker can receive push messages from a server, even when the application is not active. It let us show notifications to the user on their device even when the application is closed and still notify about the updates of the data on the server side.

Consistency guarantees

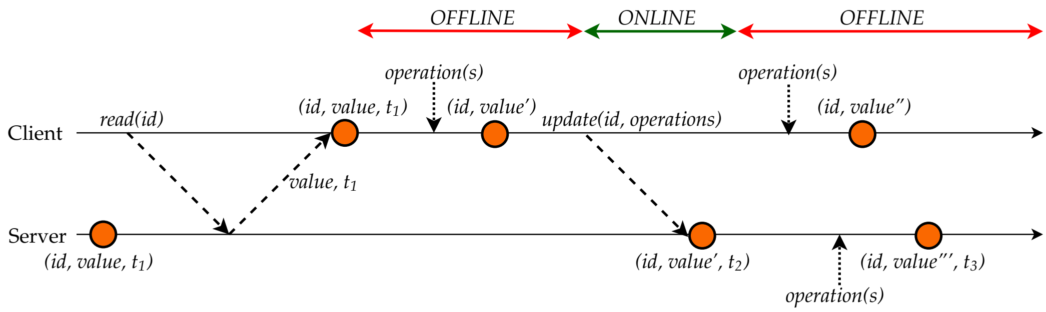


Figure 8.1: The case of breaking causal consistency guarantees in the current protocol.

In the current protocol design, there is a possibility to break the causality of applied operations, and that is what we would like to consider. Let us discuss the case with potential problems, which is illustrated in **Figure 8.1**. There, a client reads the data by *id* from the server, which has a *value* associated with that *id*, at the timestamp t_1. Once the client gets this data, it goes offline, performs some changes locally, and now it has the *value′* associated with *id*. Then, the connection gets back, and this update is sent to the server and applied. However, at this point, the connection breaks again, so the acknowledgement response from the server did not reach the client. That means, that at server side the update was applied and the element *id* got its value changed to *value′* at the timestamp t_2. Nevertheless, the client did not receive that information, the element *id* at the client side still has local changes applied to it, which change its value to *value′*. However, the interesting point here is that a client still has the timestamp t_1, stored on its side. Therefore, any further local updates performed at the client, once the internet connection is back again, will be sent to the server with information to apply them at the timestamp t_1 and not t_2, how ideally it should be. The bad part here is that while our specific client is offline, some other clients could be communicating with the server at this time which means that the server could have received some updates from them as well. The current design of the protocol does not guarantee causal consistency in such situations.

Discussing possible solutions, it all depends on the use case. Sometimes, freezing the client side functionality until it receives the acknowledgement from the server, might be acceptable. However, as it might take a long time, this is not a desirable solution. The other option is to check the states that are received after the server eventually responses (consisting possible changes of the other clients) and find a solution by looking at the difference with the previous state, which is stored at the client side. However, the is a question, which is open for further investigation.

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