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Distributed Data Management – Exam

Winter Term 2018/2019

Matriculation Number: _____

0	1	2	3	4	5	6	7	Σ
1	10	7	6	7	13	5	21	70

Important Rules:

- The exam must be solved within **180 minutes** (09:00 – 12:00).
- Fill in your matriculation number (Matrikelnummer) above and **on every page**.
- Answers can be given in English or German.
- Any usage of external resources (such as scripts, prepared pages, electronic devices, or books) is not permitted.
- Make all **calculations transparent and reproducible**!
- Use the **free space under each task for your answers**. If you need more space, continue on the **back of the page**. Use the extra pages at the end of the exam only if necessary. **Provide a pointer to an extra page** if it should be considered for grading. The main purpose of the extra pages is for drafting.
- Please write clearly. **Do not use the color red or pencils**.
- If you have any questions, raise your hand.
- The exam consists of 30 pages including cover page and extra pages.
- For any multiple choice question, more or fewer than one answer might be correct.
- Good luck!

Task 0: Matriculation Number

Fill in your matriculation number (Matrikelnummer) on every page including the cover page and the extra pages (even if you don't use them).

Hint: Do it now! **1 point**

Task 1: Distributed Systems

1. Which of the following statements about distributed systems are true? Tick all true statements. **4 points**

   ☐ A distributed system is a group of independent compute nodes that communicate and collaborate to solve a common task.

   ☐ Distributed systems are designed for vertical scaling.

   ☐ Distributed systems can increase their reliability with the help of redundancy and replication techniques.

   ☐ According to the CAP theorem, distributed systems can support BASE but not ACID.

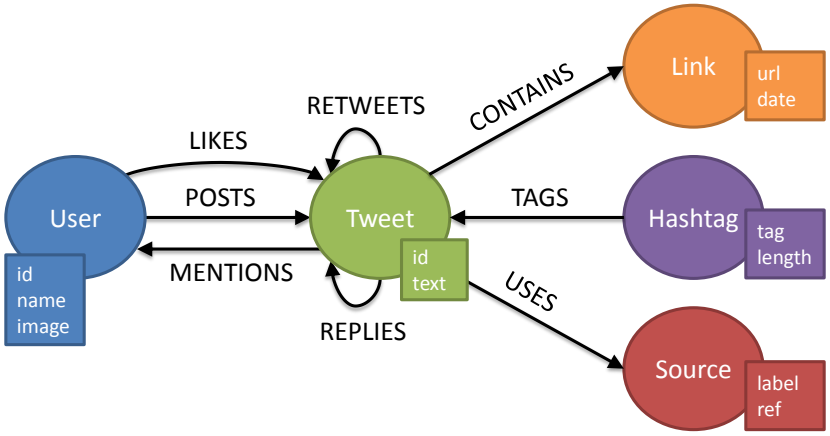
2. Assume that you wrote a distributed algorithm in Akka. After careful analysis of the algorithm, you know that 80% of its execution time would profit from parallelization, while 20% of it is non-parallelizable. According to Amdahl's Law, what is the maximum speedup that this algorithm can achieve on an idealized cluster that has no inherent distribution overhead and infinite size? **3 points**

3. To solve some particular task, it might be necessary that a client node synchronizes its local time with a dedicated time server using the network time protocol (NTP): The client frequently sends a time message to the server to collect four timestamps: t_0, t_1, t_2, and t_3. Assume that for our client node the local clock failed completely after sending a time message. Hence, when the time message returns, t_3 has no value. Fortunately, the node monitors the round-trip delay δ, which had a very stable value of $\delta = 2$ *sec* over the last few hundred time synchronizations. Reconstruct the lost value t_3 and calculate the time shift θ between the server and the client node given the following timestamps:

   t_0 = 10:32:02, t_1 = 10:32:20, t_2 = 10:32:21 (with pattern *hh:mm:ss*) **3 points**

Task 2: Data Models and Query Languages

The following graph describes the schema of a database storing twitter users and their tweets. Each circle describes a possible label for node instances and each edge their possible relationships to other nodes. Assume that the graph/schema is not completely shown here and further nodes and edges might exist (open world assumption). The database was created in Neo4J and you have to use Cypher to query its content.



1. Write a query that reports the ids of all `User` nodes that posted at least one `Tweet` tagged with the `Hashtag` tag "#ClimateChange". **3 points**

2. We are interested in replies to `Tweets` that talk about Michael Stonebraker's project *Tamr*. A `Tweet` talks about this project, if it mentions the `User` "Michael Stonebraker" and contains a `Link` to the url "www.tamr.com". Write a query that returns all `Tweet` nodes that either directly or indirectly (via up to 5 replies) reply to such a project tweet. **4 points**

Task 3: Replication and Partitioning

1. Assume you have a cluster of 800 nodes. The cluster runs a leaderless replicated, distributed database. Quorum reads and writes are used to ensure consistency and a gossip protocol ensures that all updates will eventually spread to all nodes in the cluster.

   Which read (r) and write (w) values do we need to define in our quorum q(r,w) if writes should return as fast as possible and every successfully written value should reach all cluster nodes in expectedly not more than five rounds of gossip? **4 points**

2. Assume you have a dataset that is stored on a cluster with 3 nodes. For partitioning, the space of key hashes is split as follows:

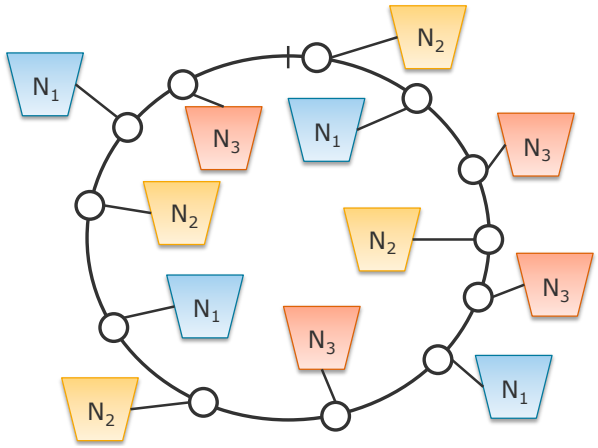


Abbildung 1: A partitioned space of key hashes

Now a new node N_4 enters the cluster and wants to get its share of the dataset. Add node N_4 to the partitioned key space of Figure 1 by drawing it into the image. Use *consistent hashing* and the *fixed number of partitions per node* strategy. **2 points**

Task 4: Failure Detection

The ϕ accrual failure detector method calculates a suspicion level ϕ for monitored processes from their heartbeat history. One important part of that calculation is the formula $P_{later}(t) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \int_t^{+\infty} e^{-\frac{(x-\mu)^2}{2 \cdot \sigma^2}} dx$.

1. What does the formula for $P_{later}(t)$ calculate, i.e., what does it mean? **1 points**

2. Consider the probability density function $f(t) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{(t-\mu)^2}{2 \cdot \sigma^2}}$ of heartbeat arrival times that is used to calculate $P_{later}(t)$. Figure 2 depicts the graph of $f(t)$ for some mean μ and variance σ of heartbeat arrival times. How does $f(t)$ change if the variance σ of the heartbeats increases due to higher network traffic? Draw one curve with higher variance σ into Figure 2 and describe the change in a few words. **2 points**

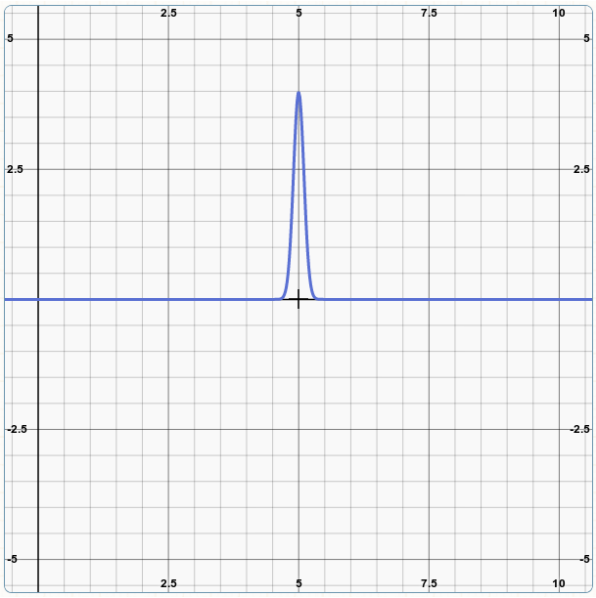


Abbildung 2: The probability density function $f(t)$

3. How can we turn the monotonically decreasing $P_{later}(t)$ into the suspicion level $\phi(t_{now})$, given that T_{last} denotes the arrival time of the last heartbeat and t_{now} the current time? Write down the formula. **2 points**

   $\phi(t_{now}) =$

4. The suspicion level ϕ needs to fulfill four important properties for being used by a failure detector. Name two of them. **2 points**

Task 5: Batch Processing

Suppose you are given three datasets: A `students` dataset that contains general information about students, a `courses` dataset that describes available courses for the students, and an `enrollment` dataset, which is basically a join table between `students` and their `courses`. The following code snippets read the three datasets into Spark `Datasets`:

```
val students = spark
  .read
  .option("quote", "\"")
  .option("delimiter", ",")
  .csv(s"data/students.csv")
  .toDF("ID", "Name", "Semester", "Supervisor")
  .as[(String, String, String, String)]

val enrollments = spark
  .read
  .option("quote", "\"")
  .option("delimiter", ",")
  .csv(s"data/enrollments.csv")
  .toDF("StudentID", "CourseID", "Credits")
  .as[(String, String, String)]

val courses = spark
  .read
  .option("quote", "\"")
  .option("delimiter", ",")
  .csv(s"data/courses.csv")
  .toDF("ID", "Title", "Teacher", "Topic")
  .as[(String, String, String, String)]
```

Use the three `Datasets` to solve the following tasks. You may use Spark's *Dataset* and/or *DataFrame* API but no SQL! Also have a look at the *Dataset* API documentation at the end of this task. If you are not sure about how a particular interface, call, or class works, make a good guess and provide a comment on how you *think* it works.

1. Write a Spark transformation pipeline that starts with the `students Dataset`, then filters all those students that are supervised by "Prof. Dumbledore", maps these students to their `ID` and `Semester`, and finally displays the results in tabular form on the standard output. **3 points**

2. Translate the following SQL query into a Spark transformation pipeline. **5 points**

```
SELECT *
FROM {
    SELECT DISTINCT Title
    FROM courses
    WHERE Teacher = "Prof. Snape"
  } INTERSECT {
    SELECT DISTINCT Title
    FROM courses
    WHERE Teacher = "Prof. Moody"
  }
ORDER BY Title
```

3. Implement a join between the `students` and the `enrollments` dataset as a Spark batch job without using Spark's `joinWith()` transformation. The result should be a `Dataset` with two columns: one column containing the student record and one column containing the enrollment record. Join on `students.ID = enrollments.StudentID` and finalize the pipeline with some action of your choice. Do *not* implement the join as a broadcast join or any map-side join, because both relations are large. **5 points**

   Hint: Remember how reduce-side joins work in the MapReduce framework.

Typed transformations

def **as**(alias: String): Dataset[T]
Returns a new Dataset with an alias set.

def **distinct**(): Dataset[T]
Returns a new Dataset that contains only the unique rows from this Dataset.

def **except**(other: Dataset[T]): Dataset[T]
Returns a new Dataset containing rows in this Dataset but not in another Dataset.

def **filter**(func: FilterFunction[T]): Dataset[T]
(Java-specific) Returns a new Dataset that only contains elements where func returns true.

def **filter**(func: (T) ⇒ Boolean): Dataset[T]
(Scala-specific) Returns a new Dataset that only contains elements where func returns true.

def **flatMap**[U](f: FlatMapFunction[T, U], encoder: Encoder[U]): Dataset[U]
(Java-specific) Returns a new Dataset by first applying a function to all elements of this Dataset, and then flattening the results.

def **flatMap**[U](func: (T) ⇒ TraversableOnce[U])(*implicit* arg0: Encoder[U]): Dataset[U]
(Scala-specific) Returns a new Dataset by first applying a function to all elements of this Dataset, and then flattening the results.

def **groupByKey**[K](func: MapFunction[T, K], encoder: Encoder[K]): KeyValueGroupedDataset[K, T]
(Java-specific) Returns a KeyValueGroupedDataset where the data is grouped by the given key func.

def **groupByKey**[K](func: (T) ⇒ K)(*implicit* arg0: Encoder[K]): KeyValueGroupedDataset[K, T]
(Scala-specific) Returns a KeyValueGroupedDataset where the data is grouped by the given key func.

def **intersect**(other: Dataset[T]): Dataset[T]
Returns a new Dataset containing rows only in both this Dataset and another Dataset.

def **joinWith**[U](other: Dataset[U], condition: Column): Dataset[(T, U)]
Using inner equi-join to join this Dataset returning a Tuple2 for each pair where condition evaluates to true.

def **map**[U](func: MapFunction[T, U], encoder: Encoder[U]): Dataset[U]
(Java-specific) Returns a new Dataset that contains the result of applying func to each element.

def **map**[U](func: (T) ⇒ U)(*implicit* arg0: Encoder[U]): Dataset[U]
(Scala-specific) Returns a new Dataset that contains the result of applying func to each element.

def **sort**(sortExprs: Column*): Dataset[T]
Returns a new Dataset sorted by the given expressions.

def **sort**(sortCol: String, sortCols: String*): Dataset[T]
Returns a new Dataset sorted by the specified column, all in ascending order.

def **union**(other: Dataset[T]): Dataset[T]
Returns a new Dataset containing union of rows in this Dataset and another Dataset.

Untyped transformations

def **col**(colName: String): Column
Selects column based on the column name and return it as a Column.

Actions

def **collect**(): Array[T]
Returns an array that contains all rows in this Dataset.

def **show**(numRows: Int, truncate: Int): Unit
Displays the Dataset in a tabular form.

def **foreach**(f: (T) ⇒ Unit): Unit
Applies a function f to all rows.

def **reduce**(func: ReduceFunction[T]): T
(Java-specific) Reduces the elements of this Dataset using the specified binary function.

def **reduce**(func: (T, T) ⇒ T): T
(Scala-specific) Reduces the elements of this Dataset using the specified binary function.

class **KeyValueGroupedDataset**[K, V] extends Serializable

def **mapGroups**[U](f: MapGroupsFunction[K, V, U], encoder: Encoder[U]): Dataset[U]
(Java-specific) Applies the given function to each group of data.

def **mapGroups**[U](f: (K, Iterator[V]) ⇒ U)(*implicit* arg0: Encoder[U]): Dataset[U]
(Scala-specific) Applies the given function to each group of data.

Task 6: Stream Processing

Consider the following stream analytics program written in Flink:

```
import org.apache.flink.api.java.tuple.*;
import org.apache.flink.streaming.api. *;
import org.apache.flink.util.Collector;
import java.util.Date;

public class SensorProcessing {

  public static void main(String[] args) throws Exception {
    StreamExecutionEnvironment env = StreamExecutionEnvironment.getExecutionEnvironment();
    env.setStreamTimeCharacteristic(TimeCharacteristic.EventTime);

    DataStream<Tuple3<Integer, Date, Float>> readings = env
      .socketTextStream("localhost", 9999)
      .map(SensorProcessing::lineToReading)
      .assignTimestampsAndWatermarks(new AscendingTimestampExtractor<Tuple3<Integer, Date, Float>>() {
          @Override
          public long extractAscendingTimestamp(Tuple3<Integer, Date, Float> element) {
            return element.f1.getTime();
          }
        });

    readings
      .filter(r -> (r.f2 > -50.0f) && (r.f2 < 50.0f))
      .keyBy(r -> r.f0)
      .timeWindow(Time.days(1), Time.days(1))
      .apply(new StandingQuery())
      .print();

    env.execute("Sensor Processing");
  }

  public static class StandingQuery implements WindowFunction
      <Tuple3<Integer, Date, Float>, Tuple2<Integer, Date>, Integer, TimeWindow> {

    @Override
    public void apply(Integer key, TimeWindow window,
                Iterable<Tuple3<Integer, Date, Float>> values,
                Collector<Tuple2<Integer, Date>> out) {

      for (Tuple3<Integer, Date, Float> reading : values) {
        if (reading.f2 > 30.0f) {
          out.collect(new Tuple2<>(key, reading.f1));
          return;
        }
      }
    }
  }

  // Reading(SensorID, Timestamp, Temperature)
  private static Tuple3<Integer, Date, Float> lineToReading(String line) {...}
}
```

1. What does the program calculate? Describe what events the `StandingQuery` outputs and what these events mean. **2 points**

2. The input stream for the Flink program might start like this:

`SensorID`	`Timestamp`	`Temperature`
#	*dd-mm-yy hh:mm:ss*	$°C$
1	21-05-18 00:00:00	12.1
2	21-05-18 00:00:00	28.0
3	21-05-18 00:00:00	15.4
1	21-05-18 06:00:00	12.3
2	21-05-18 06:00:00	29.8
3	21-05-18 06:00:00	14.7
1	21-05-18 12:00:00	12.7
2	21-05-18 12:00:00	31.1
3	21-05-18 12:00:00	89.9
1	21-05-18 18:00:00	13.0
2	21-05-18 18:00:00	32.9
3	21-05-18 18:00:00	14.6
1	22-05-18 00:00:00	11.3
2	22-05-18 00:00:00	27.1
3	22-05-18 00:00:00	15.6
...	...	...

Write down the output of the program after processing all depicted events. **2 points**

3. Given the start of the stream as depicted above. What is the degree of parallelism for the standing query, i.e., how many windows are processed in parallel on that stream? **1 points**

Task 7: Actor Programming

1. The Actor model implementation in Akka makes two guarantees for the messaging (when used in conjunction with the TCP protocol). What are these two guarantees? **2 points**

2. Which of the following statements on the actor model and actor programming are *true*? Tick the true ones. **6 points**

   ☐ An `ActorSystem` in Akka is a named hierarchy of actors that also includes components for event streaming, thread dispatching, and message remoting.

   ☐ Actors are created as passive entities that become active only if they receive messages; after processing a message, they return to their passive state.

   ☐ Actors can open dedicated mailboxes, which serve as site-channels for large messages such that these large messages do not block the communication that happens on the primary mailbox.

   ☐ For parallel message processing, an `ActorSystem` can serve one actor instance with two threads: one thread processes the first message from the queue while the second thread processes the second message.

   ☐ Actor messages usually carry the sender of a message allowing the receiver to respond to that message; for this reason, actors need to be serializable, i.e., implement Java's `Serializable` interface.

   ☐ Blocking ask messages are not supported by the general actor model, but they can be implemented using Java's `Futures` and the *ask pattern*.

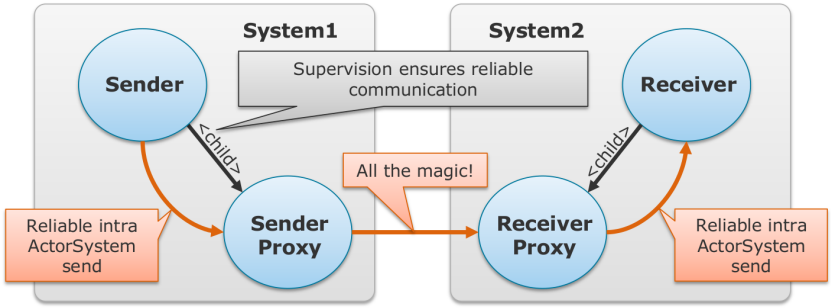
3. Consider the following actor implementation. What fundamental problem does this implementation have and to what consequences might this problem lead? **2 points**

```
public class BadActor extends AbstractLoggingActor {

    private Map<String, Integer> histogram = new HashMap<>();

    public Receive createReceive() {
       return receiveBuilder()
          .match(String.class, s -> sender().tell(histogram, self()))
          .build();
    }
    ...
}
```

4. The *Reliable Communication Proxy* pattern ensures that all messages that a `Sender` actor tells to a `Receiver` actor are transmitted exactly once and in order. From a conceptual view, the pattern looks as follows:



Implement the two proxies of the *Reliable Communication Proxy* pattern in Akka given the actor templates below. The message that the `Sender` actor wants to tell to the `Receiver` actor is a simple `String`. The `Receiver` should receive this `String` message as if the `Sender` would have told it directly to it. **11 points**

Hint: Use the space on this page for drafting. Then write your solution into the provided gaps. Use the back of the template pages if you need more space.

```java
import java.util.HashMap;
import java.util.Map;
import java.util.concurrent.TimeUnit;

import akka.actor.AbstractLoggingActor;
import akka.actor.ActorRef;
import akka.actor.Cancellable;
import akka.actor.Props;
import de.hpi.octopus.ReceiverProxy.ReliableMessage;
import scala.concurrent.duration.Duration;

public class SenderProxy extends AbstractLoggingActor {

    private ActorRef receiverProxy;
    [redacted]

    public SenderProxy(ActorRef receiverProxy) {
        this.receiverProxy = receiverProxy;
    }

    public static Props props(ActorRef receiverProxy) {
        return Props.create(SenderProxy.class, () -> new SenderProxy(receiverProxy));
    }

    @Override
    public Receive createReceive() {
        return receiveBuilder()
                .match(String.class, this::handle)
                [redacted]
                .matchAny(object -> this.log().info("Unknown message: \"{}\"", object.toString()))
                .build();
    }

    private void handle(String message) {
        [redacted]
    }

    private void handle([redacted] message) {
        [redacted]
    }

    private Cancellable createCancellableFor(ReliableMessage message) {
        return this.getContext().system().scheduler().schedule(
                Duration.create(0, TimeUnit.SECONDS),
                Duration.create(3, TimeUnit.SECONDS),
                this.receiverProxy,
                message,
                this.getContext().dispatcher(),
                this.self());
    }

    private void stopCancellable(Cancellable cancellable) {
        cancellable.cancel();
    }
}
```

```java
import java.io.Serializable;
import java.util.HashMap;
import java.util.Map;

import akka.actor.AbstractLoggingActor;
import akka.actor.ActorRef;
import akka.actor.Props;

public class ReceiverProxy extends AbstractLoggingActor {

    private ActorRef receiver;

    public ReceiverProxy(ActorRef receiver) {
        this.receiver = receiver;
    }

    public static Props props(ActorRef receiver) {
        return Props.create(ReceiverProxy.class, () -> new ReceiverProxy(receiver));
    }

    public static class ReliableMessage implements Serializable {
        private static final long serialVersionUID = -3254147511955012292L;

    }

    @Override
    public Receive createReceive() {
        return receiveBuilder()
                .match(ReliableMessage.class, this::handle)
                .matchAny(object -> this.log().info("Unknown message: \"{}\"", object.toString()))
                .build();
    }

    private void handle(ReliableMessage message) {

    }
}
```

Extra page 1

Extra page 2

Extra page 3