defoe: A Spark-based Toolbox for Analysing Digital Historical Textual Data

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Abstract—This work presents defoe, a new scalable and portable digital eScience toolbox that enables historical research. It allows for running text mining queries across large datasets, such as historical newspapers and books in parallel via Apache Spark. It handles queries against collections that comprise several XML schemas and physical representations. The proposed tool has been successfully evaluated using five different large-scale historical text datasets and two HPC environments, as well as on desktops. Results show that defoe allows researchers to query multiple datasets in parallel from a single command-line interface and in a consistent way, without any HPC environment-specific requirements.

Index Terms—text mining, distributed queries, Apache Spark, High-Performance Computing, XML schemas, digital tools, digitised primary historical sources, humanities research

I. INTRODUCTION

Over the past three decades, large scale digitisation has been transforming the collections of libraries, archives, and museums [1], [2]. The volume and quality of available digitised text now makes searching and linking these data feasible, where previous attempts were restricted due to limited data availability, quality, and lack of shared infrastructures [3].

There is hunger for large scale text mining facilities from the humanities community, with commercial providers allowing limited access to their own digitised collections [4]. However, there are barriers to querying the wealth of newspapers and books that now exist in digitised, openly licensed form at scale, which would allow humanists to be in control of their text mining research [5].

For example, although the product of most digitisation of historical text is structured XML files derived from Optical Character Recognition (OCR) (see Figure 1[4]), the schemas, structure, and size of the datasets are heterogeneous, and they are often difficult to link and cross-query. Additionally, the humanities community has limited capacity and/or skills to use High-Performance Computing (HPC) environments and analytic frameworks to create applications to mine large-scale digital collections effectively.

This work focuses on removing some these obstacles by enabling complex analysis of digital datasets at scale. By bringing together computer scientists with humanities and computational linguistics researchers, we have created a new

\^[1]XML has been commonly adopted by the cultural heritage and digital humanities community for the delivery of large scale datasets, commonly with some relationship to the Text Encoding Initiatives guidelines for structuring such texts: https://tei-c.org.
portable humanities research toolbox, called defoe\(^2\) for interrogating large and heterogeneous text-based archives. defoe uses the power of analytic frameworks, such as Apache Spark\(^6\), Jupyter Notebooks, and HPC environments to manipulate and mine huge digitised archives in parallel at great speed using a simple command line. It can be installed and used in different computing environments (cloud systems, HPC clusters, laptops), making humanities research portable and reproducible.

We have demonstrated the feasibility of defoe by using two case studies as undertaken at the University of Edinburgh (Eruption of Krakatoa Volcano in 1883 and Female Emigration), two HPC clusters (Cray Urika and Eddie), and five different digital collections.

This paper is structured as follows. Section II presents background. Section III discusses defoe design features. Section IV presents two case studies for testing feasibility of the tool. Section V describes the computing environments used for our studies. We conclude with a summary of achievements and outline future work.

II. RELATED WORK

The work presented in this paper builds on two previous Python text analysis packages, cluster-code\(^7\) and i_newspaper_rods\(^7\), created by members of the author team in collaboration with the Research IT Services at University College London (UCL)\(^7\).

cluster-code\(^7\) analyses British Library (BL) books conforming to a particular XML schema, while i_newspaper_rods has been designed for analysing British Library newspapers conforming to another XML schema. XML schemas describe either the structure of a digital object or the actual textual content of the object including the word content, styles, and layout elements. However, the two XML schemas used by both packages are slightly different in terms of metadata attributes, tags, and document structure.

Even though cluster-code and i_newspaper_rods share a common behaviour, they are implemented and run in different ways. cluster-code uses mpi4py\(^8\) (a wrapper to MPI) to query data, while i_newspaper_rods uses the Apache Spark framework. Each defines a single object model based on the physical representation and XML schemas of the data that each has been designed to ingest. Furthermore, each was originally designed to extract data held within a UCL deployment of the data management software, and run queries on UCLs HPC services. This means, that we cannot use cluster-code for analysing BL newspapers or i_newspaper_rods for British Library books, and we have to make several modifications to both codebases to run them in different HPC environments.

Among the range of text mining queries supported by cluster-code we can count the total number of pages across all books, count the frequencies of a given list of words, find the locations of figures, etc. Some examples of i_newspaper_rods queries are counting the number of articles per year, the frequencies of words in a given list of words, and finding expressions that match a given pattern.

In terms of preprocessing the raw text data, both libraries only include a basic normalisation strategy by removing non-‘a-z—A-Z’ characters and converting all text to lower case.

With defoe we aimed to create a portable tool for analysing historical collections that conform to either of several XML schemas and different physical representations, expanding the range of supported queries, and including natural language processing capabilities. All of these functionalities should be provided using Apache Spark as the distributed and parallel engine. More details about defoe are given in the next section.

III. THE DEFOE DIGITAL HUMANITIES TOOL

defoe is the result of merging, extending and refactoring codebases introduced in Sec. II in the same place, allowing queries from a single command-line interface in a consistent way. The main component of defoe is the text analysis pipeline (see Figure 2), which resides at its core and has been implemented using Apache Spark.

Apache Spark is an open source HPC distributed computing framework for large-scale data processing. It uses a directed acyclic graphs (DAG) that allow for processing multi-stage pipelines chained in one job. Apache Spark provides an ability to cache large datasets in memory between stages of the calculation and to reuse intermediate results of the computation in iterative algorithms. Resilient Distributed Datasets (RDD) are the fundamental data structures of Apache Spark, which is an immutable distributed collection of objects. RDDs are partitioned into logical partitions across cluster nodes and operate in parallel through transformations and actions. A transformation is a function that produces new RDD from existing ones. Transformations are not executed immediately, only after an action is called. On the other hand, action are operations that trigger execution of transformation and return values.

Therefore, we chose Apache Spark because it provides automatic parallelisation and scalability for the four steps of our text analysis pipeline. It loads digital collections into RDDs in

\(^2\) Daniel Defoe was both a journalist and a novelist, which are the two datasets that this toolkit work with. Therefore, we decided to name it after him. defoe source code available at https://github.com/alan-turing-institute/defoe
https://github.com/UCL-dataspring/cluster-code
https://github.com/UCL/i_newspaper_rods
https://www.ucl.ac.uk/isd/services/research-it-services
memory, cleans data and runs text mining queries in parallel, returning results as YAML files. To complement defoe, a repository of Jupyter notebooks, called defoe visualisation, has been developed to allow researchers to visualise and explore further results obtained with defoe.

Furthermore, a lot of work has gone into defoe to remove all HPC environment-specific requirements, allowing us to run defoe in any computing environment that has Apache Spark installed. The following subsections give a detailed explanation of each step of the defoe text analysis pipeline.

A. Data Ingestion

We are able to consume historical textual collections scanned via OCR into XML documents using defoe. It has specific support for newspapers and books conforming any of these three physical representations: 1) one XML document per issue; 2) one XML document with search results including several articles; and 3) one XML metadata document and XML page. It also supports the following digital library standards:

- METS XML schema 6 for descriptive, structural, technical and administrative metadata;
- MODS XML schema 7 for encoding bibliographic metadata;
- ALTO XML schema 8 for encoding OCR text;
- British Library-specific XML schema 9 for OCR text; and
- PaperPast-specific XML schema 10 for encoding OCR text.

As we mentioned before, XML schemas describe either the structure of a digital document or the actual textual content. All of these are slightly different, and none of them is universally used. Therefore, we have created three object models (PAPERS, NZPP and ALTO) to map the physical representations and XMLs schemas (see Figure 3) mentioned before. These allows defoe to ingest digital collections into Spark RDDs, which is the only requirement to select the appropriate object model the digital collection to analyse is mapped onto.

For example, if we want to import a historical newspaper collection to be analysed, first we have to check whether the collection has been digitised using a document per issue and the British Library-specific XML schema, in which case the PAPERS object model needs to be selected. If, on the other hand, each XML document follows the PaperPast-specific XML schema and holds a collection of articles that corresponds to one more issues, the NZPP object should be selected instead. In the case of analysing ALTO archives, the ALTO model should be selected.

We have also explored the option of ingesting XML documents using Spark SQL and DataFrames. Unlike an RDD, DataFrames organise data into named columns, and impose a structure on a distributed collection of data. To use this option, we also need to infer the different XML schemas.

Therefore, we developed two new python parsers 11 based on the databricks spark-xml package 12 which has been designed to read XML documents as DataFrames.

However, due to the nested nature of the historical XML schemas (such as ALTO, METS and British-Library specific XML), the spark-xml package is not able to infer them automatically, requiring a lot of manual work to flatten their attributes. Since this option did not add further benefits to what we already had, we decided to continue with our original implementation using RDDs.

Once the data is loaded into RDDs with a particular object model, defoe continues the analysis with the Natural Language Processing (NLP) step for cleaning the text. Note that Apache Spark ingests the data in parallel which is automatically partitioned (in memory) across the Spark cluster.

To evaluate defoe, we have used a range of digital collections, which main features are summarised in Table I.

---

6http://www.loc.gov/standards/mets/
7http://www.loc.gov/standards/mods/
8https://www.loc.gov/standards/alto/
9http://www.jisc.ac.uk/media/documents/programmes/digitisation/blfinal.pdf
10https://paperspast.natlib.govt.nz/about
11https://github.com/rosafilgueira/SparkSQL_DataFrames_Defoe
12https://github.com/databricks/spark-xml
<table>
<thead>
<tr>
<th>Dataset</th>
<th>Period</th>
<th>Structure</th>
<th>Scale</th>
<th>Size</th>
<th>Object Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>British Library Books (BLB)</td>
<td>1510-1899</td>
<td>ZIP per book with a XML metadata (METS schema) and a XML per page (ALTO schema)</td>
<td>63700 ZIP files</td>
<td>220 GB</td>
<td>ALTO model</td>
</tr>
<tr>
<td>British Library Newspapers (BLN)</td>
<td>1714-1950</td>
<td>XML document per issue (British Library-specific XML schema)</td>
<td>179669 XML documents</td>
<td>424 GB</td>
<td>PAPERS model</td>
</tr>
<tr>
<td>Times Digital Archive (TDA)</td>
<td>1785-1848</td>
<td>XML (British Library-specific XML schema) per issue</td>
<td>69699 XML documents</td>
<td>362 GB</td>
<td>PAPERS model</td>
</tr>
<tr>
<td>Papers Past New Zealand and Pacific newspapers (NZPP)</td>
<td>1839-1863</td>
<td>XML document (with 22 articles) corresponds to results from a search via an API</td>
<td>13411 XML documents (PaperPast-specific XML schema)</td>
<td>4 GB</td>
<td>NZPP model</td>
</tr>
<tr>
<td>Find My Past (FPM)</td>
<td>1752 -1957</td>
<td>Folder per issue, with a XML metadata document (METS) and XML file per issue page (ALTO)</td>
<td>2067235 XML documents</td>
<td>1.8TB</td>
<td>ALTO model</td>
</tr>
</tbody>
</table>

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TABLE I: Main features, abbreviations and defoe object models for the digital collections explored.

B. NLP Text Preprocessing

The poor quality that often emerges from large-scale text digitisation is well-documented [9], [10]. This can create issues for searching and research based on imperfect digital copies of text. Basic string-matching searching is unlikely to return all the results intended by the user. We have implemented a NLP preprocessing pipeline (see Figure 4) that deals with character-level errors in the OCR, which is a first step towards allowing a more semantically meaningful exploration of the data. Our NLP pipeline consists in the following steps. After the raw text (from pages or articles) is ingested, the first step is to split it into sentences. Then, each sentence is tokenised separately, which results in a new sequence of tokens that roughly correspond to ‘words’. Later each token is normalised by removing non-‘a-z—A-Z’ characters and making them lower-case. Once tokens are normalised, users can choose whether to apply stemming or lemmatisation. Stemming reduces words to their word stem (base or root form), whereas lemmatisation reduces inflectional forms to a common base form.

After that, the pipeline performs Part-Of-Speech (POS) tagging, which assigns parts of speech to each token (tagging them as nouns, verbs, adjectives, and others) based on its definition and context. Finally, the pipeline proceeds with the named-entity recognition (NER) step to find named entities in the tagged tokens and classify them into pre-defined categories (names of persons, locations, organisations, times, etc).

Since the NLP pipeline is implemented in Apache Spark, each step is a transformation, in which a function (e.g. sentence splitter, tokenisation, normalisation, etc) produces new RDDs from the existing ones.

Furthermore, we have implemented two versions of this pipeline using widely used NLP frameworks: NLTK [11] and spaCy [12] (see Listing 5). spaCy is an open-source software library for advanced NLP written in Python and Cython. NLTK is a suite of libraries and programs for symbolic and statistical NLP for English written in Python. Their main features are shown in Table II.

We are currently evaluating end-to-end performance by comparing the outputs of the two versions of the pipeline.

TABLE II: Comparison of spaCy and NLTK features.
against a gold standard dataset of historical texts that is being manually annotated. This will inform which library is most suitable for preprocessing historical newspapers and books. At the time of writing, both implementations are available in defoe.

Sentence: "And devoted some time to social work in London."

<table>
<thead>
<tr>
<th>spaCy preprocessing</th>
<th>Word Normaliz. Lemma PoS Tag NER</th>
</tr>
</thead>
<tbody>
<tr>
<td>devoted devoted</td>
<td>devote VBN (S devoted/VBN)</td>
</tr>
<tr>
<td>some some</td>
<td>some DT (S some/DT)</td>
</tr>
<tr>
<td>time time</td>
<td>time NN (S NP time/NN)</td>
</tr>
<tr>
<td>to to</td>
<td>to ADP IN</td>
</tr>
<tr>
<td>social social</td>
<td>social ADJ JJ</td>
</tr>
<tr>
<td>work work</td>
<td>work NOUN NN</td>
</tr>
<tr>
<td>in in</td>
<td>in ADP IN</td>
</tr>
<tr>
<td>London london</td>
<td>London PROPN NNP GPE</td>
</tr>
<tr>
<td>.</td>
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</table>

<table>
<thead>
<tr>
<th>NLTK preprocessing</th>
<th>Word Normaliz. Lemma Stem PoS Tag NER</th>
</tr>
</thead>
<tbody>
<tr>
<td>devoted devoted</td>
<td>devoted VBN (S And/CC)</td>
</tr>
<tr>
<td>some some</td>
<td>some DT (S some/DT)</td>
</tr>
<tr>
<td>time time</td>
<td>time NN (S NP time/NN)</td>
</tr>
<tr>
<td>to to</td>
<td>to TO (S to/TO)</td>
</tr>
<tr>
<td>social social</td>
<td>social JJ (S social/JJ)</td>
</tr>
<tr>
<td>work work</td>
<td>work NOUN NN (S NP work/NN)</td>
</tr>
<tr>
<td>in in</td>
<td>in IN (S in/IN)</td>
</tr>
<tr>
<td>London london</td>
<td>London NNP (S GPE London/NPP)</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
</tr>
</tbody>
</table>

Fig. 5: defoe preprocessing output example. The sentence belongs to the FMP digital corpus.

C. Text mining queries

After preprocessing the raw text data, defoe executes the selected text mining query over clean RDDs. It offers users a wide range of queries, some of which were directly imported from i.newspapers.rods (such as total_issues, total_articles or normalize). Others were imported from cluster-code (such as total_pages or total_books), but these need to be re-implemented first in Apache Spark, since they were written in mpi4py. We also augmented these query types with a number of new ones, such as:

- **keyword_and_concordance_by_date:** Searches for occurrences of any word in a list of keywords and returns information on each matching article including title, matching keyword, article text and filename. Results are grouped by dates.
- **collocates_by_year:** Searches for two co-located words separated by a maximum number of intervening words. For each match, information about the matching book/issue, including the book/article title, the matching words, the intervening words, and the book/newspaper file name are returned. Results are grouped by dates.
- **keysentence_by_year:** Searches for occurrences of a sentence (or phrase) and returns counts of the number of articles that include the sentence. Results are grouped by year.
- **target_and_concordance_collocation_by_date:** Searches for occurrences of a target word occurring with any word in a list of keywords and returns counts of occurrences of each target word and these keywords. Results are grouped by year.
- **target_keywords_count_by_year:** Searches for occurrences of a target word occurring with any word in a list of keywords and returns counts of occurrences of each target word and these keywords. Results are grouped by year.
- **target_and_keywords_count_by_year:** Searches for occurrences of a target word occurring with any word in a list of keywords and returns counts of occurrences of each target word and these keywords. Results are grouped by year.

All defoe queries are based on a number of transformations (e.g. filter, flatMap, reduceByKey, etc.) and actions (e.g. reduce, collect, etc.) that are combined to perform text mining analyses. Listing 6 shows as an implementation example, the ocr_quality_by_year query, in which a flatMap transformation is applied to issues RDDs. For each article stored inside a given issue RDD, the transformation extracts the information from the quality and years attributes (check these on the PAPERS object model shown in Figure 3.a) and returns it as a new qualities RDD. Later the reduceByKey transformation is applied to group the qualities by years. Finally the collect action is performed to trigger the execution of previous transformations and to gather the result in a YAML file.

```python
def do_query(issues, config_file=None, logger=None):
    # {{[year, [quality]], ...]}
    qualities = issues.flatMap(
        lambda issue:
            [(
                issue.date.year,
                [article.quality]
            )
            for article in issue.articles])
    result = qualities \
        .reduceByKey(concat) \
        .collect() \
    return result
```

Fig. 6: defoe ocr_quality_by_year query: Gets the information on the OCR accuracy of each article and groups the results by year.

Apache Spark excels at distributing these transformations and actions across a cluster while abstracting away many of the underlying implementation details, and runs them in parallel.

D. Results

As we mentioned before, defoe generates results into YAML files. Listing 7 shows the result obtained by the ocr_quality_by_year query using a small subset of BLN digital corpus. For simplification, only OCR qualities from 1850 and 1851 articles are displayed.

Furthermore, a new repository of Jupyter Notebooks, called defoe visualization has been developed to visualise and evaluate further results/answers obtained from defoe. For example,
IV. CASE STUDIES

There are two common ways that scholars in the humanities use text mining. One is to visualise overall patterns and trends in text. The other is to use the search facility to return a sub-corpus (such as whole newspaper articles that include given terms), which can then be subject to further computational analysis as well as manual closer analysis. defoe supports both types of use, which we describe further with two different case studies below.

A. Female Emigration

The first case study is part of the Oceanic Exchanges project and aims to mine the TDA and BLN archives for attitudes towards female emigration from Great Britain to the ‘Colonies’ and North America from 1850 to 1914. It seeks to understand the role that newspapers may have played as an agent of empire, asking the following question: Can we detect an emphasis on a ‘service of the British empire’ narrative as a motivating factor and driver in the pursuit of female emigration?

Therefore, three text mining questions were designed to move from a purely quantitative, birds-eye view into a more semantic analysis of the topic of female emigration:

- Normalised frequencies of the names of female emigration societies, for which we used keysentence_by_year and normalise defoe queries (described in Sec. III-C).
- Normalised frequencies of specially chosen taxonomy terms relating to female emigration, for which we used target_and_keywords_by_year, target_and_keywords_count_by_year, and normalize defoe queries (described in Sec. III-C).
- Analysing the concordance and collocation of the taxonomy terms, for which we used target_concordance_collocation_by_date defoe query (described in Sec. III-C).

defoe was not only used for running these queries in parallel using TDA and BLN newspapers, but also for aggregating, transforming results into CVS files (see Figure 10), post-processing analyses, and visualising results. Analysis of the results continues, but we can demonstrate the ability of defoe to create n-grams to visualise the occurrences of the words “daughter”, “engagement”, and “empire” across the corpus, as shown in Figure 11.

B. Eruption of Krakatoa Volcano in 1883

Krakatoa (Krakatau in Indonesian) erupted over 26-27th August 1883 and was one of the most spectacular volcanic eruptions in contemporary times. defoe was used to identify every mention of this eruption using the BLN, TDA, and NZPP newspapers, but also for aggregating, transforming results into CVS files (see Figure 10), post-processing analyses, and visualising results. Analysis of the results continues, but we can demonstrate the ability of defoe to create n-grams to visualise the occurrences of the words “daughter”, “engagement”, and “empire” across the corpus, as shown in Figure 11.
Fig. 10: Snapshot of the taxonomy terms concordance and collocation results, using a window of 10 words preceding and following each match across the TDA corpus. OCR quality for each article is also captured.

Fig. 11: N-gram for the normalised frequencies of the words “daughter”, “engagement”, and “empire” across the TDA corpus.

newspaper corpus from late 1883 in order to contribute to an international analysis on how the story was reported around the world, looking at news dissemination in the late Victorian period.

For this analysis, we used the keyword_and_concordance_by_date query described at Sec. III-C which searches for occurrences of “krakatoa” and “krakatua” and returns information on each matching article.

The resulting small corpus of approximately 50 newspaper articles from all over England provides a rich data set where we can track copying and transmission of text, and this is being analysed at the time of writing by historians, and visualised in more advanced ways by data scientists. Further results are available in the Jupyter Notebook repository 21

As we mentioned before, defoe allows for querying datasets from a single command-line interface and in a consistent way. It hides all the complexity to users, allowing to query data just specifying the corpus, object model, and query to use via the command line (see Listing 12).

V. COMPUTING ENVIRONMENTS

We have run the previous case studies using defoe on two HPC clusters, Urika-GX and Eddie, both hosted at the University of Edinburgh. We briefly describe these two systems.

A. The Cray Urika-GX system

The Cray Urika-GX system is a high-performance analytics cluster with a pre-integrated stack of popular analytics packages, including Apache Spark, Apache Hadoop and Jupyter

![Apache Spark Architecture in Urika-GX](https://github.com/alan-turing-institute/defoeVisualization)

Fig. 12: Example of the command line for submitting the keyword_and_concordance_by_date query. Users needs to select the digital corpus to use (bln_files), the corresponding object model (papers), the query (keyword_and_concordance_by_date), the preprocessing pipeline implementation (preprocess.yml), the file to save the results in (results_krakatoa) and the number of processes to use (324).

Notebooks, all managed using the Apache Mesos22 resource manager. These are complemented with myriad of tools and frameworks to allow data analytics applications to be developed in Python, Scala, R and Java.

The Alan Turing Institutes deployment of the Urika-GX system (hereon called Urika) includes 12 compute nodes (each with 2x18 core Broadwell CPUs), 256GB of memory and 60TB of storage (within a Lustre high-performance parallel file system) and 2 login nodes. Both compute and login nodes run the CentOS 7.4 operating system.

Little work was needed to run the defoe queries in Urika-GX using several nodes. The Urika-GX software stack includes a fault-tolerant Spark cluster configured and deployed to run under Mesos, which acts as the cluster manager.

Therefore, we just needed to adjust four Spark parameters: Spark master with the URL of the Mesos master node; number of executors (worker nodes’ processes in charge of running individual Spark tasks); number of cores per executor (up to 36 cores); and the amount of memory to be allocated to each executor (up to 250GB). Even though Urika-GX has 12 nodes, at the time of our experiments, only 9 nodes and 324 cores were available.

21https://github.com/alan-turing-institute/defoeVisualization

22http://mesos.apache.org/
Not all researchers have access to *Urika-GX*. It is useful to enable researchers to use *defoe* on other HPC environments upon which, unlike *Urika-GX*, Spark has not been pre-installed and configured. *Eddie* is a University of Edinburgh HPC cluster. It consists of some 7000 Intel Xeon cores with up to 3TB of memory available per compute node. The cluster uses the Open Grid Scheduler batch system on Scientific Linux 7.

In the future we would like to extend *defoe* to identify and extract commonality across the object models and run queries across them transparently to users. We are currently exploring different ways to store the preprocessed RDDs (e.g., in object storage) so we will be able to run more than a query reusing these RDDs without the necessity to ingest a digital collection repeatedly. Finally, we plan to create a web interface (e.g., virtual environment) for enabling researchers to select query(ies) to run against selected data collection(s) in a distributed computing environment (in a transparent way for researchers) and obtain the results in this interface. In this way, we hope to make this facility more accessible to humanities researchers hoping to access text mining facilities.

**ACKNOWLEDGEMENTS**

This work was funded by Scottish Enterprise as part of the Alan Turing Institute-Scottish Enterprise Data Engineering Programme, and by AHRC as part of the *Living with Machines* via the Strategic Priorities Fund.

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