

Dear SIGMOD Chair and Referees:

We thank the reviewers and chair for the very helpful feedback on our paper. We have addressed all of the concerns and include references to the revised text in this cover letter. We have significantly revised and clarified the presentation and exposition of the paper. To summarize the major changes:

1. We have revised the introduction and background sections to clarify the relationship between ActiveClean and related work that applies active learning for data cleaning (e.g., [16, 36, 35]).
2. We formalize our definition of dirty data and our model for data cleaning.
3. We formalize the two subproblems addressed in this work: correctly incrementally updating a convex statistical model with newly clean data, and making data cleaning more efficient.
4. We clarified our system architecture by highlighting essential components for correctness and optional optimizations. We also present a clear overview of the data flow in ActiveClean and which components are user-specified.
5. We have expanded our running example to clarify the key technical contributions of the paper and revised the exposition of the technical sections.
6. We included references to the related work suggested by the reviewing committee.

Below we address each reviewer comment in detail:

Meta Review Details

We would first like to clarify an important point about the subject and scope of our paper in relation to related work. Active learning (see survey [31]) is an increasingly popular technique to maximize the benefit of interactive data cleaning procedures [36, 16, 35, 19]. In typical applications of active learning, the data cleaning algorithm is posed as a supervised learning problem (e.g., classify pairs of records as duplicates [16]) where humans iteratively label a small number of proposed fixes. Active learning is the process of prioritizing supervisor input to a machine learning model that maximizes the convergence rate. Active learning algorithms use the current best model to acquire the most valuable future data.

The growing popularity of predictive models in data analytics [1, 5, 10, 21] presents a new opportunity to apply active learning for data cleaning. We explore how to prioritize cleaning data to maximally improve downstream statistical analysis. In other words, this paper explores the problem of model training *after* data cleaning as opposed to using a model *for* data cleaning. This problem is subtly different than active learning as currently applied in data cleaning. Current work uses machine learning models to enhance data cleaning by predicting clean data from dirty data. In ActiveClean, the machine learning model is part of the data analysis, and this requires predicting clean data from *clean* data. This small change raises a number of challenges in ensuring correctness and prioritization.

M1. There should be a formal vocabulary introduced early on. The exact idea of “dirty” here can be hard to follow: what is the exact error type(s) that the system is intended to clean?

We thank the reviewers for this important feedback and clarified that our system applies to data cleaning operations that can

be modeled as record-by-record mappings between two relations with the same schema. This model is sufficiently expressive for our experiments and a number of real-world dirty data scenarios such as attribute value canonicalization and missing value filling. We hope to explore additional data cleaning models that include record deduplication or schema mapping in future work. We added the following clarification to Section 2.1:

This paper explores a model for data error where attributes of records in a relation R are incorrect or missing. Formally, the data is corrupted in a way such that there exists a supervisor (human or algorithm, in either case expensive to query), that given a dirty record can return the unique correct clean record. Note that this does not cover errors that simultaneously affect multiple records like deduplication or schema transformation problems. This is modeled by a record-by-record cleaning operation $C(\cdot)$ can be applied to a record $r \in R$ to recover r_{clean} . Therefore, for every $r \in R_{\text{dirty}}$ there exists a unique $r' \in R_{\text{clean}}$, and a cleaning function $C(\cdot)$, is a function that maps each r to its corresponding r' . We assume that there is a featurization $F(\cdot)$ which is defined over both R_{dirty} and R_{clean} and maps rows to vectors in \mathbb{R}^d . So each row corresponds to one training example in the predictive model.

M2. Sections 5-7 are the technical core of the paper, and appear formal at the expense of aiding understanding. They appear to implement something that resembles active learning or bootstrapping, except inside the gradient descent loop. The motivation of some of this is not clear; is it necessary to integrate with the gradient descent? This is not how most active learning methods are implemented. Is it possible to implement these approaches in a way that is orthogonal to the SGD algorithm? The current writeup entangles some of these design choices.

Thank you for bringing this to our attention. In broadening interactive data cleaning to also include the downstream data analysis, the key new question is statistical validity. ActiveClean addresses two problems: (1) the correctness problem of how to update a dirty statistical model after data cleaning and (2) the efficiency problem of how to prioritize data cleaning based on the current best model. In the revised text, we formalize these two problems independently (Section 3.2 and Section 3.3 respectively).

We re-organized the paper to first describe a solution to problem (1). We argue that without an incremental optimization approach, there is a problem of model training after progressive data cleaning. Figure 2 describes straight-forward applications of progressive data cleaning and model training and why these approaches have issues. These issues can occur whether or not the data cleaning is interactive or passive, as the problem is not with the data cleaning but with the model updating procedure. The basic problem is that given the new data the model has to be incrementally updated rather than training on a mix of dirty and clean data. The integration with SGD is one approach to addressing problem (1).

Next, the paper describes the basic solution to problem (2). We motivate our specific choice of prioritization by describing optimality with respect to the SGD update, but we clarify the data flow and independence of these components. Finally, we separate optional optimizations which greatly improve the efficiency of ActiveClean in a final technical section.

M3. In general, the distinction between an “architecture” and an “algorithm that fits into the architecture” is quite unclear. The problem with SGD/Active Learning above is one example.

We have revised the architecture section to highlight: user inputs, data flows in ActiveClean, components that are essential for correctness, and components that are optimizations. We formalize algorithmic problems independent of the system architecture and

overview the architecture in pseudocode that describes the API for each of the components.

M4. The paper, and especially the technical sections, would benefit enormously from a detailed running example showing how the algorithm works

We have added a number of examples at the end of each of the technical sections. Section 4 (Architecture) ends with a intuitive end-to-end running example without technical details (Example 1). Section 5 (Update Problem) ends with an SVM example of how updates are propagated and calculated (Example 2). Section 7.1 (Detection) contains two examples for how the two different types of detectors can be used (Example 3 and 4). Section 7.2 (Estimation) ends with an example summarizing how linearization could be applied to SVM estimation.

M5. Some connections to related work that combines machine learning and data cleaning should be made. See the other reviewers' comments.

We highlight related work in the background section (Section 2.2):

There are a number of recent approaches that apply active learning to reduce number of records that need to be cleaned by a human. The main idea is to treat human input as binary labels in a supervised learning problem [27]. For example, Gokhale et al. [16] applies crowdsourcing to label likely pairs of records as duplicates. Yakout et al. [36] proposed a technique called Guided Data Repair, where human input was used to confirm proposed repairs that satisfy pre-declared data quality rules. In Gokhale et al. and Yakout et al., the goal of the learning model is to anticipate the human input and only require labels when uncertain.

Active learning is a very powerful and general concept that goes beyond binary labels and essentially argues that not all information is created equal. It iteratively uses the current best model to acquire the most valuable future data. We explore how to apply this idea to analysis-driven data cleaning. Some data are more relevant than others to a downstream analytics, and thus, more valuable to clean. However, the problem of prioritizing cleaning by using a user-specified downstream model is subtly different than active learning as currently applied in data cleaning. Using machine learning to enhance data cleaning means predicting clean data from dirty data. In ActiveClean, machine learning is the data analysis and this requires predicting clean data from clean data. This small change raises a number of challenges in ensuring correctness and prioritization.

It turns out that these two definitions are not incompatible and ActiveClean explores a more general problem setting. For example, rather than replacing the dirty data, corresponding clean data can be added into new columns. Thus, ActiveClean can be used to train models for some learning-based data cleaning algorithms. It can apply in a wider set of problems than existing work such as when data quality rules do not exist and numerical value imputation where human input is not binary.

In our related work section, we highlighted the suggested references to progressive data cleaning: *When data cleaning is expensive, it is desirable to apply it progressively, where analysts can inspect early results with only $k \ll N$ records cleaned. Progressive data cleaning is a well studied problem especially in the context of entity resolution [6, 2, 30, 17]. Prior work has focused the problem of designing data structures and algorithms to apply data cleaning progressively. This is challenging because many data cleaning algorithms require information from entire relations, and designing incremental models is a challenging problem even for just entity resolution. However, over the last 5 years a number of new results*

have expanded progressive data cleaning to rule based systems [26, 36, 35]. ActiveClean explores the statistical implications of using progressive data cleaning before high-dimensional predictive modeling.

Recently, in works such as SampleClean [33], the application (i.e., query workload) are used to inform data cleaning methodology. It suffices to clean a sample of data when the data will be used to answer aggregate queries. Sampling has also been applied to assess the number of duplicates in a relation [20]. When the workload is made up of aggregate queries, cleaning samples of data may suffice. Similarly, Bergman et al. explore the problem of query-oriented data cleaning [7]. Given a query they clean data relevant to that query.

Review 1 Details

R1.1: At first, the problem seems a bit too specialized. The abstract is too loaded with technical terms and a turn-off. This is then mitigated in the introduction.

As mentioned above, the abstract is (to me) overly technical and did not make me curious. I did not know off the bat what a convex loss model is, what importance sampling is, etc.

We revised the abstract to be more accessible:

A perennial challenge in data analytics is presence of dirty data in the form of missing, duplicate, incorrect, or inconsistent values. Although errors can be mitigated through data cleaning, it is often very time consuming. One approach to making data cleaning more efficient is to leverage knowledge of the downstream data analysis to prioritize those records that are most likely to affect the result. However, data analytics increasingly consist of statistical analysis and predictive modeling which can be highly sensitive to dirty data which is only partially cleaned. This paper explores reliable model update procedures and prioritization for progressive data cleaning. We focus on two problems for a popular class of models called convex loss models (e.g., linear regression and SVMs): (1) the methodological problem of updating a model with partially clean data, and (2) the algorithmic problem of using information from the model to prioritize data cleaning. The key insight of our framework is that data cleaning can be applied simultaneously with incremental optimization allowing for progressive cleaning while preserving provable properties. Evaluation on four real-world datasets suggests that for a fixed cleaning budget, ActiveClean returns more accurate models than uniform sampling and Active Learning when systematic corruption is sparse.

R1.2: Poor embrace of the duplicate detection problem (see details below). Your model of the cleaner seems to preclude any duplicate detection, which certainly cannot happen on individual records. Also your extension for a set of record does not fit the problem of duplicate detection. This is in contrast, for instance, to your ER example in the second column of that page. Appendix A.1 is misleading here, as you mention with Example 7 "in entity resolution problems..." but do not actually address that problem in the example. Fixing some common inconsistency is not entity resolution.

We apologize for the confusing terminology and have revised our paper to clarify that we do not address record-level deduplication. We formalized our data cleaning model to clarify this. However, we intended to bring attention to the fact that some types of attribute level inconsistencies are addressed in similar ways to record deduplication. For example, in our experimental dataset, the inconsistencies "Pfizer Inc.", "Pfizer Incorporated", and "Pfizer" can be addressed using a blocking and matching procedure similar to that used in record deduplication but over a projection. That said, we

have removed references to entity resolution and described this in more precise terms.

R1.3: Cheated by using a narrower font than required. Will have trouble with camera ready copy if publisher insists on proper font.

- I would not use "overview" as a verb... - 3.2: the detector select -> the detector selects - 4.3: Wrong quotation marks around "learning". - QED symbols on page 8 are ugly when placed directly after formula. - References need a clean up. Just as an example: Venue is missing for [24], year is mentioned 3 times for [8], [11], etc. Page numbers appear sporadically.

We have addressed all of the formatting and copy editing issues.

R1.4: There is some related work specifically addressing progressive/incremental entity resolution. You might want to point your readers to this.

E.g.

- Incremental entity resolution on rules and data, Whang et al. VLDB Journal 2014

- Progressive duplicate detection, Papenbrock et al., TKDE 2015

- Incremental record linkage, Gruenheid et al., PVLDB 2014

- Another work that is related is "Estimating the Number and Sizes of Fuzzy-Duplicate Clusters" by Heise et al. CIKM 2014, which also incrementally cleans samples of data to predict in this case the number of record matches.

Thank you for highlighting these references, and we have included them in our related work.

- Page 1, last paragraph in column 1 reads as if reference to [3] is a reaction to the work referenced in the previous sentence, i.e., the term "remains" is misleading. - I did not quite understand the short paragraph on crowd-sourcing. Why is this even relevant? I believe it would suffice to simply state that cleansing is expensive...

We appreciate the thorough feedback and have tightened up the writing in the introduction. In particular, we have consolidated the motivation to a single paragraph describing the expense of data cleaning.

Review 2 Details

R2.1: The definition of "clean data" is imprecise and not clear. It appears that "cleaning" in this system refers to entity resolution, cleaning w.r.t. dependencies, and possibly other actions as needed by the application. This makes it difficult to gauge overall accuracy when there are different interpretations of cleanliness. It is not clear how entity resolution and cleaning w.r.t. dependencies can be done holistically.

As mentioned above, we have included a formalizing of the data cleaning models addressed in this paper in Section 2.1.

R2.2: The paper describes a problem setting focused on modelling the iterative cleaning process rather than actual data management problems. The paper may be better suited at an ML venue.

We have revised the paper to emphasize its relevance to a database audience. We argue that the straight-forward application of existing progressive data cleaning methods, which have been widely proposed in the community can lead to error-prone and misleading results if used in conjunction with predictive modeling.

R2.3: Missing references to related work on interactive data cleaning. For the comparative evaluation, 2/3 techniques are ML based techniques, not interactive data cleaning systems. See D2.

D2: Data cleaning systems have also considered interactive en-

gagement with the user and the application of ML techniques.

i) Mohamed Yakout, Laure Berti-Equille, Ahmed K. Elmagarmid. Don't be SCARed: use SCalable Automatic REpairing with maximal likelihood and bounded changes. SIGMOD Conference 2013: 553-564 ii) Mohamed Yakout, Ahmed K. Elmagarmid, Jennifer Neville, Mourad Ouzzani, Ihab F. Ilyas. Guided data repair. PVLDB 4(5): 279-289 (2011).

We thank the reviewer for these references and have clarified the key differences with our work.

R2.4: Sampling is an important part of the framework and influences the accuracy of the cleaning. Yet, there is little discussion on sampling rate, or how a sample is chosen.

We revised Section 6 and 7 to be more precise about the sampling. Section 6 describes sampling without estimation or detection:

The model update received a sample with probabilities $p(\cdot)$. ActiveClean uses a sampling algorithm that selects the most valuable records to clean with higher probability.

Section 7 describes how sampling can be improved with estimation and detection and intuition on why those optimizations improve result accuracy.

R2.5: An end-to-end running example in Section 5 is needed to highlight the intuition of the cleaning process.

We have added a number of examples to describe the intuition for each of the technical sections.

Review 3 Details

R3.1: The authors do not distinguish between the system architecture and the individual issues that they are presenting.

As mentioned earlier we now distinguish between the correctness problem and the efficiency problem. We have revised to emphasize that ActiveClean is one implementation of algorithms that address this problem.

R3.2: The paper uses lots of definitions, and a multitude of that do not necessarily contribute to readability. Without being an expert in the field, I found it extremely difficult to follow the paper as it touches upon multiple problems at the same time: data cleaning, model training, convex analytics, etc., uses definitions, notation and lots of examples that did not allow me to have a global understanding of the work.

I would prefer to have a more focused paper on one of these aspects that has concrete goals and then, having an overview of the architecture of the system as a small section. I believe that the architecture should not be the focus and the skeleton of this paper. Instead, I believe that the authors could focus on the individual problems.

We have revised the paper to improve readability. In particular, we have consolidated a number of sections and moved non-essential equations to the appendix. We do however believe that data cleaning needs to be understood as an essential part of the model training process. Data analysis is increasingly using predictive models and these models are highly sensitive to data cleaning procedures.

ActiveClean: Progressive Data Cleaning For Convex Data Analytics

ABSTRACT

A perennial challenge in data analytics is presence of dirty data in the form of missing, duplicate, incorrect, or inconsistent values. Although errors can be mitigated through data cleaning, it is often very time consuming. One approach to making data cleaning more efficient is to leverage knowledge of the downstream data analysis to prioritize those records that are most likely to affect the result. However, data analytics increasingly consist of statistical analysis and predictive modeling which can be highly sensitive to dirty data which is only partially cleaned. This paper explores reliable model update procedures and prioritization for progressive data cleaning. We focus on two problems for a popular class of models called convex loss models (e.g., linear regression and SVMs): (1) the methodological problem of updating a model with partially clean data, and (2) the algorithmic problem of using information from the model to prioritize data cleaning. The key insight of our framework is that data cleaning can be applied simultaneously with incremental optimization allowing for progressive cleaning while preserving provable properties. Evaluation on four real-world datasets suggests that for a fixed cleaning budget, ActiveClean returns more accurate models than uniform sampling and Active Learning when systematic corruption is sparse.

1. INTRODUCTION

Data are susceptible to various forms of corruption such as missing, incorrect, or inconsistent representations. Data analysts report that data cleaning is one of the most time consuming steps in the analysis process [3]. Cleaning can require a significant amount of developer effort in writing software or rules to fix the corruption. Due to this expense, there are a number of techniques to avoid cleaning entire datasets such as sampling [33], identifying the most relevant records to queries of interest [7], and active learning [16].

These approaches are effective because they leverage knowledge about how the cleaned data will be used. For example, sampling may suffice when the downstream queries on the cleaned data are aggregates and active learning applies when cleaned data will be used to train a statistical model. Active learning (see survey [31]) is an increasingly popular technique to maximize the benefit of interactive data cleaning procedures [36, 16, 35, 19]. In typical applications of active learning, the data cleaning algorithm is posed as a supervised learning problem (e.g., classify pairs of records as duplicates [16]) where humans iteratively label a small number of proposed fixes. Active learning is a family of algorithms that prioritize supervisor input to a machine learning model in a way that maximizes the convergence rate. The growing popularity of predictive models in data analytics [1, 5, 10, 21] presents a new application for active learning. In principle, similar ideas can be applied to prioritize cleaning records that maximally affect a downstream

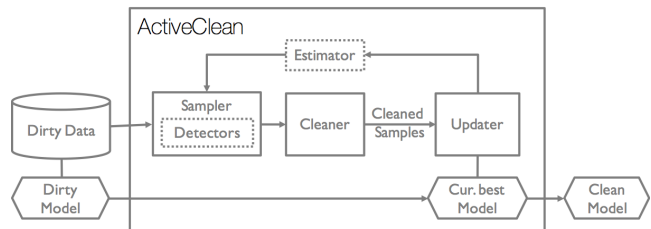


Figure 1: ActiveClean allows users to train predictive models while progressively cleaning data. The framework adaptively selects the best data to clean and can optionally integrate with pre-defined detection rules and estimation algorithms for improved confidence.

statistical model. In other words, this paper explores the problem of model training *after* data cleaning as opposed to using a model *for* data cleaning.

In broadening interactive data cleaning to also include the downstream data analysis, the key new question is statistical validity. The analyst may query and evaluate the model **progressively** with $k \ll N$ records cleaned, and clear semantics about the accuracy of the intermediate results are needed. Unfortunately, training a model on a mixture of dirty and clean data can lead to misleading relationships in even simple scenarios (Figure 2). An alternative is to clean k records and to disregard all of the remaining dirty records (e.g., sampling [33]). While this avoids the mixing problem, accurate model training may require a large amount of training data and k examples may not be enough for a viable model. Furthermore, if the k records are not selected uniformly at random, the trained model might be highly biased. The errors and inefficiencies introduced by these three problems may dominate any gains from data cleaning, leading to unreliable or misleading conclusions about data or model quality.

We present a system called ActiveClean which applies progressive data cleaning actively while preserving the statistical validity of downstream predictive analysis. We focus on two subproblems for a popular class of models called convex loss models (e.g., includes linear regression and SVMs): (1) the correctness problem of estimating and bounding the error in a model trained from dirty and clean data, and (2) the efficiency problem of actively selecting data to clean while preserving correctness. We show that instead of re-training the model, the model can be incrementally maintained with gradient descent given newly cleaned data, a technique that is guaranteed to converge under suitable conditions. Such guarantees allow analysts to trust early results during the data exploration and cleaning phase and facilitate reliable comparisons between: expensive data cleaning operations, different types of models, and different featurization techniques.

The ActiveClean architecture (Figure 1) consists of a *detector*, *sampler*, *cleaner*, *update process*, and *estimator*. The cleaner is a user-provided data cleaning technique, and ActiveClean provides the remaining components to apply the cleaner progressively. We analyze a model where the user specifies a cleaning function $C(\cdot)$ where given any record, it returns a cleaned version of the record. To summarize the contributions:

- **Correctness** (Section 5). We show how data cleaning can be integrated with stochastic gradient descent to ensure convergence even with non-uniform samples. This update is guaranteed to converge, and for batch size b and iterations T , converges with rate $O(\frac{1}{\sqrt{bT}})$.
- **Efficiency** (Section 6). We derive a theoretical optimal sampling distribution that minimizes the update error and an approximation algorithm to estimate the theoretical optimum.
- **Detection** (Section 7.1). We show how ActiveClean can be integrated with optional dirty data detection to guide data cleaning towards records expected to be dirty.
- The experiments evaluate these components on four datasets with real and synthetic corruption (Section 8). Results suggest that for a fixed cleaning budget, ActiveClean returns more accurate models than uniform sampling and Active Learning when systematic corruption is sparse.

2. BACKGROUND AND PROBLEM SETUP

This section describes the challenges in predictive modeling after progressive data cleaning and describes concrete example applications.

2.1 Dirty Data Model

This paper explores a model for data error where attributes of records in a relation R are incorrect or missing. Formally, the data is corrupted in a way such that there exists a supervisor (human or algorithm, in either case expensive to query), that given a dirty record can return the unique correct clean record. Note that this does not cover errors that simultaneously affect multiple records like deduplication or schema transformation problems. This is modeled by a record-by-record cleaning operation $C(\cdot)$ can be applied to a record $r \in R$ to recover r_{clean} . Therefore, for every $r \in R_{dirty}$ there exists a unique $r' \in R_{clean}$, and a cleaning function $C(\cdot)$, is a function that maps each r to its corresponding r' . We assume that there is a featurization $F(\cdot)$ which is defined over both R_{dirty} and R_{clean} and maps rows to vectors in \mathbb{R}^d . So each row corresponds to one training example in the predictive model.

2.2 Active Learning and Data Cleaning

There are a number of recent approaches that apply active learning to reduce number of records that need to be cleaned by a human. The main idea is to treat human input as binary labels in a supervised learning problem [27]. For example, Gokhale et al. [16] applies crowdsourcing to label likely pairs of records as duplicates. Yakout et al. [36] proposed a technique called Guided Data Repair, where human input was used to confirm proposed repairs that satisfy pre-declared data quality rules. In Gokhale et al. and Yakout et al., the goal of the learning model is to anticipate the human input and only require labels when uncertain.

Active learning is a very powerful and general concept that goes beyond binary labels and essentially argues that not all information is created equal. It iteratively uses the current best model to acquire the most valuable future data. We explore how to apply this idea to analysis-driven data cleaning. Some data are more relevant than others to a downstream analytics, and thus, more valuable

to clean. However, the problem of prioritizing cleaning by using a user-specified downstream model is subtly different than active learning as currently applied in data cleaning. Using machine learning to enhance data cleaning means predicting clean data from dirty data. In ActiveClean, machine learning is the data analysis and this requires predicting clean data from *clean data*. This small change raises a number of challenges in ensuring correctness and prioritization.

It turns out that these two definitions are not incompatible and ActiveClean explores a more general problem setting. For example, rather than replacing the dirty data, corresponding clean data can be added into new columns. Thus, ActiveClean can be used to train models for some learning-based data cleaning algorithms. It can apply in a wider set of problems than existing work such as when data quality rules do not exist and numerical value imputation where human input is not binary.

2.3 Correctness

The key challenge in ActiveClean is correctness of the statistical model. The straight-forward application of progressive or incremental data cleaning methods proposed in the literature is to fix those errors in place. Suppose $k \ll N$ records are cleaned, but all of the remaining dirty records are retained in the dataset. Figure 2 highlights the dangers of this approach on a very simple dirty dataset and a linear regression model i.e., the best fit line for two variables. One of the variables is systematically corrupted with a translation in the x-axis (Figure 2a). The dirty data is marked in brown and the clean data in green, and their respective best fit lines are in blue. After cleaning only two of the data points (Figure 2b), the resulting best fit line is in the opposite direction of the true model. This is a well-known phenomenon called Simpson's paradox, where mixtures of different populations of data can result in spurious relationships [32]. Training models on a mixture of dirty and clean data can lead to unreliable results, where artificial trends introduced by the mixture can be confused for the effects of data cleaning.

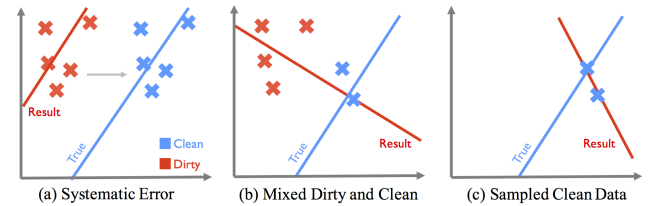


Figure 2: (a) Systematic corruption in one variable can lead to a shifted model. (b) Mixed dirty and clean data results in a less accurate model than no cleaning. (c) Small samples of only clean data can result in similarly inaccurate models.

An alternative is to avoid the dirty data altogether instead of mixing the two populations. Suppose k records are randomly sampled from the dataset and cleaned. The model is trained only on the cleaned sample of data. This is similar to SampleClean [33], which was proposed to approximate the results of aggregate queries by applying them to a clean sample of data. However, high-dimensional models are highly sensitive to sample size. Figure 2c illustrates that, even in two dimensions, models trained from small samples can be as incorrect as the mixing solution described before.

2.4 Intuitive Solution

Our first goal is to find an update methodology that avoids Simpson's Paradox and the strong dependence on sample size. Instead

of mixing dirty and clean data, ActiveClean uses a model trained on the dirty data as an initialization, and then iteratively updates this model using samples of clean data. The intuition is that this algorithm smoothly transitions the model from one population (the dirty data) to another (the clean data), leading to provable guarantees about intermediate results. Our next goal is to prioritize which data to clean based on information from the model. We design ActiveClean to make greater progress at these small sample sizes using the dirty model as an initialization. Doing so is not trivial since data may look unimportant to a dirty model but when cleaned are very important. Also, data cleaning and model training can happen at very different time scales, we have to carefully budget our effort to ensure that any optimizations actually address rate-determining steps in the workflow.

2.5 Use Case: Dollars for Docs [2]

ProPublica collected a dataset of corporate donations to doctors to analyze conflicts of interest. They reported that some doctors received over \$500,000 in travel, meals, and consultation expenses [4]. ProPublica laboriously curated and cleaned a dataset from the Centers for Medicare and Medicaid Services that listed nearly 250,000 research donations, and aggregated these donations by physician, drug, and pharmaceutical company. We collected the raw unaggregated data and explored whether suspect donations could be predicted with a model. This problem is typical of analysis scenarios based on observational data seen in finance, insurance, medicine, and investigative journalism. The dataset has the following schema:

```
Contribution(pi_specialty, drug_name, device_name,
             corporation, amount, dispute, status)
```

`pi_specialty` is a textual attribute describing the specialty of the doctor receiving the donation.

`drug_name` is the branded name of the drug in the research study (null if not a drug).

`device_name` is the branded name of the device in the study (null if not a device).

`corporation` is the name of the pharmaceutical providing the donation.

`amount` is a numerical attribute representing the donation amount. `dispute` is a Boolean attribute describing whether the research was disputed.

`status` is a string label describing whether the donation was allowed under the declared research protocol. The goal is to predict disallowed donation.

However, this dataset is very dirty, and the systematic nature of the data corruption can result in an inaccurate model. On the ProPublica website [2], they list numerous types of data problems that had to be cleaned before publishing the data (see Appendix I). For example, the most significant donations were made by large companies whose names were also more often inconsistently represented in the data e.g., "Pfizer Inc.", "Pfizer Incorporated", "Pfizer". In a scenario such as this one, the effect of systematic error can be serious. Duplicate representations could artificially reduce the correlation between these entities and suspected contributions. There were nearly 40,000 of the 250,000 records that had either naming inconsistencies or other inconsistencies in labeling the allowed or disallowed `status`. Without data cleaning and using a Support Vector Machine model, the detection rate of suspect donations was 66%. Applying the data cleaning to the entire dataset improved this rate to 97% in the clean data (Section 8.6.1), and the experiments describe how ActiveClean can achieve an 80% detection rate for less than 4000 records cleaned.

3. PROBLEM FORMALIZATION

This section formalizes the problem addressed in the paper.

3.1 Convex Models

This work focuses on an initial class of well analyzed predictive analytics problems; ones that can be expressed as the minimization of convex loss functions. Convex loss minimization problems are amenable a variety of incremental optimization methodologies with provable guarantees (see Friedman, Hastie, and Tibshirani [15] for an introduction). Examples includes all generalized linear models (including linear and logistic regression), all variants of support vector machines, and in fact, means and medians are also special cases.

Formally, for labeled training examples $\{(x_i, y_i)\}_{i=1}^N$, the problem is to find a vector of *model parameters* θ by minimizing a loss function ϕ over all training examples:

$$\theta^* = \arg \min_{\theta} \sum_{i=1}^N \phi(x_i, y_i, \theta)$$

Where ϕ is a convex function in θ . For example, in a linear regression ϕ is:

$$\phi(x_i, y_i, \theta) = \|\theta^T x_i - y_i\|_2^2$$

Typically, a *regularization* term $r(\theta)$ is added to this problem. $r(\theta)$ penalizes high or low values of feature weights in θ to avoid over-fitting to noise in the training examples.

$$\theta^* = \arg \min_{\theta} \sum_{i=1}^N \phi(x_i, y_i, \theta) + r(\theta)$$

In this work, without loss of generality, we will include the regularization as part of the loss function i.e., $\phi(x_i, y_i, \theta)$ includes $r(\theta)$.

3.2 Problem 1. Correct Update Problem

Let $R_{dirty} \subseteq R$ be the subset of records that are dirty, and S be a sample (possibly non-uniform but with known probabilities) of the records R_{dirty} . ActiveClean applies the user specified cleaning function $C(\cdot)$ to the sample:

$$S_{clean} = C(S)$$

Given newly cleaned data S_{clean} and a dirty model $\theta^{(d)}$, the model update problem is to calculate θ^{new} . θ^{new} will have some error between with respect to the true model $\theta^{(c)}$ (if the entire dataset is cleaned):

$$error(\theta^{new}) = \|\theta^{new} - \theta^{(c)}\|$$

We call the update algorithm "reliable" if the expected error is upper bounded by a monotonically decreasing function f of the amount of cleaned data:

$$\mathbb{E}(error(\theta^{new})) = O(f(|S_{clean}|))$$

and is also upper bounded by a monotonically increasing function of the initial error:

$$\mathbb{E}(error(\theta^{new})) = O(g(\|\theta^{(d)} - \theta^{(c)}\|))$$

Intuitively, reliable means that more cleaning and less initial error should imply more accuracy; avoiding the pitfalls of dimensionality and Simpson's paradox.

The Correct Update Problem is to reliably update the model $\theta^{(d)}$ with a sample of cleaned data.

3.3 Problem 2. Efficiency Problem

The efficiency problem is to select S_{clean} such that the expected error $\mathbb{E}(\text{error}(\theta^{new}))$ is minimized. ActiveClean uses previously cleaned data to estimate the value of data cleaning on new records. Then it draws a sample of records $S_{dirty} \subseteq R_{dirty}$. This is a non-uniform sample where each record r has a sampling probability $p(r)$ based on the estimates. We derive the optimal sampling distribution for the SGD updates, and show how the theoretical optimal can be approximated.

The Efficiency Problem is to select a sampling distribution $p(\cdot)$ over all records such that the expected error w.r.t to the model if trained on fully clean data is minimized.

3.4 Metrics

There are two standard metrics that we will use to measure the performance of ActiveClean:

Model Error. Let θ be the model trained with ActiveClean, and let θ^* be the model trained on the same data if all of the records were cleaned. Then the model error is defined as $\|\theta - \theta^*\|$.

Testing Error. Let θ be the model trained with ActiveClean, and let θ^* be the model trained on the same data if all of the records were cleaned. Let $T(\theta)$ be the out-of-sample testing error when the dirty model is applied to the clean data, and $T(\theta^*)$ be the test error when the clean model is applied to the clean data. The testing error is defined as $T(\theta) - T(\theta^*)$.

4. ARCHITECTURE

This section presents the ActiveClean architecture.

4.1 Overview

Figure 1 illustrates the ActiveClean architecture. The dotted boxes describe optional components that the user can supply to improve the efficiency of the system.

4.1.1 User Input

To use ActiveClean, the user provides the following:

Convex Model and Initialization. The user provides a predictive model specified as a convex loss optimization problem $L(\cdot)$ and a function $F(\cdot)$ that featurizes the data by mapping a record to a feature vector x and label y pair.

Cleaning Function. The data cleaning is specified as a function $C(\cdot)$ that maps dirty records to clean records as per our definition in Section 2.1. The record-by-record cleaning model is not a fundamental restriction of this approach, and in the extensions (Section A.1), there is a discussion on a compatible “set of records” cleaning model. Consider the case where an analyst finds a dirty record, and is able to fix all records (possibly outside the sample) the with same error throughout the dataset efficiently.

Budget. At initialization, there are two hyperparameters to set, the cleaning budget k and the batch size b (the number of iterations is $T = \frac{k}{b}$). We discuss how to set b and the tradeoffs in setting a larger or smaller b in Section 5.

4.1.2 Data Flow

The system first trains the model $L(\cdot)$ on the dirty dataset to find an initial model $\theta^{(d)}$ that the system will subsequently improve. The *Sampler* selects a sample of size b records from the dataset and passes the sample to the *cleaner*, which executes $C(\cdot)$ for each sample record and outputs their cleaned versions. The updater uses the cleaned sample to update the weights of the model, thus moving the model closer to the true cleaned model (in expectation). Finally, the

system either terminates due to a stopping condition (e.g., $C(\cdot)$ has been called a maximum number of times k , or training error convergence), or passes control to the *Sampler* for the next iteration.

A user provided *Detector* can be used to identify records that are more likely to be dirty, and thus improves the likelihood that the next sample will contain true dirty records. Furthermore, the *Estimator* uses previously cleaned data to estimate the effect that cleaning a given record will have on the model. These components can be used separately (if only one is supplied) or together to focus the system’s cleaning efforts on records that will most improve the model. Sections 7 describes several instantiations of these components for different data cleaning problems.

4.2 Pseudocode and Example

To summarize in pseudocode:

1. Init(`dirty_data`, `cleaned_data`, `dirty_model`, `batch`, `iter`)
2. For each t in $\{1, \dots, T\}$
 - (a) `dirty_sample` = `Sampler`(`dirty_data`, `sample_prob`, `detector`, `batch`)
 - (b) `clean_sample` = `Cleaner`(`dirty_sample`)
 - (c) `current_model` = `Update`(`current_model`, `sample_prob`, `clean_sample`)
 - (d) `cleaned_data` = `cleaned_data` + `clean_sample`
 - (e) `dirty_data` = `dirty_data` - `clean_sample`
 - (f) `sample_prob` = `Estimator`(`dirty_data`, `cleaned_data`, `detector`)
 - (g) `detector` = `DetectorUpdater`(`detector`, `cleaned_data`)
3. Output: `current_model`

Here is an example application of ActiveClean:

EXAMPLE 1. *The analyst first trains an SVM model on the dirty data ignoring the effects of the errors resulting in a model $\theta^{(d)}$. She decides that she has a budget of cleaning 100 records, and decides to clean the 100 records in batches of 10 (set based on how fast she can clean the data, and how often she wants to see an updated result). She initializes ActiveClean with $\theta^{(d)}$. ActiveClean samples an initial batch of 10 records. She manually cleans those records by merging similar drug names, making corporation names consistent, and fixing incorrect labels. After each batch, the model is updated with the most recent cleaning results $\theta^{(t)}$. The model improves after each iteration. After $t = 10$ of cleaning, the analyst has an accurate model trained with 100 cleaned records but still utilizes the entire dirty data.*

5. UPDATES WITH CORRECTNESS

This section describes one approach for reliable model updates. The updater assumes that it is given a sample of data S_{dirty} from R_{dirty} where $i \in S_{dirty}$ has a known sampling probability $p(i)$. The following sections show how to optimize $p(i)$ and the analysis in this section applies for any sampling distribution $p(\cdot)$.

5.1 Geometric Derivation

The update algorithm intuitively follows from the convex geometry of the problem. Consider this problem in one dimension (i.e., the parameter θ is a scalar value), so then the goal is to find the minimum point (θ) of a curve $l(\theta)$. The consequence of dirty data is that the wrong loss function is optimized. Figure 3A illustrates the consequence of this optimization. The red dotted line shows the loss function on the dirty data. Optimizing this loss function

finds θ that at the minimum point (red star). However, the true loss function (w.r.t to the clean data) is in blue, thus this optimal value on the dirty data is in fact a suboptimal point on clean curve (red circle).

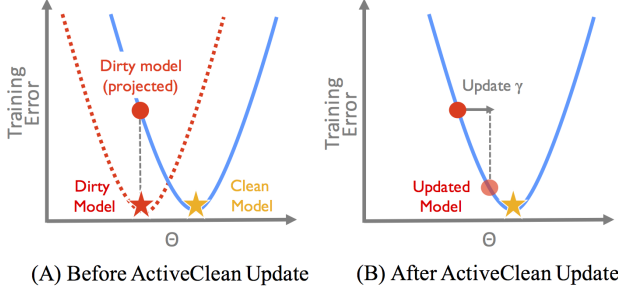


Figure 3: (A) A model trained on dirty data can be thought of as a sub-optimal point w.r.t to the clean data. (B) The gradient gives us the direction to move the suboptimal model to approach the true optimum.

The optimal clean model $\theta^{(c)}$ is visualized as a yellow star. The first question is which direction to update θ (i.e., left or right). For this class of models, given a suboptimal point, the direction to the global optimum is the gradient of the loss function. The gradient is a d -dimensional vector function of the current model θ and the clean data. Given this direction, ActiveClean needs to update $\theta^{(d)}$ some distance γ (Figure 3B):

$$\theta^{new} \leftarrow \theta^{(d)} - \gamma \cdot \nabla \phi(\theta^{(d)})$$

At the optimal point, the magnitude of the gradient will be zero. So intuitively, this approach iteratively moves the model downhill (transparent red circle) – correcting the dirty model until the desired accuracy is reached. However, this formulation gradient depends on all of the clean data which is not available and ActiveClean will have to approximate this gradient from a sample. The main intuition is that if the gradient steps are on average correct, the model still moves downhill albeit with a reduced convergence rate proportional to the inaccuracy of the sample-based estimate.

To derive a sample-based update rule, the most important property is that sums commute with derivatives and gradients. The convex loss class of models are sums of losses, so given the current best model θ , the gradient $g^*(\theta)$ is:

$$g^*(\theta) = \nabla \phi(\theta) = \frac{1}{N} \sum_i \nabla \phi(x_i^{(c)}, y_i^{(c)}, \theta)$$

ActiveClean needs to estimate $g^*(\theta)$ from a sample S is drawn from the dirty data R_{dirty} so this sum has two components the gradient on the already clean data g_C which can be computed without cleaning and g_S the gradient estimate from a sample of dirty data to be cleaned:

$$g(\theta) = \frac{|R_{clean}|}{|R|} \cdot g_C(\theta) + \frac{|R_{dirty}|}{|R|} \cdot g_S(\theta)$$

g_C can be calculated by applying the gradient to all of the already cleaned records:

$$g_C(\theta) = \frac{1}{|R - R_{dirty}|} \sum_{i \in R - R_{dirty}} \nabla \phi(x_i^{(c)}, y_i^{(c)}, \theta)$$

g_S can be estimated from a sample by taking the gradient w.r.t each record, and re-weighting the average by their respective sampling probabilities. Before taking the gradient the cleaning function $C(\cdot)$

is applied to each sampled record. Therefore, let S be a sample of data, where each $i \in S$ is drawn with probability $p(i)$:

$$g_S(\theta) = \frac{1}{|S|} \sum_{i \in S} \frac{1}{p(i)} \nabla \phi(x_i^{(c)}, y_i^{(c)}, \theta)$$

Then, at each iteration t , the update becomes:

$$\theta^{(t+1)} \leftarrow \theta^{(t)} - \gamma \cdot g(\theta^{(t)})$$

5.2 Model Update Algorithm

To summarize, the algorithm is initialized with $\theta^{(1)} = \theta^{(d)}$ which is the dirty model. There are three user set parameters the budget k , batch size b , and the step size γ . In the following section, we will provide references from the convex optimization literature that allow the user to appropriately select these values. At each iteration $t = \{1, \dots, T\}$, the cleaning is applied to a batch of data b selected from the set of candidate dirty records R_{dirty} . Then, an average gradient is estimated from the cleaned batch and the model is updated. Iterations continue until $k = T \cdot b$ records are cleaned.

1. Calculate the gradient over the sample of clean data and call the result $g_S(\theta^{(t)})$
2. Calculate the average gradient over all the data in $R_{clean} = R - R_{dirty}$, and call the result $g_C(\theta^{(t)})$
3. Apply the following update rule:

$$\theta^{(t+1)} \leftarrow \theta^{(t)} - \gamma \cdot \left(\frac{|R_{dirty}|}{|R|} \cdot g_S(\theta^{(t)}) + \frac{|R_{clean}|}{|R|} \cdot g_C(\theta^{(t)}) \right)$$

5.3 Analysis with Stochastic Gradient Descent

This update policy can be formalized as a class of very well studied algorithms called Stochastic Gradient Descent. This provides a theoretical framework to understand and analyze the update rule and bound the error. Mini-batch stochastic gradient descent (SGD) is an algorithm for finding the optimal value given the convex loss and data. In mini-batch SGD, random subsets of data are selected at each iteration and the average gradient is computed for every batch.

One key difference with traditional SGD models is that ActiveClean applies a *full* gradient step on the already clean data and averages this with a stochastic gradient step (i.e., calculated from a sample) on the dirty data. Therefore, ActiveClean iterations can take multiple passes over the clean data but at most a single cleaning pass of the dirty data. This update method can be thought of as a variant of SGD that lazily materializes the clean value. As data is sampled at each iteration, data is cleaned when needed by the optimization. It is well known that even for an arbitrary initialization SGD makes significant progress in less than one epoch (a pass through the entire dataset) [9]. In practice, the dirty model can be much more accurate than an arbitrary initialization as corruption may only affect a few features and combined with the full gradient step on the clean data the updates coverage very quickly.

Setting the step size γ : There is extensive literature in machine learning for choosing the step size γ appropriately. γ can be set either to be a constant or decayed over time. Many machine learning frameworks (e.g., MLLib, Sci-kit Learn, Vowpal Wabbit) automatically set learning rates or provide different learning scheduling frameworks. In the experiments, we use a technique called inverse scaling where there is a parameter $\gamma_0 = 0.1$, and at each iteration it decays to $\gamma_t = \frac{\gamma_0}{|S|t}$.

Setting the batch size: The batch size should be set by the user to have the desired properties. Larger batches will take longer to clean and will make more progress towards the clean model, but

will have less frequent model updates. On the other hand, smaller batches are cleaned faster and have more frequent model updates but make less progress. The overheads introduced by ActiveClean are more evident at smaller batch sizes. There are diminishing returns to increasing the batch size $O(\frac{1}{\sqrt{b}})$. Empirically, in the experiments, batch sizes of 50 converge the fastest. If a data cleaning technique requires a larger batch size than this, i.e., data cleaning is fast enough that the iteration overhead is significant compared to cleaning 50 records, ActiveClean can apply the updates in smaller batches. For example, the batch size set by the user might be $b = 1000$, but the model updates after every 50 records are cleaned. This dissociates the batching requirements of SGD and the batching requirements of the data cleaning technique.

5.3.1 Convergence Conditions and Properties

Convergence properties of batch SGD formulations have been well studied [11]. Essentially, if the gradient estimate is unbiased and the step size is appropriately chosen, the algorithm is guaranteed to converge. In the appendix, we show that the gradient estimate from ActiveClean is indeed unbiased and our choice of step size is one that is established to converge. The convergence rates of SGD are also well analyzed [11, 8, 37]. This gives a bound on the error of intermediate models and the expected number of steps before achieving a model within a certain error. For a general convex loss, a batch size b , and T iterations, the convergence rate is bounded by $O(\frac{\sigma^2}{\sqrt{bT}})$. σ^2 is the variance in the estimate of the gradient at each iteration:

$$\mathbb{E}(\|g_S - g^*\|^2)$$

If the loss is non-convex, the update procedure will converge towards a local minimum rather than the global minimum (See Appendix A.3).

5.4 Example

This example describes an application of the update algorithm.

EXAMPLE 2. Recall that the analyst has a dirty SVM model on the dirty data $\theta^{(d)}$. She decides that she has a budget of cleaning 100 records, and decides to clean the 100 records in batches of 10 (set based on how fast she can clean the data, and how often she wants to see an updated result). All of the data is initially treated as dirty with $R_{dirty} = R$ and $R_{clean} = \emptyset$. The gradient of a basic SVM is given by the following function:

$$\nabla\phi(x, y, \theta) = \begin{cases} -y \cdot x & \text{if } y \cdot x \cdot \theta \leq 1 \\ 0 & \text{if } y \cdot x \cdot \theta \geq 1 \end{cases}$$

For each iteration t , a sample of 10 records S is drawn from R_{dirty} . ActiveClean then applies the cleaning function to the sample:

$$\{(x_i^{(c)}, y_i^{(c)})\} = \{C(i) : \forall i \in S\}$$

Using these values, ActiveClean estimates the gradient on the newly cleaned data:

$$g_S(\theta) = \frac{1}{10} \sum_{i \in S} \frac{1}{p(i)} \nabla\phi(x_i^{(c)}, y_i^{(c)}, \theta)$$

ActiveClean also applies this gradient to the already clean data (initially non-existent):

$$g_C(\theta) = \frac{1}{|R_{clean}|} \sum_{i \in R - R_{dirty}} \nabla\phi(x_i^{(c)}, y_i^{(c)}, \theta)$$

Then, it calculates the update rule:

$$\theta^{(t+1)} \leftarrow \theta^{(t)} - \gamma \cdot \left(\frac{|R_{dirty}|}{|R|} \cdot g_S(\theta^{(t)}) + \frac{|R_{clean}|}{|R|} \cdot g_C(\theta^{(t)}) \right)$$

Finally, $R_{dirty} \leftarrow R_{dirty} - S$, $R_{clean} \leftarrow R_{clean} + S$, and continue to the next iteration.

6. EFFICIENCY WITH SAMPLING

The model update received a sample with probabilities $p(\cdot)$. For any distribution where $p(\cdot) > 0$, we can preserve correctness. ActiveClean uses a sampling algorithm that selects the most valuable records to clean with higher probability.

6.1 Oracle Sampling Problem

Recall that the convergence rate of an SGD algorithm is bounded by σ^2 which is the variance of the gradient. Intuitively, the variance measures how accurately the gradient is estimated from a uniform sample. Other sampling distributions, while preserving the sample expected value, may have a lower variance. Thus, the oracle sampling problem is defined as a search over sampling distributions to find the minimum variance sampling distribution.

DEFINITION 1 (ORACLE SAMPLING PROBLEM). Given a set of candidate dirty data R_{dirty} , $\forall r \in R_{dirty}$ find sampling probabilities $p(r)$ such that over all samples S of size k it minimizes:

$$\mathbb{E}(\|g_S - g^*\|^2)$$

It can be shown that the optimal distribution over records in R_{dirty} is probabilities proportional to:

$$p_i \propto \|\nabla\phi(x_i^{(c)}, y_i^{(c)}, \theta^{(t)})\|$$

We provide proofs and theoretical justification in appendix, but intuitively, records with higher gradients should be sampled with higher probability as they affect the update more significantly. However, this cannot exclude records with lower gradients as that would induce a bias hurting convergence. The problem is that this optimal distribution leads to a chicken-and-egg problem: the optimal sampling distribution requires knowing $(x_i^{(c)}, y_i^{(c)})$, however, cleaning is required to know those values.

6.2 Dirty Gradient Solution

Such an oracle does not exist, and one solution is to use the gradient w.r.t to the dirty data:

$$p_i \propto \|\nabla\phi(x_i^{(d)}, y_i^{(d)}, \theta^{(t)})\|$$

It turns out that this solution works reasonably well in practice on our experimental datasets and has been studied in Machine Learning as the Expected Gradient Length heuristic [31]. The contribution in this work is integrating this heuristic with statistically valid updates. However, intuitively, approximating the oracle as closely as possible can result in improved prioritization. The subsequent section describes two components, the detector and estimator, that can be used to achieve this. Our experiments suggest up to a 2x improvement in convergence when using these optional optimizations (Section 8.3.2).

7. OPTIMIZATIONS

In this section, we describe two approaches to optimization, the *Detector* and the *Estimator*, that improves the efficiency of the cleaning process. Both approaches are designed to increase the likelihood that the *Sampler* will pick dirty records that, once cleaned, most move the model towards the true clean model.

7.1 The Detector

ActiveClean improves the progress of each update iteration by intelligently partitioning the data into expected dirty and clean partitions. This ensures that sampling draws data that are likely to be dirty.

7.1.1 Goals

The detector returns two important aspects of a record: (1) whether the record is dirty, and (2) if it is dirty, what is wrong with the record. The sampler can use (1) to select a subset of dirty records to sample at each batch. The estimator can use (2) estimate the value of data cleaning based on other records with the same corruption. ActiveClean supports two types of detectors: *a priori* and *adaptive*. In the *a priori* case, there is a way to select the set of dirty records before any cleaning. This case is possible for some types of data errors. In the adaptive case, detection is learned as data is cleaned.

7.1.2 A Priori Case

For many types of dirtiness such as missing attribute values and constraint violations, it is possible to efficiently enumerate a set of corrupted records and determine how the records are corrupted.

DEFINITION 2 (A PRIORI DETECTION). Let r be a record in R . An *a priori* detector is a detector that returns a Boolean of whether the record is dirty and a set of columns e_r that are dirty.

$$D(r) = (\{0, 1\}, e_r)$$

From the set of columns that are dirty, find the corresponding features that are dirty f_r and labels that are dirty l_r .

Here are example use cases of this definition using data cleaning methodologies proposed in the literature.

Constraint-based Repair: One model for detecting errors involves declaring constraints on the database.

Detection. Let Σ be a set of constraints on the relation \mathcal{R} . In the detection step, the detector selects a subset of records $\mathcal{R}_{dirty} \subseteq \mathcal{R}$ that violate at least one constraint. The set e_r is the set of columns for each record which have a constraint violation.

EXAMPLE 3. An example of a constraint on the running example dataset is that the *status* of a contribution can be only “allowed” or “disallowed”. Any other value for *status* is an error.

7.1.3 Adaptive Detection

A priori detection is not possible in all cases. The detector also supports adaptive detection where detection is learned from previously cleaned data. Note that this “learning” is distinct from the “learning” at the end of the pipeline. The challenge in formulating this problem is that detector needs to describe how the data is dirty (e.g. e_r in the *a priori* case). The detector achieves this by categorizing the corruption into u classes. These classes are corruption categories that do not necessarily align with features, but every record is classified with at most one category. For example, suppose there are records with outliers and missing values, there are three classes of corruption: outliers, missing values, and both.

While the number of corruption classes is combinatorial in the individual types, the only classes that need to be enumerated are ones that are manifest in the data. When using adaptive detection, the repair step has to clean the data and report to which of the u classes the corrupted record belongs. When an example (x, y) is cleaned, the repair step labels it with one of the clean, 1, 2, ..., $u + 1$ classes (including one for “not dirty”). It is possible that u increases each

iteration as more types of dirtiness are discovered. Then, the detection problem reduces to a multiclass classification problem. This problem can be addressed by any multiclass classifier, and we use an all-versus-one SVM in our experiments.

DEFINITION 3 (ADAPTIVE CASE). Select the set of records for which κ gives a positive error classification (i.e., one of the u error classes). After each sample of data is cleaned, the classifier κ is retrained. So the result is:

$$D(r) = (\{1, 0\}, \{1, \dots, u + 1\})$$

Adaptive Detection With OpenRefine:

EXAMPLE 4. *OpenRefine* is a spreadsheet-based tool that allows users to explore and transform data. However, it is limited to cleaning data that can fit in memory on a single computer. Since the cleaning operations are coupled with data exploration, ActiveClean does not know what is dirty in advance (the analyst may discover new errors as she cleans).

Suppose the analyst wants to use *OpenRefine* to clean the running example dataset with ActiveClean. She takes a sample of data from the entire dataset and uses the tool to discover errors. For example, she finds that some drugs are incorrectly classified as both drugs and devices. She then removes the device attribute for all records that have the drug name in question. As she fixes the records, she tags each one with a category tag of which corruption it belongs to.

7.2 The Estimator

To get around the problem with oracle sampling, the estimator will estimate the cleaned value with previously cleaned data. The estimator will also take advantage of the detector from the previous section. There are a number of different approaches, such as regression, that could be used to estimate the cleaned value given the dirty values. However, there is a problem of scarcity, where errors may affect a small number of records. As a result, the regression approach would have to learn a multivariate function with only a few examples. This makes high-dimensional regression ill-suited for the estimator. Conversely, it could try a very simple estimator that just calculates an average change and adds this change to all of the gradients. This estimator can be highly inaccurate as it also applies the change to records that are known to be clean.

ActiveClean leverages the detector for an estimator that is in between these two extremes. The estimator calculates average changes feature-by-feature and selectively corrects the gradient when a feature is known to be corrupted based on the detector. It also applies a linearization that leads to improved estimates when the sample size is small. We evaluate this linearization in Section 8.5 against alternatives, and find that it provides more accurate estimates for a small number of samples cleaned. This is a biased estimator, and when the number of cleaned samples is large the alternative techniques are comparable or even slightly better due to the bias.

Estimation For A Priori Detection.

If most of the features are correct, it would seem like the gradient is only incorrect in one or two of its components. The problem is that the gradient $\nabla\phi(\cdot)$ can be a very non-linear function of the features that couple features together. For example, the gradient for linear regression is:

$$\nabla\phi(x, y, \theta) = (\theta^T x - y)x$$

It is not possible to isolate the effect of a change of one feature on the gradient. Even if one of the features is corrupted, all of the gradient components will be incorrect.

To address this problem, the gradient can be approximated in a way that the effects of dirty features on the gradient are decoupled. Recall, in the *a priori* detection problem, that associated with each $r \in R_{dirty}$ is a set of errors f_r, l_r which is a set that identifies a set of corrupted features and labels. This property can be used to construct a coarse estimate of the clean value. The main idea is to calculate average changes for each feature, then given an uncleaned (but dirty) record, add these average changes to correct the gradient.

To formalize this intuition, instead of computing the actual gradient with respect to the true clean values, compute the conditional expectation given that a set of features and labels f_r, l_r are corrupted:

$$p_i \propto \mathbb{E}(\nabla \phi(x_i^{(c)}, y_i^{(c)}, \theta^{(t)}) \mid f_r, l_r)$$

Corrupted features are defined as that:

$$i \notin f_r \implies x^{(c)}[i] - x^{(d)}[i] = 0$$

$$i \notin l_r \implies y^{(c)}[i] - y^{(d)}[i] = 0$$

The needed approximation represents a linearization of the errors, and the resulting approximation will be of the form:

$$p(r) \propto \|\nabla \phi(x, y, \theta^{(t)}) + M_x \cdot \Delta_{rx} + M_y \cdot \Delta_{ry}\|$$

where M_x, M_y are matrices and Δ_{rx} and Δ_{ry} are vectors with one component for each feature and label where each value is the average change for those features that are corrupted and 0 otherwise. Essentially, it the gradient with respect to the dirty data plus some linear correction factor. In the appendix, we present a derivation using a Taylor series expansion and a number of M_x and M_y matrices for common convex losses. The appendix also describes how to maintain Δ_{rx} and Δ_{ry} as cleaning progresses.

Estimation For Adaptive Case.

A similar procedure holds in the adaptive setting, however, it requires reformulation. Here, ActiveClean uses u corruption classes provided by the detector. Instead of conditioning on the features that are corrupted, the estimator conditions on the classes. So for each error class, it computes a Δ_{ux} and Δ_{uy} . These are the average change in the features given that class and the average change in labels given that class.

$$p(r_u) \propto \|\nabla \phi(x, y, \theta^{(t)}) + M_x \cdot \Delta_{ux} + M_y \cdot \Delta_{uy}\|$$

7.2.1 Example

Here is an example of using the optimization to select a sample of data for cleaning.

EXAMPLE 5. Consider using ActiveClean with an *a priori* detector. Let us assume that there are no errors in the labels and only errors in the features. Then, each training example will have a set of corrupted features (e.g., $\{1, 2, 6\}$, $\{1, 2, 15\}$). Suppose that the cleaner has just cleaned the records r_1 and r_2 represented as tuples with their corrupted feature set: $(r_1, \{1, 2, 3\})$, $(r_2, \{1, 2, 6\})$. For each feature i , ActiveClean maintains the average change between dirty and clean in a value in a vector $\Delta_x[i]$ for those records corrupted on that feature.

Then, given a new record $(r_3, \{1, 2, 3, 6\})$, Δ_{r_3x} is the vector Δ_x where component i is set to 0 if the feature is not corrupted. Suppose the data analyst is using an SVM, then the M_x matrix is as follows:

$$M_x[i, i] = \begin{cases} -y[i] & \text{if } y \cdot x \cdot \theta \leq 1 \\ 0 & \text{if } y \cdot x \cdot \theta \geq 1 \end{cases}$$

Thus, we calculate a sampling weight for record r_3 :

$$p(r_3) \propto \|\nabla \phi(x, y, \theta^{(t)}) + M_x \cdot \Delta_{r_3x}\|$$

To turn this into a probability, ActiveClean normalizes over all dirty records.

8. EXPERIMENTS

First, the experiments evaluate how various types of corrupted data benefit from data cleaning. Next, the experiments explore different prioritization and model update schemes for progressive data cleaning. Finally, ActiveClean is evaluated end-to-end in a number of real-world data cleaning scenarios.

8.1 Experimental Setup and Notation

The main metric for evaluation is a relative measure of the trained model and the model if all of the data is cleaned.

Relative Model Error. Let θ be the model trained on the dirty data, and let θ^* be the model trained on the same data if it was cleaned. Then the model error is defined as $\frac{\|\theta - \theta^*\|}{\|\theta^*\|}$.

8.1.1 Scenarios

Income Classification (Adult): In this dataset of 45,552 records, the task is to predict the income bracket (binary) from 12 numerical and categorical covariates with an SVM classifier.

Seizure Classification (EEG): In this dataset, the task is to predict the onset of a seizure (binary) from 15 numerical covariates with a thresholded Linear Regression. There are 14980 data points in this dataset. This classification task is inherently hard with an accuracy on completely clean data of only 65%.

Handwriting Recognition (MNIST) ¹: In this dataset, the task is to classify 60,000 images of handwritten images into 10 categories with an one-to-all multiclass SVM classifier. The unique part of this dataset is the featurized data consists of a 784 dimensional vector which includes edge detectors and raw image patches.

Dollars For Docs: The dataset has 240,089 records with 5 textual attributes and one numerical attribute. The dataset is featurized with bag-of-words featurization model for the textual attributes which resulted in a 2021 dimensional feature vector, and a binary SVM is used to classify the status of the medical donations.

8.1.2 Compared Algorithms

Here are the alternative methodologies evaluated in the experiments:

Robust Logistic Regression [14]. Feng et al. proposed a variant of logistic regression that is robust to outliers. We chose this algorithm because it is a robust extension of the convex regularized loss model, leading to a better apples-to-apples comparison between the techniques. (See details in Appendix H.1)

Discarding Dirty Data. As a baseline, dirty data is discarded.

SampleClean (SC) [33]. SampleClean takes a sample of data, applies data cleaning, and then trains a model to completion on the sample.

Active Learning (AL) [18]. An Active Learning algorithm that integrates with stochastic optimization (See details in Appendix H.2).

ActiveClean Oracle (AC+O): In ActiveClean Oracle, instead of an estimation step, the true clean value is used to evaluate the theoretical ideal performance of ActiveClean.

¹http://ufldl.stanford.edu/wiki/index.php/Using_the_MNIST_Dataset

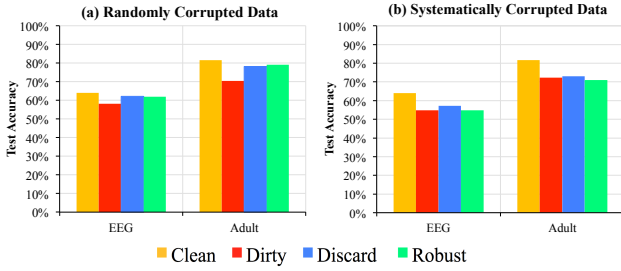


Figure 4: (a) Robust techniques and discarding data work when corrupted data are random and look atypical. (b) Data cleaning can provide reliable performance in both the systematically corrupted setting and randomly corrupted setting.

8.2 Does Data Cleaning Matter?

The first experiment evaluates the benefits of data cleaning on two of the example datasets (EEG and Adult). This is done without sampling to understand which types of data corruption are amenable to data cleaning and which are better suited for robust statistical techniques. The experiment compares four schemes: (1) full data cleaning, (2) baseline of no cleaning, (3) discarding the dirty data, and (4) robust logistic regression. We corrupted 5% of the training examples in each dataset in two different ways:

Random Corruption: Simulated high-magnitude random outliers. 5% of the examples are selected at random and a random feature is replaced with 3 times the highest feature value.

Systematic Corruption: Simulated innocuous looking (but still incorrect) systematic corruption. The model is trained on the clean data, and the three most important features (highest weighted) are identified. The examples are sorted by each of these features and the top examples are corrupted with the mean value for that feature (5% corruption in all). It is important to note that examples can have multiple corrupted features.

Figure 4 shows the test accuracy for models trained on both types of data with the different techniques. The robust method performs well on the random high-magnitude outliers with only a 2.0% reduction in clean test accuracy for EEG and 2.5% reduction for Adult. In the random setting, discarding dirty data also performs relatively well. However, the robust method falters on the systematic corruption with a 9.1% reduction in clean test accuracy for EEG and 10.5% reduction for Adult. The problem is that without cleaning, there is no way to know if the corruption is random or systematic and when to trust a robust method. While data cleaning requires more effort, it provides benefits in both settings. In the remaining experiments, unless otherwise noted, the experiments use systematic corruption.

Summary: A 5% systematic corruption can introduce a 10% reduction in test accuracy even when using a robust method.

8.3 ActiveClean: A Priori Detection

The next set of experiments evaluate different approaches to cleaning a sample of data compared to ActiveClean using a *a priori* detection. A *a priori* detection assumes that all of the corrupted records are known in advance but their clean values are unknown.

8.3.1 Active Learning and SampleClean

The next experiment evaluates the samples-to-error tradeoff between four alternative algorithms: ActiveClean (AC), SampleClean, Active Learning, and ActiveClean + Oracle (AC+O). Figure 5 shows the model error and test accuracy as a function of the number of cleaned records. In terms of model error, ActiveClean gives its

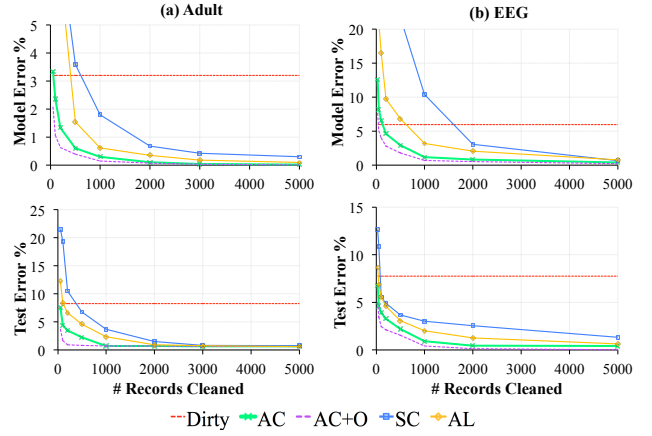


Figure 5: The relative model error as a function of the number of examples cleaned. ActiveClean converges with a smaller sample size to the true result in comparison to Active Learning and SampleClean.

largest benefits for small sample sizes. For 500 cleaned records of the Adult dataset, ActiveClean has 6.1x less error than SampleClean and 2.1x less error than Active Learning. For 500 cleaned records of the EEG dataset, ActiveClean has 9.6x less error than SampleClean and 2.4x less error than Active Learning. Both Active Learning and ActiveClean benefit from the initialization with the dirty model as they do not retrain their models from scratch, and ActiveClean improves on this performance with detection and error estimation. Active Learning has no notion of dirty and clean data, and therefore prioritizes with respect to the dirty data. These gains in model error also correlate well to improvements in test error (defined as the test accuracy difference w.r.t cleaning all data). The test error converges more quickly than model error, emphasizing the benefits of progressive data cleaning, since it is not necessary to clean all the data to get a model with essentially the same performance as the clean model. For example, to achieve a test error of 1% on the Adult dataset, ActiveClean cleans 500 fewer records than Active Learning.

Summary: ActiveClean with a priori detection returns results that are more than 6x more accurate than SampleClean and 2x more accurate than Active Learning for cleaning 500 records.

8.3.2 Source of Improvements

The next experiment compares the performance of ActiveClean with and without various optimizations at 500 records cleaned point. This is a vertical slice of the plots in the previous experiments. ActiveClean without detection is denoted as (AC-D) (that is at each iteration we sample from the entire dirty data), and ActiveClean without detection and importance sampling is denoted as (AC-D-I). Figure 6 plots the relative error of the alternatives and ActiveClean with and without the optimizations. Without detection (AC-D), ActiveClean is still more accurate than Active Learning. Removing the importance sampling, ActiveClean is slightly worse than Active Learning on the Adult dataset but is comparable on the EEG dataset.

Summary: Both a priori detection and non-uniform sampling significantly contribute to the gains over Active Learning.

8.3.3 Mixing Dirty and Clean Data

Training a model on mixed data is an unreliable methodology lacking the same guarantees as Active Learning or SampleClean even in the simplest of cases. For thoroughness, the next experi-

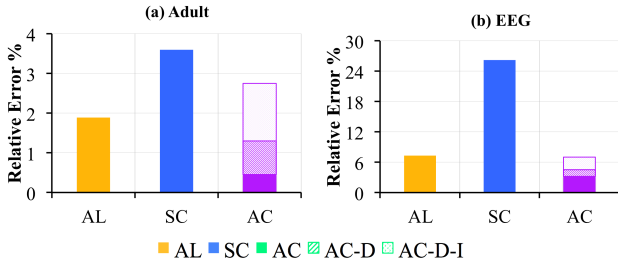


Figure 6: -D denotes no detection, and -D-I denotes no detection and no importance sampling. Both optimizations significantly help ActiveClean outperform SampleClean and Active Learning.

ments include the model error as a function of records cleaned in comparison to ActiveClean. Figure 7 plots the same curves as the previous experiment comparing ActiveClean, Active Learning, and two mixed data algorithms. PC randomly samples data, clean, and writes-back the cleaned data. PC+D randomly samples data from using the dirty data detector, cleans, and writes-back the cleaned data. For these errors PC and PC+D give reasonable results (not always guaranteed), but ActiveClean converges faster. This is because ActiveClean tunes the weighting when averaging dirty and clean data into the gradient.

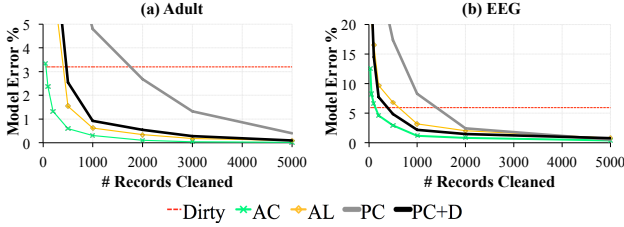


Figure 7: The relative model error as a function of the number of examples cleaned. ActiveClean converges with a smaller sample size to the true result in comparison to partial cleaning (PC, PC+D).

Summary: ActiveClean converges faster than mixing dirty and clean data since it reweights data based on the fraction that is dirty and clean. Partial cleaning is not guaranteed to give sensible results.

8.3.4 Corruption Rate

The next experiment explores how much of the performance is due to the initialization with the dirty model (i.e., SampleClean trains a model from “scratch”). Figure 8 varies the systematic corruption rate and plots the number of records cleaned to achieve 1% relative error for SampleClean and ActiveClean. SampleClean does not use the dirty data and thus its error is essentially governed by the Central Limit Theorem. SampleClean outperforms ActiveClean only when corruptions are very severe (45% in Adult and nearly 60% in EEG). When the initialization with the dirty model is inaccurate, ActiveClean does not perform as well.

Summary: SampleClean is beneficial in comparison to ActiveClean when corruption rates exceed 45%.

8.4 ActiveClean: Adaptive Detection

This experiment explores how the results of the previous experiment change when using an adaptive detector instead of the *a priori* detector. Recall, in the systematic corruption, 3 of the most informative features were corrupted, thus we group these problems into

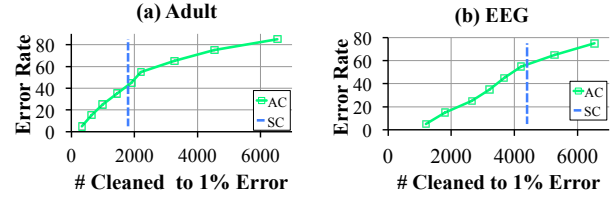


Figure 8: ActiveClean performs well until the corruption is so severe that the dirty model is not a good initialization. The error of SampleClean does not depend on the corruption rate so it is a vertical line.

9 classes. We use an all-versus-one SVM to learn the categorization.

8.4.1 Basic Performance

Figure 9 overlays the convergence plots in the previous experiments with a curve (denoted by AC+C) that represents ActiveClean using a classifier instead of the *a priori* detection. Initially ActiveClean is comparable to Active Learning; however, as the classifier becomes more effective the detection improves the performance. Over both datasets, at the 500 records point on the curve, adaptive ActiveClean has a 30% higher model error compared to *a priori* ActiveClean. At 1000 records point on the curve, adaptive ActiveClean has about 10% higher error.

Summary: For 500 records cleaned, adaptive ActiveClean has a 30% higher model error compared to *a priori* ActiveClean, but still outperforms Active Learning and SampleClean.

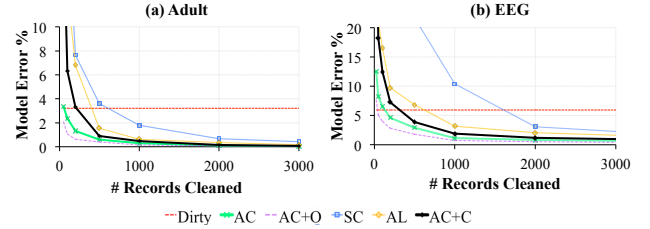


Figure 9: Even with a classifier ActiveClean converges faster than Active Learning and SampleClean.

8.4.2 Classifiable Errors

The adaptive case depends on being able to predict corrupted records. For example, random corruption not correlated with any other data features may be hard to learn. As corruption becomes more random, the classifier becomes increasingly erroneous. The next experiment explores making the systematic corruption more random. Instead of selecting the highest valued records for the most valuable features, we corrupt random records with probability p . We compare these results to AC-D where we do not have a detector at all at one vertical slice of the previous plot (cleaning 1000 records). Figure 10a plots the relative error reduction using a classifier. When the corruption is about 50% random then there is a break even point where no detection is better. This is because the classifier is imperfect and misclassifies some data points incorrectly as cleaned.

Summary: When errors are increasingly random (50% random) and cannot be accurately classified, adaptive detection provides no benefit over no detection.

8.5 Estimation

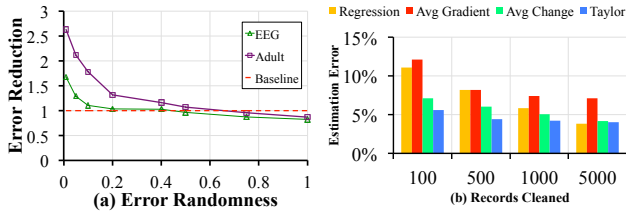


Figure 10: (a) Data corruptions that are less random are easier to classify, and lead to more significant reductions in relative model error. (b) The Taylor series approximation gives more accurate estimates when the amount of cleaned data is small.

The next experiment compares estimation techniques: (1) “linear regression” trains a linear regression model that predicts the clean gradient as a function of the dirty gradient, (2) “average gradient” which does not use the detection to inform how to apply the estimate, (3) “average feature change” uses detection but no linearization, and (4) the Taylor series linear approximation. Figure 10b measures how accurately each estimation technique estimates the gradient as a function of the number of cleaned records on the EEG dataset.

Estimation error is measured using the relative L2 error with the true gradient. The Taylor series approximation proposed gives more accurate for small cleaning sizes, confirming the analysis in Section ???. Linear regression and the average feature change technique do eventually perform comparably but only after cleaning much more data.

Summary: Linearized gradient estimates are more accurate when estimated from small samples.

8.6 Real World Scenarios

The next set of experiments evaluate ActiveClean in two real world scenarios, one demonstrating the *a priori* case and the other for the adaptive detection case.

8.6.1 A Priori: Constraint Cleaning

The first scenario explores the Dollars for Docs dataset published by ProPublica described throughout the paper. To run this experiment, the entire dataset was cleaned up front, and simulated sampling from the dirty data and cleaning by looking up the value in the cleaned data (see Appendix I for constraints, errors, and cleaning methodology). Figure 11a shows that ActiveClean converges faster than Active Learning and SampleClean. To achieve a 4% relative error (i.e., a 75% error reduction from the dirty model), ActiveClean cleans 40000 fewer records than Active Learning. Also, for 10000 records cleaned, ActiveClean has nearly an order of magnitude smaller error than SampleClean.

Figure 11b shows the detection rate (fraction of disallowed research contributions identified) of the classifier as a function of the number of records cleaned. On the dirty data, we can only correctly classify 66% of the suspected examples (88% overall accuracy due to a class imbalance). On the cleaned data, this classifier is nearly perfect with a 97% true positive rate (98% overall accuracy). ActiveClean converges to the cleaned accuracy faster than the alternatives with a classifier of 92% true positive rate for only 10000 records cleaned.

Summary: To achieve an 80% detection rate, ActiveClean cleans nearly 10x less records than Active Learning.

8.6.2 Adaptive: Replacing Corrupted Data

The next experiment explores the MNIST handwritten digit recognition dataset with a MATLAB image processing pipeline. In this scenario, the analyst must inspect a potentially corrupted image and

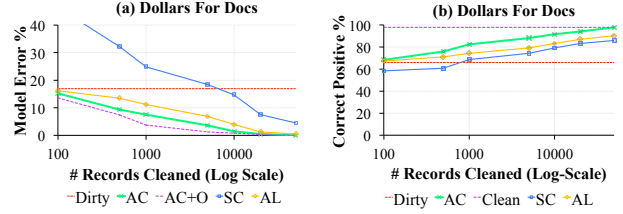


Figure 11: (a) The relative model error as a function of the number of cleaned records. (b) The true positive rate as a function of the number of cleaned records.

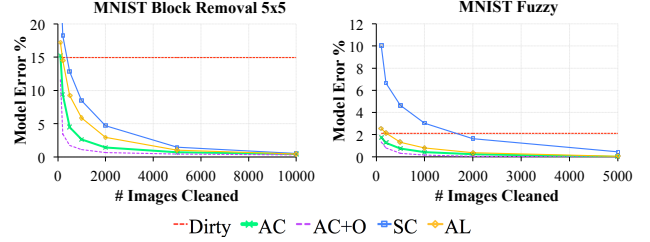


Figure 12: In a real adaptive detection scenario with the MNIST dataset, ActiveClean outperforms Active Learning and SampleClean.

replace it with a higher quality one. The MNIST dataset consists of 64x64 grayscale images. There are two types of simulated corruptions: (1) 5x5 block removal where a random 5x5 block is removed from the image by setting its pixel values to 0, and (2) Fuzzy where a 4x4 moving average patch is applied over the entire image. These corruptions are applied to a random 5% of the images, and mimic the random (Fuzzy) vs. systematic corruption (5x5 removal) studied in the previous experiments. The adaptive detector uses a 10 class classifier (one for each digit) to detect the corruption.

Figure 12 shows that ActiveClean makes more progress towards the clean model with a smaller number of examples cleaned. To achieve a 2% error for the block removal, ActiveClean can inspect 2200 fewer images than Active Learning and 2750 fewer images than SampleClean. For the fuzzy images, both Active Learning and ActiveClean reach 2% error after cleaning fewer than 100 images, while SampleClean requires 1750.

Summary: In the MNIST dataset, ActiveClean significantly reduces (more than 2x) the number of images to clean to train a model with 2% error.

9. RELATED WORK

Data Cleaning and Databases: When data cleaning is expensive, it is desirable to apply it **progressively**, where analysts can inspect early results with only $k \ll N$ records cleaned. Progressive data cleaning is a well studied problem especially in the context of entity resolution [6, 2, 30, 17]. Prior work has focused the problem of designing data structures and algorithms to apply data cleaning progressively. This is challenging because many data cleaning algorithms require information from entire relations, and designing incremental models is a challenging problem even for just entity resolution. However, over the last 5 years a number of new results have expanded progressive data cleaning to rule based systems [26, 36, 35]. ActiveClean explores the statistical implications of using progressive data cleaning before high-dimensional predictive modeling.

Recently, in works such as SampleClean [33], the application (i.e., queries) are used to inform data cleaning methodology. It suffices to clean a sample of data when the data will be used to answer aggregate queries. Sampling has also been applied to assess the

number of duplicates in a relation [20]. When the workload is made up of aggregate queries, cleaning samples of data may suffice. Similarly, Bergman et al. explore the problem of query-oriented data cleaning [7]. Given a query they clean data relevant to that query. Bergman et al. does not explore the Machine Learning applications studied in this work. Deshpande et al. studied data acquisition in sensor networks [12]. They explored value of information based prioritization of data acquisition for estimating aggregate queries of sensor readings. Similarly, Jeffery et al. [22] explored similar prioritization based on value of information. We see this work as pushing prioritization further down the pipeline to the end analytics. Finally, incremental optimization methods like SGD have a connection to incremental materialized view maintenance as the argument for incremental maintenance over recomputation is similar (i.e., relatively sparse updates). Krishnan et al. explored how samples of materialized views can be maintained similar to how models are updated with a sample of clean data in this work [24]

Stochastic Optimization and Active Learning: Zhao and Tong recently proposed using importance sampling in conjunction with stochastic gradient descent [37]. The ideas applied in ActiveClean are well rooted in the Machine Learning and Optimization literature, and we apply these ideas to the data cleaning problem. This line of work builds on prior results in linear algebra that show that some matrix columns are more informative than others [13], and Active Learning which shows that some labels are more informative than others [31]. Active Learning largely studies the problem of label acquisition [31], and recently the links between Active Learning and Stochastic optimization have been studied [18]. We use the work in Guillory et al. to evaluate a state-of-the-art Active Learning technique against ActiveClean.

Transfer Learning and Bias Mitigation: ActiveClean has a strong link to a field called Transfer Learning and Domain Adaptation [29]. The basic idea of Transfer Learning is that suppose a model is trained on a dataset D but tested on a dataset D' . Much of the complexity and contribution of ActiveClean comes from efficiently tuning such a process for expensive data cleaning applications – costs not studied in Transfer Learning. In robotics, Mahler et al. explored a calibration problem in which data was systematically corrupted [25] and proposed a rule-based technique for cleaning data. Other problems in bias mitigation (e.g., Krishnan et al. [23]) have the same structure, systematically corrupted data that is feeding into a model. In this work, we try to generalize these principles given a general dirty dataset, convex model, and data cleaning procedure.

Secure Learning: ActiveClean is also related to work in adversarial learning [28], where the goal is to make models robust to adversarial data manipulation. This line of work has extensively studied methodologies for making models private to external queries and robust to malicious labels [34], but the data cleaning problem explores more general corruptions than just malicious labels. One widely applied technique in this field is reject-on-negative impact, which essentially, discards data that reduces the loss function—which will not work when we do not have access to the true loss function (only the “dirty loss”).

10. DISCUSSION AND FUTURE WORK

The experimental results suggest the following conclusions about ActiveClean: (1) when the data corruption rate is relatively small (e.g., 5%), ActiveClean cleans fewer records than Active Learning or SampleClean to achieve the same model accuracy, (2) all of the optimizations in ActiveClean (importance sampling, detec-

tion, and estimation) lead to significantly more accurate models at small sample sizes, (3) only when corruption rates are very severe (e.g. 50%) , SampleClean outperforms ActiveClean, and (4) two real-world scenarios demonstrate similar accuracy improvements where ActiveClean returns significantly more accurate models than SampleClean or Active Learning for the same number of records cleaned.

There are also a few additional points for discussion. ActiveClean provides guarantees for training error on models trained with progressive data cleaning, however, there are no such guarantees on test error. This work focuses on the problem where an analyst has a large amount of dirty data and would like explore data cleaning and predictive models on this dataset. By providing the analyst more accurate model estimates, the value of different data cleaning techniques can be judged without having to clean the entire dataset. However, the exploratory analysis problem is distinct from the model deployment problem (i.e., serving predictions to users from the model), which we hope to explore in more detail in future work. It implicitly assumes that when the model is deployed, it will be applied in a setting where the test data is also clean. Training on clean data, and testing on dirty data, defeats the purpose of data cleaning and can lead to unreliable predictions.

As the experiments clearly show, ActiveClean is not strictly *better* than Active Learning or SampleClean. ActiveClean is optimized for a specific design point of sparse errors and small sample sizes, and the empirical results suggest it returns more accurate models in this setting. As sample sizes and error rates increase, the benefits of ActiveClean are reduced. Another consideration for future work is automatically selecting alternative techniques when ActiveClean is expected to perform poorly.

Beyond these limitations, there are several exciting new avenues for future work. The data cleaning models explored in this work can be extended to handle non-uniform costs, where different errors have a different cleaning cost. Next, the empirical success of Deep Learning has led to increasing industry and research adoption of non-convex losses in many tasks that were traditionally served by convex models. In future work, we hope to explore how we can integrate with such frameworks.

11. CONCLUSION

The growing popularity of predictive models in data analytics adds additional challenges in managing dirty data. Progressive data cleaning in this setting is susceptible to errors due to mixing dirty and clean data, sensitivity to sample size, and the sparsity of errors. The key insight of ActiveClean is that an important class of predictive models, called convex loss models (e.g., linear regression and SVMs), can be simultaneously trained and cleaned. Consequently, there are provable guarantees on the convergence and error bounds of ActiveClean. ActiveClean also includes numerous optimizations such as: using the information from the model to inform data cleaning on samples, dirty data detection to avoid sampling clean data, and batching updates. The experimental results are promising as they suggest that these optimizations can significantly reduce data cleaning costs when errors are sparse and cleaning budgets are small. Techniques such as Active Learning and SampleClean are not optimized for the sparse low-budget setting, and ActiveClean achieves models of similar accuracy for significantly less records cleaned.

12. REFERENCES

- [1] Berkeley data analytics stack.
<https://amplab.cs.berkeley.edu/software/>.
- [2] Dollars for docs.<http://projects.propublica.org/open-payments/>.

- [3] For big-data scientists, 'janitor work' is key hurdle to insights. <http://www.nytimes.com/2014/08/18/technology/for-big-data-scientists-hurdle-to-insights-is-janitor-work.html>.
- [4] A pharma payment a day keeps docs' finances okay. <https://www.propublica.org/article/a-pharma-payment-a-day-keeps-docs-finances-ok>.
- [5] A. Alexandrov, R. Bergmann, S. Ewen, J. Freytag, F. Hueske, A. Heise, O. Kao, M. Leich, U. Leser, V. Markl, F. Naumann, M. Peters, A. Rheinländer, M. J. Sax, S. Schelter, M. Höger, K. Tzoumas, and D. Warneke. The stratosphere platform for big data analytics. *VLDB J.*, 23(6):939–964, 2014.
- [6] Y. Altowim, D. V. Kalashnikov, and S. Mehrotra. Progressive approach to relational entity resolution. *PVLDB*, 7(11):999–1010, 2014.
- [7] M. Bergman, T. Milo, S. Novgorodov, and W. C. Tan. Query-oriented data cleaning with oracles. In *SIGMOD Conference*, pages 1199–1214, 2015.
- [8] D. P. Bertsekas. Incremental gradient, subgradient, and proximal methods for convex optimization: A survey. *CoRR*, abs/1507.01030, 2015.
- [9] L. Bottou. Stochastic gradient descent tricks. In *Neural Networks: Tricks of the Trade - Second Edition*, pages 421–436, 2012.
- [10] A. Crotty, A. Galakatos, and T. Kraska. Tupeware: Distributed machine learning on small clusters. *IEEE Data Eng. Bull.*, 37(3):63–76, 2014.
- [11] O. Dekel, R. Gilad-Bachrach, O. Shamir, and L. Xiao. Optimal distributed online prediction using mini-batches. *JMLR*, 13:165–202, 2012.
- [12] A. Deshpande, C. Guestrin, S. Madden, J. M. Hellerstein, and W. Hong. Model-driven data acquisition in sensor networks. In *VLDB*, pages 588–599, 2004.
- [13] P. Drineas, M. Magdon-Ismail, M. W. Mahoney, and D. P. Woodruff. Fast approximation of matrix coherence and statistical leverage. *JMLR*, 13:3475–3506, 2012.
- [14] J. Feng, H. Xu, S. Mannor, and S. Yan. Robust logistic regression and classification. In *NIPS*, pages 253–261, 2014.
- [15] J. Friedman, T. Hastie, and R. Tibshirani. *The elements of statistical learning*, volume 1. Springer series in statistics Springer, Berlin, 2001.
- [16] C. Gokhale, S. Das, A. Doan, J. F. Naughton, N. Rampalli, J. Shavlik, and X. Zhu. Corleone: Hands-off crowdsourcing for entity matching. In *SIGMOD*, 2014.
- [17] A. Gruenheid, X. L. Dong, and D. Srivastava. Incremental record linkage. *PVLDB*, 7(9):697–708, 2014.
- [18] A. Guillory, E. Chastain, and J. Bilmes. Active learning as non-convex optimization. In *International Conference on Artificial Intelligence and Statistics*, pages 201–208, 2009.
- [19] D. Haas, S. Krishnan, J. Wang, M. J. Franklin, and E. Wu. Wisteria: Nurturing scalable data cleaning infrastructure. *PVLDB*, 8(12):2004–2015, 2015.
- [20] A. Heise, G. Kasneci, and F. Naumann. Estimating the number and sizes of fuzzy-duplicate clusters. In *CIKM Conference*, pages 959–968, 2014.
- [21] J. M. Hellerstein, C. Ré, F. Schoppmann, D. Z. Wang, E. Fratkin, A. Gorajek, K. S. Ng, C. Welton, X. Feng, K. Li, and A. Kumar. The madlib analytics library or MAD skills, the SQL. *PVLDB*, 5(12):1700–1711, 2012.
- [22] S. R. Jeffery, G. Alonso, M. J. Franklin, W. Hong, and J. Widom. Declarative support for sensor data cleaning. In *Pervasive Computing*, pages 83–100, 2006.
- [23] S. Krishnan, J. Patel, M. J. Franklin, and K. Goldberg. A methodology for learning, analyzing, and mitigating social influence bias in recommender systems. In *RecSys*, pages 137–144, 2014.
- [24] S. Krishnan, J. Wang, M. J. Franklin, K. Goldberg, and T. Kraska. Stale view cleaning: Getting fresh answers from stale materialized views. *PVLDB*, 8(12):1370–1381, 2015.
- [25] J. Mahler, S. Krishnan, M. Laskey, S. Sen, A. Murali, B. Kehoe, S. Patil, J. Wang, M. Franklin, P. Abbeel, and K. Y. Goldberg. Learning accurate kinematic control of cable-driven surgical robots using data cleaning and gaussian process regression. In *CASE*, pages 532–539, 2014.
- [26] C. Mayfield, J. Neville, and S. Prabhakar. ERACER: a database approach for statistical inference and data cleaning. In *SIGMOD Conference*, pages 75–86, 2010.
- [27] B. Mozafari, P. Sarkar, M. J. Franklin, M. I. Jordan, and S. Madden. Scaling up crowd-sourcing to very large datasets: A case for active learning. *PVLDB*, 8(2):125–136, 2014.
- [28] B. Nelson, B. I. P. Rubinstein, L. Huang, A. D. Joseph, S. J. Lee, S. Rao, and J. D. Tygar. Query strategies for evading convex-inducing classifiers. *JMLR*, 13:1293–1332, 2012.
- [29] S. J. Pan and Q. Yang. A survey on transfer learning. *TKDE*, 22(10):1345–1359, 2010.
- [30] T. Papenbrock, A. Heise, and F. Naumann. Progressive duplicate detection. *TKDB*, 27(5):1316–1329, 2015.
- [31] B. Settles. Active learning literature survey. *University of Wisconsin, Madison*, 52(55-66):11, 2010.
- [32] E. H. Simpson. The interpretation of interaction in contingency tables. *Journal of the Royal Statistical Society. Series B (Methodological)*, pages 238–241, 1951.
- [33] J. Wang, S. Krishnan, M. J. Franklin, K. Goldberg, T. Kraska, and T. Milo. A sample-and-clean framework for fast and accurate query processing on dirty data. In *SIGMOD Conference*, pages 469–480, 2014.
- [34] H. Xiao, B. Biggio, G. Brown, G. Fumera, C. Eckert, and F. Roli. Is feature selection secure against training data poisoning? In *ICML*, pages 1689–1698, 2015.
- [35] M. Yakout, L. Berti-Equille, and A. K. Elmagarmid. Don't be scared: use scalable automatic repairing with maximal likelihood and bounded changes. In *SIGMOD Conference*, pages 553–564, 2013.
- [36] M. Yakout, A. K. Elmagarmid, J. Neville, M. Ouzzani, and I. F. Ilyas. Guided data repair. *PVLDB*, 4(5):279–289, 2011.
- [37] P. Zhao and T. Zhang. Stochastic optimization with importance sampling for regularized loss minimization. In *ICML*, pages 1–9, 2015.

APPENDIX

A. EXTENSIONS

A.1 Set-of-Records Cleaning Model

In paper, we formalized the analyst-specified data cleaning as follows. We take the sample of the records S_{dirty} , and apply data cleaning $C(\cdot)$. C is applied to a record and produces the clean record:

$$S_{clean} = \{C(r) : \forall r \in S_{dirty}\}$$

The record-by-record cleaning model is a formalization of the costs of data cleaning where each record has the same cost to clean and this cost does not change throughout the entire cleaning session. There are, however, some cases when cleaning the first record of a certain type of corruption is expensive but all subsequent records are cheaper.

EXAMPLE 6. *In most spell checking systems, when a misspelling is identified, the system gives an option to fix all instances of that misspelling.*

EXAMPLE 7. *In inconsistency problems, when an inconsistent value is identified all other records with the same inconsistency can be efficiently fixed.*

This model of data cleaning can fit into our framework and we formalize it as the “Set-of-Records” model as opposed to the “Record-by-Record” model. In this model, the cleaning function $C(\cdot)$ is not restricted to updating only the records in the sample. $C(\cdot)$ takes the entire dirty sample as an argument (that is the cleaning is a function of the sample), the dirty data, and updates the entire dirty data:

$$R'_{dirty} = C(S_{dirty}, R_{dirty})$$

we require that for every record $s \in S_{dirty}$, that record is completely cleaned after applying $C(\cdot)$, giving us S_{clean} . Records outside of S_{dirty} may be cleaned on a subset of dirty attributes by $C(\cdot)$. After each iteration, we re-run the detector, and move any $r \in R'_{dirty}$ that are clean to R_{clean} . Such a model allows us to capture data cleaning operations such as in Example 6 and Example 7.

A.2 Proofs

Deriving α and β : The first problem is to choose α and β such that the estimate of the gradient is unbiased. SGD will converge when the estimate is unbiased and the step-size is chosen appropriately. The batch S_{dirty} is drawn only from R_{dirty} . Since the sizes of R_{dirty} and its complement are known, it follows that the gradient over the already clean data g_C and the recently cleaned data g_S can be combined as follows:

$$g(\theta^t) = \frac{|R_{dirty}| \cdot g_S + |R_{clean}| \cdot g_C}{|R|}$$

Therefore,

$$\alpha = \frac{|R_{clean}|}{|R|}, \beta = \frac{|R_{dirty}|}{|R|}$$

LEMMA 1. *The gradient estimate $g(\theta)$ is unbiased if g_S is an unbiased estimate of:*

$$\frac{1}{|R_{dirty}|} \sum g_i(\theta)$$

PROOF SKETCH. This result follows directly from the linearity of expectation (See Appendix B). \square

A.3 Non-convex losses

We acknowledge that there is an increasing popularity of non-convex losses in the Neural Network and Deep Learning literature. However, even for these losses, gradient descent techniques still apply. Instead of converging to a global optimum they converge to a locally optimal value. Likewise, ActiveClean will converge to the closest locally optimal value to the dirty model. Because of this, it is harder to reason about the results. Different initializations will lead to different local optima, and thus, introduces a complex dependence on the initialization with the dirty model. This problem is not fundamental to ActiveClean and any gradient technique suffers this challenge for general non-convex losses, and we hope to explore this more in the future.

B. PROOF OF LEMMA 1

LEMMA 2. *The gradient estimate $g(\theta)$ is unbiased if g_S is an unbiased estimate of:*

$$\frac{1}{|R_{dirty}|} \sum g_i(\theta)$$

PROOF SKETCH.

$$\mathbb{E}\left(\frac{1}{|R_{dirty}|} \sum g_i(\theta)\right) = \frac{1}{|R_{dirty}|} \cdot \mathbb{E}(\sum g_i(\theta))$$

By symmetry,

$$\mathbb{E}\left(\frac{1}{|R_{dirty}|} \sum g_i(\theta)\right) = g(\theta)$$

$$\mathbb{E}\left(\frac{1}{|R_{dirty}|} \sum g_i(\theta)\right) = \frac{|R_{dirty}| \cdot g_S + |R_{clean}| \cdot g_C}{|R|}$$

\square

C. CONVEX VS. STRONGLY CONVEX

The error bound discussed in Proposition 2 can be tightened for a class of models called strongly convex (see [8] for a definition).

PROPOSITION 1. *For a strongly convex loss, a batch size b , and T iterations, the convergence rate is bounded by $O(\frac{\sigma^2}{bT})$.*

D. PROOF OF LEMMA 2

This lemma describes the optimal distribution over a set of scalars:

LEMMA 3. *Given a set of real numbers $A = \{a_1, \dots, a_n\}$, let \hat{A} be a sample with replacement of A of size k . If μ is the mean \hat{A} , the sampling distribution that minimizes the variance of μ , i.e., the expected square error, is $p(a_i) \propto a_i$.*

Lemma 3 shows that when estimating a mean of numbers with sampling, the distribution with optimal variance is sampling proportionally to the values.

The variance of this estimate is given by:

$$Var(\mu) = \mathbb{E}(\mu^2) - \mathbb{E}(\mu)^2$$

Since the estimate is unbiased, we can replace $\mathbb{E}(\mu)$ with the average of A :

$$Var(\mu) = \mathbb{E}(\mu^2) - \bar{A}^2$$

Since \bar{A} is deterministic, we can remove that term during minimization. Furthermore, we can write $\mathbb{E}(\mu^2)$ as:

$$\mathbb{E}(\mu^2) = \frac{1}{n^2} \sum_i \frac{a_i^2}{p_i}$$

Then, we can solve the following optimization problem (removing the proportionality of $\frac{1}{n^2}$) over the set of weights $P = \{p(a_i)\}$:

$$\min_P \sum_i \frac{a_i^2}{p_i}$$

$$\text{subject to: } P > 0, \sum P = 1$$

Applying Lagrange multipliers, an equivalent unconstrained optimization problem is:

$$\min_{P > 0, \lambda > 0} \sum_i \frac{a_i^2}{p_i} + \lambda \cdot (\sum P - 1)$$

If, we take the derivatives with respect to p_i and set them equal to zero:

$$-\frac{a_i^2}{2 \cdot p_i^2} + \lambda = 0$$

If, we take the derivative with respect to λ and set it equal to zero:

$$\sum P - 1$$

Solving the system of equations, we get:

$$p_i = \frac{|a_i|}{\sum_i |a_i|}$$

D.1 Linearization

If d is the dirty value and c is the clean value, the Taylor series approximation for a function f is given as follows:

$$f(c) = f(d) + f'(d) \cdot (d - c) + \dots$$

Ignoring the higher order terms, the linear term $f'(d) \cdot (d - c)$ is a linear function in each feature and label. Then, taking expected values, it follows that:

$$\approx \nabla \phi(x, y, \theta) + M_x \cdot \mathbb{E}(\Delta x) + M_y \cdot \mathbb{E}(\Delta y)$$

where $M_x = \frac{\partial}{\partial X} \nabla \phi$ and $M_y = \frac{\partial}{\partial Y} \nabla \phi$ (See Appendix E for derivation). Recall that the feature space is d dimensional and label space is l dimensional. Then, M_x is an $d \times d$ matrix, and M_y is a $d \times l$ matrix. Both of these matrices are computed for each record (see Appendix F for an example derivation). Δx is a d dimensional vector where each component represents a change in that feature and Δy is an l dimensional vector that represents the change in each of the labels.

This linearization allows ActiveClean to maintain per feature (or label) average changes and use these changes to center the optimal sampling distribution around the expected clean value. To estimate $\mathbb{E}(\Delta x)$ and $\mathbb{E}(\Delta y)$, consider the following for a single feature i : If we average all $j = \{1, \dots, K\}$ records cleaned that have an error for that feature, weighted by their sampling probability:

$$\bar{\Delta}_{xi} = \frac{1}{NK} \sum_{j=1}^K (x^{(d)}[i] - x^{(c)}[i]) \times \frac{1}{p(j)}$$

Similarly, for a label i :

$$\bar{\Delta}_{yi} = \frac{1}{NK} \sum_{j=1}^K (y^{(d)}[i] - y^{(c)}[i]) \times \frac{1}{p(j)}$$

Each $\bar{\Delta}_{xi}$ and $\bar{\Delta}_{yi}$ represents an average change in a single feature. A single vector can represent the necessary changes to apply to a record r : For a record r , the set of corrupted features is f_r, l_r . Then, each record r has a d -dimensional vector Δ_{rx} which is constructed as follows:

$$\Delta_{rx}[i] = \begin{cases} 0 & i \notin f_r \\ \bar{\Delta}_{xi} & i \in f_r \end{cases}$$

Each record r also has an l -dimensional vector Δ_{ry} which is constructed as follows:

$$\Delta_{ry}[i] = \begin{cases} 0 & i \notin l_r \\ \bar{\Delta}_{yi} & i \in l_r \end{cases}$$

Finally, the result is:

$$p_r \propto \|\nabla \phi(x, y, \theta^{(t)}) + M_x \cdot \Delta_{rx} + M_y \cdot \Delta_{ry}\|$$

E. TAYLOR APPROXIMATION

We can take the expected value of the Taylor series expansion around the dirty value. If d is the dirty value and c is the clean value, the Taylor series approximation for a function f is given as follows:

$$f(c) = f(d) + f'(d) \cdot (d - c) + \dots$$

If we ignore the higher order terms, we see that the linear term $f'(d) \cdot (d - c)$ decouples the features. We only have to know the change in each feature to estimate the change in value. In our case the function f is the gradient $\nabla \phi$. So, the resulting linearization is:

$$\begin{aligned} \nabla \phi(x_i^{(c)}, y_i^{(c)}, \theta) &\approx \nabla \phi(x, y, \theta) + \frac{\partial}{\partial X} \nabla \phi(x, y, \theta) \cdot (x - x^{(c)}) \\ &+ \frac{\partial}{\partial Y} \nabla \phi(x, y, \theta) \cdot (y - y^{(c)}) \end{aligned}$$

When we take the expected value:

$$\begin{aligned} \mathbb{E}(\nabla \phi(x_{clean}, y_{clean}, \theta)) &\approx \nabla \phi(x, y, \theta) + \frac{\partial}{\partial X} \nabla \phi(x, y, \theta) \cdot \mathbb{E}(\Delta x) \\ &+ \frac{\partial}{\partial Y} \nabla \phi(x, y, \theta) \cdot \mathbb{E}(\Delta y) \end{aligned}$$

So the resulting estimation formula takes the following form:

$$\approx \nabla \phi(x, y, \theta) + M_x \cdot \mathbb{E}(\Delta x) + M_y \cdot \mathbb{E}(\Delta y)$$

Recall that we have a d dimensional feature space and l dimensional label space. Then, $M_x = \frac{\partial}{\partial X} \nabla \phi$ is an $d \times d$ matrix, and $M_y = \frac{\partial}{\partial Y} \nabla \phi$ is a $d \times l$ matrix. Both of these matrices are computed with respect to dirty data, and we will present an example. Δx is a d dimensional vector where each component represents a change in that feature and Δy is an l dimensional vector that represents the change in each of the labels.

F. EXAMPLE M_X, M_Y

Linear Regression:

$$\nabla \phi(x, y, \theta) = (\theta^T x - y)x$$

For a record, r , suppose we have a feature vector x . If we take the partial derivatives with respect to x , M_x is:

$$M_x[i, i] = 2x[i] + \sum_{i \neq j} \theta[j]x[j] - y$$

$$M_x[i, j] = \theta[j]x[i]$$

Similarly M_y is:

$$M_y[i, 1] = x[i]$$

Logistic Regression:

$$\nabla \phi(x, y, \theta) = (h(\theta^T x) - y)x$$

where

$$h(z) = \frac{1}{1 + e^{-z}}$$

we can rewrite this as:

$$h_\theta(x) = \frac{1}{1 + e^{\theta^T x}}$$

$$\nabla \phi(x, y, \theta) = (h_\theta(x) - y)x$$

In component form,

$$g = \nabla \phi(x, y, \theta)$$

$$g[i] = h_\theta(x) \cdot x[i] - yx[i]$$

Therefore,

$$M_x[i, i] = h_\theta(x) \cdot (1 - h_\theta(x)) \cdot \theta[i]x[i] + h_\theta(x) - y$$

$$M_x[i, j] = h_\theta(x) \cdot (1 - h_\theta(x)) \cdot \theta[j]x[i] + h_\theta(x)$$

$$M_y[i, 1] = x[i]$$

SVM:

$$\nabla \phi(x, y, \theta) = \begin{cases} -y \cdot x & \text{if } y \cdot x \cdot \theta \leq 1 \\ 0 & \text{if } y \cdot x \cdot \theta \geq 1 \end{cases}$$

Therefore,

$$M_x[i, i] = \begin{cases} -y[i] & \text{if } y \cdot \mathbf{x} \cdot \theta \leq 1 \\ 0 & \text{if } y \cdot \mathbf{x} \cdot \theta \geq 1 \end{cases}$$

$$M_x[i, j] = 0$$

$$M_y[i, 1] = x[i]$$

G. AGGREGATE QUERIES AS CONVEX LOSSES

G.1 AVG and SUM queries

avg, sum queries are a special case of the convex loss minimization discussed in the paper: If we define the following loss, it is easy to verify the the optimal θ is the mean μ :

$$\phi = (x_i - \theta)^2$$

with the appropriate scaling it can support avg, sum queries with and without predicates. Taking the gradient of that loss:

$$\nabla \phi = 2(x_i - \theta)$$

It is also easy to verify that the bound on errors is $O(\frac{\mathbb{E}((x-\mu)^2)}{bT})$, which is essentially the CLT. The importance sampling results are intuitive as well. Applying the linearization:

$$M_x = 2$$

The importance sampling prioritizes points that it expects to be far away from the mean.

G.2 MEDIAN

Similarly, we can analyze the median query. If we define the following loss, it is easy to verify the the optimal θ is the median m :

$$\phi = |x_i - \theta|$$

Taking the gradient of that loss:

$$\nabla \phi = 1 \text{ if } < m, -1 \text{ if } > m$$

Applying the linearization:

$$M_x = 0$$

The intuitive result is that a robust query like a median does not need to consider estimation as the query result is robust to small changes.

H. EXPERIMENTAL COMPARISON

H.1 Robust Logistic Regression

We use the algorithm from Feng et al. for robust logistic regression.

1. Input: Contaminated training samples $\{(x_1, y_1), \dots, (x_n, y_n)\}$ an upper bound on the number of outliers n , number of inliers n and sample dimension p .

2. Initialization: Set

$$T = 4\sqrt{\log p/n + \log n/n}$$

3. Remove samples (x_i, y_i) whose magnitude satisfies $\|x_i\| \geq T$.

4. Solve regularized logistic regression problem.

H.2 Active Learning

There is a well established link between Active Learning and Online Gradient-based Algorithms [18]. To fairly evaluate an Active Learning methodology in these experiments, we run a gradient descent where examples are prioritized by expected gradient length (explained in [31]). Ignoring the detection step, there are two differences between this algorithm and the one we propose. First, we calculate the gradient with respect to the an estimate of the clean data, and second we sample rather than using a deterministic ordering. While such Active Learning algorithms have been studied in the Learning Theory community, they have not been adopted in data cleaning or crowdsourcing research. Typical algorithms include uncertainty sampling, where a classifier prioritized data closest to the margin. However, algorithms such as uncertainty sampling focus on the narrow problem of label acquisition in hyperplane classifiers; a problem too narrow for application in this setting.

I. DOLLARS FOR DOCS SETUP

The dollars for docs dataset has the following schema:

```
Contribution(pi_speciality, drug_name, device_name,
corporation, amount, dispute, status)
```

To flag suspect donations, we used the `status` attribute. When the `status` was "covered" that means it was an allowed contribution under the researcher's declared protocol. When the `status` was "non-covered" that means it was a disallowed contribution under the researcher's declared protocol. The rest of the textual attributes were featurized with a bag-of-words model, and the numerical amount and dispute attributes were treated as numbers.

We cleaned the entire Dollars for Docs dataset upfront to be able to evaluate how different budgeted data cleaning strategies compare to cleaning the full data. To clean the dataset, we loaded the entire data 240089 records into Microsoft Excel. We identified four broad classes of errors:

Corporations are inconsistently represented: "Pfizer", "Pfizer Inc.", "Pfizer Incorporated".

Drugs are inconsistently represented: "TAXOTERE DOCETAXEL -PROSTATE CANCER" and "TAXOTERE"

Label of covered and not covered are not consistent: "No", "Yes", "N", "This study is not supported", "None", "Combination"

Research subject must be a drug OR a medical device and not both: "BIO FLU QPAN H7N9AS03 Vaccine" and "BIO FLU QPAN H7N9AS03 Device"

To fix these errors, we sorted by each column and merged values that looked similar and removed inconsistencies as in the status labels. When there were ambiguities, we referred to the drug company's website and whitepapers. When possible, we used batch data transformations, like find and replace (i.e. the Set-of-Records model). In all, 44234 records had some error and full data cleaning required about 2 days of efforts.

Once cleaned, in our experiment, we encoded the 4 problems as data quality constraints. To fix the constraints, we looked up the clean value in the dataset that we cleaned up front.

Rule 1: Matching dependency on corporation (Weighted Jaccard Similarity > 0.8).

Rule 2: Matching dependency on drug (Weighted Jaccard Similarity > 0.8).

Rule 3: Label must either be "covered" or "not covered".

Rule 4: Either drug or medical device should be null.

J. MNIST SETUP

We include visualization of the errors that we generated for the MNIST experiment. We generated these errors in MATLAB by taking the grayscale version of the image (a 64×64 matrix) and corrupting them by block removal and fuzzifying.

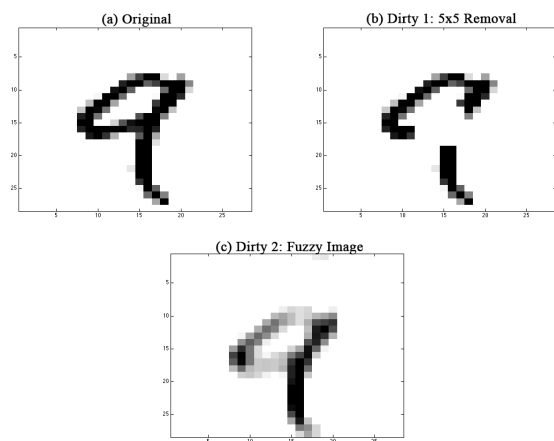


Figure 13: We experiment with two forms of corruption in the MNIST image datasets: 5x5 block removal and making the images fuzzy. Image (a) shows an uncorrupted “9”, image (b) shows one corrupted with block removal, and image (c) shows one that is corrupted with fuzziness.