Data Market Platforms: Trading Data Assets to Solve Data Problems

Raul Castro Fernandez, Pranav Subramaniam, Michael J. Franklin
The University of Chicago
[raulcf,psubramaniam,mjfranklin]@uchicago.edu

ABSTRACT

Data only generates value for a few organizations with expertise and resources to make data shareable, discoverable, and easy to integrate. Sharing data that is easy to discover and integrate is hard because data owners lack *information* (who needs what data) and they do not have *incentives* to prepare the data in a way that is easy to consume by others.

In this paper, we propose data market platforms to address the lack of information and incentives and tackle the problems of data sharing, discovery, and integration. In a data market platform, data owners want to *share* data because they will be rewarded if they do so. Consumers are encouraged to share their data needs because the market will solve the *discovery* and *integration* problem for them in exchange for some form of currency.

We consider internal markets that operate within organizations to bring down data silos, as well as external markets that operate across organizations to increase the value of data for everybody. We outline a research agenda that revolves around two problems. The problem of market design, or how to design rules that lead to desired outcomes, and the systems problem, how to implement the market and enforce the rules. Treating data as a first-class asset is sorely needed to extend the value of data to more organizations, and we propose data market platforms as one mechanism to achieve this goal.

PVLDB Reference Format:
Raul Castro Fernandez, Pranav Subramaniam, Michael Franklin. Data Market Platforms: Trading Data Assets to Solve Data Problems. *PVLDB*, 13(11): 1933-1947, 2020.
DOI: https://doi.org/10.14778/3407790.3407800

1. INTRODUCTION

Data is the new oil [73]. Like oil, it generates enormous value for the individuals and organizations that know how to tap into and refine it. Like oil, there are only a select few who know how to exploit it. In this paper, we present our vision for data market platforms: collections of *protocols* and *systems* that together enable participants to exploit the value of data.

Data only generates value for a few organizations with expertise and resources to solve the problems of data *sharing*, *discovery*, and *integration*. These problems remain difficult despite the many contributions of the database community (and others) to theory, algorithms, and systems. Solving these problems precedes advanced analytics and machine learning, explaining why the large majority of organizations only partially benefit from the data they own.

The central argument of this paper is that sharing, discovering, and integrating data is hard because data owners lack *information* and *incentives* to make their data available in a way that increases consumers' utility. Data owners do not know what data consumers want and in what format, and they are disincentivized to share data that may leak confidential information. Even within organizations, sharing data is time-consuming and it is not clear what is the return on investment. When data is finally shared via open data portals [28,93], or via data lakes [33,80], consumers still need to discover data that satisfies their needs and integrate it into the format they want, which is typically different than the format in which they found the data.

Data market platforms establish rules to share data in a way that is easy to discover and integrate into the format consumers need because markets understand the data consumers need and communicate this need to the owners. In a data market platform, data owners are encouraged to share their data because they may receive profit if a consumer is willing to pay for it. Consumers are encouraged to share their data needs because the market will solve the discovery and integration problems for them in exchange for some reward e.g., money. By spreading information among interested parties and incentivizing them, data market platforms bring data value to all participants.

In recent years we have seen the appearance of many data markets such as Dawex [31], Xignite [99], WorldQuant [99] and others to directly buy and sell data. Data brokers [81,85] are active participants in the Internet economy by trading user data for ads. Many of us participate in the data economy when we exchange our personal data for Internet services [2,87]. And hospitals and other health institutions have started exchanging data to improve patient care and treatments. The interest in trading data is not new. Economists have been considering these problems for decades [95,96] and the database community has made progress in issues such as pricing queries under different scenarios [20, 22, 61]. We believe the time is ripe to **design and implement data market platforms that tackle the sharing, discovery, and integration problems**, and we think the database

Proceedings of the VLDB Endowment, Vol. 13, No. 11
ISSN 2150-8097.
DOI: https://doi.org/10.14778/3407790.3407800

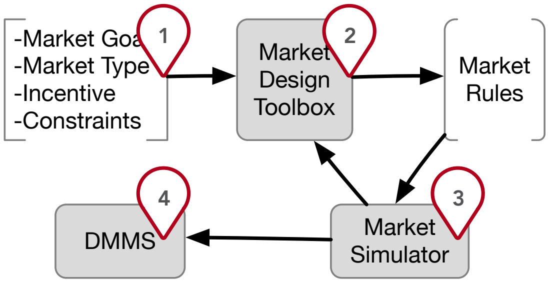

Figure 1: Given a market definition (1), a market design toolbox (2) generates the market rules, which are simulated in (3), possibly refined, and finally deployed on a DMMS (4).

community is in an advantageous position to apply decades of data management knowledge to the challenges these new data platforms introduce. In this paper, we outline challenges and a research agenda around the construction of data market platforms.

Using Data Markets to Solve Data Problems

Consider a market with *sellers*, *buyers*, and an *arbiter* that facilitates transactions between buyers and sellers. Sellers and buyers can be individuals, teams, divisions, or whole organizations. Consider the following example:

- Buyer b_1 wants to build a machine learning classifier and needs features $\langle a, b, d, e\rangle$, and at least an accuracy of 80% for the responsible engineer to trust the classifier.
- Seller 1 owns a dataset $s_1 = \langle a, b, c\rangle$ that they want to share with the arbiter.
- Seller 2 owns a dataset $s_2 = \langle a, b', f(d)\rangle$ that they will not share with the arbiter unless the dataset is guaranteed to not leak any business information.

Details of the example. In the example $f(d)$ is a function of d, such as a transformation from Celsius to Fahrenheit. The function can also be non-invertible, such as a mapping of employees to IDs. Note that neither s_1 nor s_2 owns attribute e, which b_1 wants: we discuss this attribute in Section 7.1. Last, b' is an attribute similar to b.

Challenge-1. Using s_1 alone is not enough to satisfy b_1's needs. The arbiter must incentivize Seller 2 to share s_2. The first challenge is to compensate sellers so they are incentivized to share their data. This requires *pricing* and *revenue allocation* mechanisms.

Challenge-2. Without knowing how useful s_1 or s_2 will be to train the ML model, b_1 risks overpaying for the datasets. The second challenge is to guarantee b_1 a certain quality before paying for the datasets.

Challenge-3. Neither s_1 nor s_2 *alone* fulfill b_1's need. b_1 may not want to pay for two incomplete datasets that still need to go through a slow and expensive integration process. The third challenge requires combining the datasets supplied by sellers to satisfy buyers' needs. This combination can be arbitrarily complex, such as determining how to go from $f(d)$ to d, which is the attribute the buyer wants.

Challenge-4. The degree of trust between sellers, buyers, and arbiter may vary. While it is conceivable that participants within an organization trust each other, this may not be the case in external markets. The fourth challenge is to help all participants trust each other.

Requirements of Data Market Platforms

The previous challenges motivate a list of requirements for data market platforms:

Value of Data. The market must price datasets so it creates a demand of buyers requesting data and a supply of datasets shared by sellers.

Market Design. Without the right rules to govern the participation of sellers, buyers, and arbiter, the market will be gamed and collapse. The key intellectual questions in this area are on how to design the market rules when the asset is *data*, which is freely replicable and can be combined in many different ways [18]. A requirement of a data market platform is to be resilient to strategic participants.

Plug n' Play Market Mechanisms. Markets can be of many *types*: i) internal to an organization to bring down silos of data, in which case employee compensation may be bonus points; ii) external across companies where money is an appropriate incentive; iii) across organizations but using the shared data as the incentive, such as hospitals exchanging medical data [51]. The *goals* of the market may also be varied, from optimizing the number of transactions to social welfare, data utility, and others. A requirement of data market platforms is to flexibly support markets of different types and with different goals.

Arbiter Platform. Because the supplied data will have a different format than the demanded data, a key requirement to enable transactions between sellers and buyers is an arbiter platform that can combine datasets into what we call *data mashups* to match supply and demand.

In the example above the arbiter can combine s_1 and s_2's datasets, obtaining a dataset that is much closer to b_1's need. For that, it needs to understand how to join both datasets and needs to find an inverse mapping function f' that would transform $f(d)$ into d if such a function exists, or otherwise find a mapping table that links values of $f(d)$ to values of d. In addition to these relational and non-relational operations the arbiter must also support *data fusion* operators to contrast different sources of data of the same topic. Briefly, the data fusion operators we envision produce relations that break the first normal form, that is, each cell value may be multi-valued, with each value coming from a differing source. Data fusion operators are appropriate when buyers want to contrast different sources of information that contribute the same data, i.e., weather forecast signals coming from a city dataset, a sensor, and a phone. As an illustration, note Seller 2 owns attribute b' which is almost identical to b, but has some non-overlapping, conflicting information. A buyer may be interested in looking at both signals, or at their difference, or at their similarities, etc. A data mashup is a combination of datasets using relational, non-relational, and fusion operations.

Data Market Management System (DMMS). In addition to the arbiter platform, a data market platform calls for platforms to support sellers and buyers. Sellers need access to statistical privacy techniques so they feel confident when sharing data. For example, without the capability of dealing with PII information, Seller 2 will not share data despite the potential monetary benefit of doing so because leaking such information may be ilegal. Buyers need to have the ability to describe with fine granularity their data needs and the money they are willing to pay for a certain *degree of* *satisfaction* achieved on a given task. In the example above, the buyer should have the ability to define that they are only willing to pay money for a classifier that achieves at least 80% accuracy. A requirement of a data market management system is to offer support for sellers, buyers, and the arbiter.

Building Trust. The degree of trust among sellers, buyers, and arbiter will differ depending on the scenario, i.e., whether in an internal market or across the economy. A requirement of a DMMS is to implement mechanisms to help participants trust each other, such as using decentralized architectures [11], implementing computation over encrypted data [43], and supporting contextual integrity [71].

Market Simulator. The mathematics used to make sound market designs do not account for evil, ignorant, and adversarial behavior, which exists in practice. For that reason, it is necessary to simulate market designs under adversarial scenarios before their deployment. Hence, a data market platform calls for a market simulator.

Our Vision

In the remainder of this paper, we delve into the details of our vision for data markets. The challenges are wide ranging and many fall directly within the territory of the database community. We outline our own strategy to tackle them in Section 6.2.

Our vision is to produce market designs for different scenarios (points (1) and (2) in Fig. 1) using a market design toolbox (Section 3). The market design toolbox uses techniques from game theory and mechanism design [70] to deal with the modeling and engineering of rules in strategic settings, such as data markets. Every market design is tested using a data market simulator (point (3)) (Section 6), before being finally deployed in a DMMS (point (4)), presented in Sections 4 and 5. While the output of the market design toolbox is a collection of equations, the output of the DMMS is software. There is an explicit interplay between market design and DMMS that constrains and informs the capabilities of the other. Exploring such an interplay is a critical aspect of our proposal. Before delving into the details of engineering market designs we discuss briefly the value of data (Section 2). The paper concludes with a discussion of the impact of data markets 7, related work 8, and conclusions 9.

2. THE VALUE OF DATA

What's the value of data? This question has kept academics and practitioners in economics, law, business, computer science and other disciplines busy [18, 95, 96]. This question has been explored from a macroeconomic angle to study the impact of data in an economy [39, 57]. It has been studied from a microeconomic perspective to study the impact on individual companies and firms [9, 58]. Answering the question in its full generality is outside the scope of this paper. Instead, we focus on the narrower yet challenging goal of choosing a price that satisfies sellers and buyers.

The crux of the problem is that the value of a dataset may be different for a seller and a prospective buyer. Sellers may choose to price their datasets based on the effort they spent in acquiring and preparing the data, for example. Buyers may be willing to pay for a dataset based on the expectation of profit the dataset may bring them: e.g., how much they will improve a process and how valuable that is. None of these strategies is guaranteed to converge to a price—and hence a transaction agreement—between participants.

And yet, this is how prices are set in current markets of datasets such as Dawex [31], Snowflake's Data Exchange [86], and many others. Sellers choose a price for datasets without knowing buyers' valuations and buyers who are willing to pay that price obtain the datasets, without knowing how useful the dataset is to solve their problem. This leaves both sellers and buyers unsatisfied. Buyers may pay a high price for datasets that do not yield the expected results. Similarly, sellers may undervalue datasets that could yield more profits because they lack information about what buyers want.

Finally, beyond buyers' and sellers' opinions on the dataset price, we must also take into consideration the externalities that datasets create. First, if a dataset is exchanged with exclusive rights (assuming that this is possible), the transaction creates an externality on those entities that are denied access to the dataset. Second, datasets that contain information about people generate an externality: the potential harm and privacy loss. Last, a transaction involving a dataset and a price communicates to others the value those firms put on that data. According to economic theory, all these transaction costs have an impact on real-world markets [24], and consequently they must be taken into consideration.

In this vision paper, we constrain our agenda to finding a price that permits establishing a transaction between seller and buyer, without identifying the specific components of that price, i.e., externality. This is a first step towards studying the *value of data*. Having set this goal, we move on to discuss how to price a dataset.

Intrinsic vs Extrinsic Properties of Data

A tempting option to the database community is to price datasets based on intrinsic properties, such as quality, freshness, whether the data include provenance information or not, etc. Unfortunately, pricing datasets based on the intrinsic properties of data *alone* does not work. Consider the following scenarios.

Intrinsic properties alone are insufficient. For example, given datasets with different number of missing values that are otherwise equivalent, we tend to think the one with fewer missing values is more *valuable*. However, the value of this dataset ultimately depends on the specific task for which it is used: if both datasets solve the task equally, the different ratio of missing values does not matter. Similarly, fresher datasets are intuitively considered more valuable, but this is not true if our analysis is concerned with some past date, in which case an older dataset that corresponds to that date is more valuable. Finally, the lessons from feature engineering to train statistical and machine learning models tells us that more data is not always better; diversity with respect to the task matters as well. Having established that intrinsic properties alone cannot be used to set a dataset's price we discuss how to find such price.

In the markets we envision, the price of a dataset is set by the arbiter based on the economic principles of supply and demand [82]. A dataset that lots of buyers want will be priced higher than a dataset that is hardly ever requested, regardless of the intrinsic properties of such datasets. In other words, the value of a dataset is primarily extrinsic.

The role of intrinsic properties. Intrinsic properties are important insofar the buyers indicate a preference as part of their data demands. For example, as a consequence of a buyer requesting a dataset with few missing values, sellers who provide those datasets will profit more. However, intrinsic properties do not have an associated value without explicit demand for them.

3. DESIGNING THE MARKET RULES

In this section we give a definition for *market design* in Section 3.1, we explain the challenges of engineering market designs for data (Section 3.2), and then discuss how different requirements call for different market designs in Section 3.3. Finally, we close the section with a FAQ that briefly answers some questions we cannot cover here.

We start by giving a simple market model that we use throughout this section to define and illustrate the ideas:

Market Model. The market consists of buyers ($b_i \in B$), sellers ($s_i \in S$), and an arbiter, a. Sellers own datasets (d_i) that they are willing to share with the arbiter in exchange for money. Buyers want to obtain datasets that solve their problems. In general, the datasets buyers need do not directly match the datasets sellers offer. The arbiter's goal is to combine datasets offered by sellers into a *mashup* m that fulfills buyers' needs. In exchange for finding the mashup, buyers transfer an incentive (we use money as an incentive throughout this section) to the arbiter. The arbiter uses the money from the buyers to compensate the sellers who contributed datasets that were part of the sold mashup.

A brief discussion of buyers' utility in an external market. In its simplest form, we assume a buyer's utility, u_i, is determined by a function: $u_i = v_i - p_i$, where v_i is the private valuation the buyer assigns to the data and p_i is the price they pay for it. For the buyers to participate in the market in a way that does not decrease their utility, they must know v_i. In the discussion that follows, we assume they know v_i; we differentiate cases where they know v_i before using the data (Section 3.2.2.1) and after in Section 3.2.2.2.

Data Model. To define market design we assume a market of *structured data* and consider other data models later in the paper. In a market of structured data, d_i are relations and m is a combination of d_i. The arbiter's goal is to identify a function, $F(d_i) = m$, that transforms a combination of datasets into a mashup. Note the function $F()$ does not need to use relational operations only.

3.1 Market Design

A *market design*, M, is a collection of 5 components that govern the interactions between sellers, buyers, and arbiter.

Elicitation Protocol. An elicitation protocol is established between buyers and arbiter in order to agree on a data transaction. Unlike in traditional market of goods, the mashup that a buyer desires may not exist before the arbiter builds it, so this need must be communicated. We introduce a willing-to-pay function (**WTP-function**) as a building block of elicitation protocols. The buyer uses the WTP-function to indicate the data it needs and how much it is willing to pay for it.

Allocation function. At any given time, multiple buyers may want to buy a particular mashup of interest. The allocation function solves which buyers get what mashup.

Payment function. This function indicates how much money buyers need to pay to obtain the mashup.

Revenue allocation. This function determines how much of the revenue raised by selling m is allocated to the data that led to m. In the case of markets of relational data, a mashup is a relation, and the revenue allocation function determines how much of the money raised is allocated to each row in the mashup.

Revenue sharing. Following with the previous example, if m is a relation, a row in m results from applying $F()$ to the input datasets, d. The revenue sharing function determines how the value allocated to a row in m propagates to d.

The space of market designs is vast. We are interested in market designs that lead to good outcomes when participants are strategic, i.e., they seek to maximize their own interests. In particular, we are interested in market designs that: i) guarantee incentive-compatibility; ii) that maximize a market goal, and; iii) that are practical. We briefly discuss each of the requirements for good market designs.

Incentive-compatible means that the best strategy the market players (i.e., buyers and sellers) have is to participate *truthfully*, e.g., it is in buyers' best interest to declare their true mashup valuation instead of gaming the market. This property is important for two reasons. First, it is easy for the players to understand how they participate in the market, as opposed to having to strategize based on other participants' actions. Second, it is possible for the market designer (i.e., us) to understand the market outcomes and therefore make sure it works as we wish.

Market goals. A market design can be engineered to maximize revenue, to optimize social surplus, and others. These goals can be formally guaranteed. We discuss later how different market environments require different goals.

Finally, the market design must be *practical*. This means it can be implemented in software and serve many participants; i.e., the 5 components of a market design must be computationally efficient.

3.2 Challenges and Research Agenda

We discuss next 3 challenges of market designs related to the 5 components we have described above.

3.2.1 The Unique Characteristics of Data as an Asset

The allocation and payment functions of the market design must ensure incentive-compatibility from the buyers' side. Data uniqueness as an asset makes it challenging to design these mechanisms.

The allocation and payment functions decide who gets the asset and how much they pay for it. Auctions offer an example of allocation and payment functions. For example, in a generalized second-price auction [67], buyers bid for assets and the market decides who obtains the asset in such a way that the top-K bids are allocated the K finite assets and each kth-buyer pays the bid made by the (k-1)-buyer. Auctions of this kind have been used, among others, to implement real time ad-bidding that powers today's Internet economy [48]. The technical details that explain why this mechanism works and elicits truthful behavior from participants are beyond of the scope of this paper. When designing mechanisms [70] to trade data we must pay attention to its unique characteristics as an asset: data is **freely replicable** and it **can be combined arbitrarily**.

Because data is *freely replicable*, it could be trivially allocated to anyone who wants it because its supply is infinite. That is at odds with eliciting truthful behavior from buyers because if buyers know that supply is infinite they will underbid knowing they will eventually get allocated the asset. Because data can be *combined arbitrarily* it is difficult to price a dataset before knowing how it will be used.

Mechanisms to trade digital goods with infinite supply have been proposed before [14, 45, 46]. We are building on these ideas when engineering market designs.

In particular, we are designing new allocation and payment mechanisms that work when data is the asset and that are resistant to strategic players who know how to maximize their utility (the value they get for the data they obtain) over time. The mechanisms we are designing take into consideration the externalities generated when trading data. These externalities are related, among others, to privacy loss by the individual, which is multiplied with the potential for arbitrary combination of datasets.

3.2.2 Elicitation Protocol

This challenge is concerned with the design of protocols that allow buyers and arbiter to communicate what data is needed, and how much money buyers are willing to pay for it. We introduce a WTP-function to achieve this, and consider two different protocols. The first is appropriate when buyers know how to value (v_i) the dataset a priori, and the second when they only learn v_i after seeing and using the data. For example, buyers may sometimes know the attributes they need to train a classifier or producing a report. Other times, buyers may need to engage in exploratory tasks before being able to declare he task they want to solve.

3.2.2.1 Buyers know what they want.

In its simplest case, a WTP-function contains a superset of the information required to combine datasets. In this case, buyers need to indicate: i) the task they want to solve; ii) a metric to measure the *degree of satisfaction* that a dataset achieves for given a task; iii) a price function that indicates how much they are willing to pay depending on the degree of satisfaction achieved. For example, a buyer who wants to train a machine learning classifier can specify the features desired as attributes of a relation—in a query-by-example type of interface [40]. The buyer can indicate that the metric of interest is accuracy and they may declare they are willing to pay \$100 for any dataset that permits the model achieve 80% accuracy, and \$150 if the accuracy goes beyond 90%.

Conveying all this information is hard, however, and depends on the specific task, metric, and pricing strategy. To model these needs, the **WTP-function** consists of 4 components:

•A package that includes the data task that buyers want to solve. For example, the code to train an ML classifier. The package is sent to the arbiter, so the arbiter can evaluate different datasets on the data task and measure the degree of satisfaction.

•A function that assigns a WTP price to each degree of satisfaction. For example, this function may indicate that the buyer will not pay any money for classifiers that do not achieve at least 80% classification accuracy, and that after reaching 80% accuracy, the buyer will pay \$100.

•Packaged data that buyers may already own and do not want to pay money for. For example, when buyers own multiple features relevant to train the ML model but want other datasets to augment their data with more features and training samples, they can send their code and data to the arbiter.

•List of intrinsic dataset properties such as *expiry date* to indicate for how long data is valuable to them; *freshness* to indicate that more recent datasets are more valuable; *authorship* to indicate preferences in who created the dataset; *provenance* to indicate buyer needs to know how data was generated; and many others such as semantic metadata, documentation, frequency of change, quality, etc. For example, the buyer may indicate the need for data not older than 2 months, fearing concept drift [92] will affect classification accuracy otherwise.

There are many interesting challenges around implementing WTP-functions that fall directly into the realms of database research.

Interface We are working on new interfaces to enable users to easily define WTP-functions. These new interfaces must permit declaration of data tasks without looking at the data first, for example, through a schema description [40], that is similar to query-by-example interfaces. These new interfaces require new data models to express not only relational operations but also fusion operations that would permit merging/contrasting different signals/opinions and transformation needs, such as pivoting, aggregates, confidence intervals, etc. The WTP-Functions produced need to be interpreted by the *mashup builder*, a component we introduce in the next section as part of our DMMS architecture that is in charge of matching supply and demand.

Task Multiplicity Different tasks require different metrics to measure the *degree of satisfaction*. For example, a classification task may use *accuracy* as the metric of choice. A relational query may benefit from notions of *completeness* borrowed from the approximate query processing literature [75]. Dealing with this multiplicity of tasks introduces interesting research challenges.

3.2.2.2 Buyers do not know how much to pay.

Sometimes buyers want to engage in exploratory tasks with data without having a precisely defined question a priori. In these cases, it is not possible for the buyer to describe the task they are trying to solve. It follows they cannot express how much they are willing to pay for a dataset.

We are investigating *ex post* mechanisms that work in the following way. Buyers get the data they want before they pay any money for it. After using the data and discovering—a posteriori—how much they value the dataset, they pay the corresponding quantity to the arbiter. In this situation, one may think that buyers will be motivated to misreport their true value to maximize their utility. The crucial aspect of the mechanisms we are designing is that they make reporting the real value the buyer's preferred strategy.

3.2.3 Revenue Allocation and Sharing

The last challenge is concerned with the last two components of the market design: revenue allocation and revenue sharing. Consider the arbiter uses a function, $f()$, to create a mashup m from datasets d_1, d_2 and d_3. The function can be in its simplest case a relational query but it can also contain non-relational operations. We evaluate the WTP-function provided by a buyer on m and determine that m's price is p after measuring the degree of satisfaction.

Revenue allocation. The revenue allocation problem consists of determining what portion of p is allocated to each row in m. Intuitively, this is asking how valuable is each row in the mashup. Some related work has modeled this problem as if each row in m was an agent cooperating together with all other rows to form m. Within this framework, the Shapley value [84] has been used to allocate revenue to each row individually after assuming that the involved datasets participate in a coalition. We are investigating alternative approaches that are more computationally efficient and maintain the good properties conferred by the Shapley value.

Revenue sharing. The revenue sharing problem determines how the price from each row in m is shared among the contributing datasets, in the example above d_1, d_2 and d_3. The contribution of the datasets to m is determined by the function $f()$ used by the arbiter in the first place to build m. The revenue sharing problem consists of reverse engineering such function. Note that if $f()$ is a relational function, then we can leverage the vast research in provenance [30, 50] to approach the revenue sharing problem. When $f()$ is a more general function, revenue sharing becomes challenging. We are investigating information-theory and flow control techniques to understand how to approach this problem.

3.3 Market Design Space

The space for market designs is vast and depends on the specific constraints and goals that we want the market to honor. We consider below different markets and discuss how they motivate different market designs.

External markets. In external markets, independent organizations trade data assets. In this case, money is a good incentive to get companies who own valuable information to share it with others that may benefit from its use. One possible market design for this scenario is to maximize revenue. The arbiter extracts as much money from buyers as possible so it can use that money to incentivize sellers to share their data. Variations of this market may allow sellers to set a reserve price; sellers will not sell any data unless they obtain a given quantity. Achieving these goals requires careful design of the 5 components of a market design.

Internal markets. In internal markets, members of an organization share data internally to maximize data's value. Internal data market platforms have the promise of bringing down data silos by incentivizing data owners (e.g., specific teams, or individuals) to publish their data in a way that is easy to consume by others, in exchange for some reward. In this scenario, it is reasonable that a market design optimizes social welfare, that is, the allocation of data to buyers. The mechanisms to incentivize sellers can take the form of bonus points, or time.

Barter and Gift Markets. These are markets where the participant's incentive to share their data is to receive data or services from somebody else. Existing barter markets are coalitions of hospitals [25, 51], but also the exchange of personal data for Internet services, such as social media platforms, etc. Market designs for this kind of market will differ from external and internal markets.

The variety of market designs one may want to deploy calls for plug'n'play interfaces. We aim to design data-market management systems (DMMS) that permit the declaration of a wide variety of market designs to cater for different scenarios and their deployment on the same software platform (see Fig. 1). We explain the architecture of the DMMS in the next section. Before that, we include a FAQ and a summary of this section.

3.4 FAQ: Frequently Asked Questions

Why would people use the market to share data? A well-designed market incentivizes sellers to share data to obtain some profit, which may be monetary or some other form. It also incentivizes buyers to share their data needs in exchange for having their discovery and integration problems solved by the arbiter.

What if I am not sure if my dataset is leaking personal information? Sharing data is predicated on the assumption that it is legal. Certain PII information, for example, cannot be shared across entities without users' permission. The DMMS that we present in the next section offers tools that help to reduce the risk of leaking data.

In addition, once a dataset has been assigned a price, it is possible to envision a data insurance market, where a different entity than the seller (i.e., the arbiter) takes liability for any legal problems caused by that data. In this case, the arbiter is incentivized to avoid those problems, stimulating more research in secure and responsible sharing of data.

Wouldn't markets concentrate data around a few organizations even more? Today, data is mostly concentrated around a handful of companies with the expertise and resources to generate, process and use it. Ideally, we want to design markets that bring the value of data to a broader audience. It is certainly possible that a market would only worsen this concentration by allocating data to the richest and more powerful players. Fortunately, it is possible to design markets that disincentivize this outcome: achieving that is a goal of our research.

Is there going to be enough demand for a given, single dataset? We expect certain datasets will naturally have less demand than others, as with any asset today. However, with a powerful enough arbiter, individual datasets are combined and add value to lots of different mashups that may be, in turn, designed to satisfy a varied set of buyers' needs.

Furthermore, studying the market dynamics will be important to determine, for example, if domain-specific markets (markets for finance, for health, for agriculture) would be more efficient than more general ones in concentrating and uncovering highly valuable datasets.

Why would a seller or buyer trust the arbiter? We do not assume they would, and we discuss in the next section how this is a key design goal of a DMMS.

The arbiter could prevent data duplication by assessing what datasets to accept, hence addressing one of the challenges of selling data. Regardless of the merits of that mechanism to enforce the right outcomes in the market, this design would not allow participants to trade freely. Furthermore, since datasets can be arbitrarily similar to each other, it is unclear what threshold the arbiter should use to make a decision, or how to compute that threshold in the first place.

Why would a buyer give out their code (as part of the WTP-function) when it may be an industrial secret? If a buyer knows how to specify a WTP-function for their task and they are willing to give the code away, then the mechanism explained above works. If the buyers do not know how to specify a WTP-function or they are not willing to give their code away, they can use the mechanism we

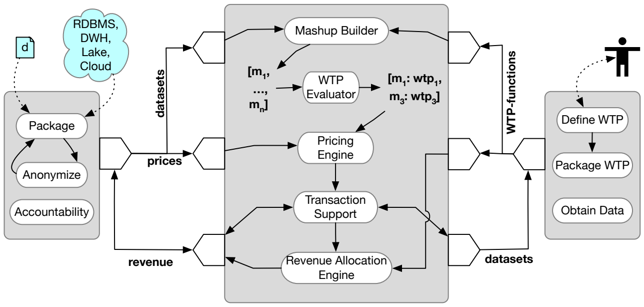

Figure 2: Architecture of a Data Market Management System.

discuss in Section 3.2.2.2 to obtain the data from the arbiter and run the code locally. The challenge in this situation is related to designing *truthful* mechanisms that incentivize buyers to tell the real value instead of reporting a low value to maximize their utility.

4. DATA MARKET MANAGMT. SYSTEM

Data market management systems must be designed to support different market designs and they must offer software support to sellers, buyers, and the arbiter. The DMMS system we propose achieves that using a seller, buyer, and arbiter management platforms, which are shown in Fig. 2.

4.1 Overview of Arbiter Managmt. Platform

The arbiter management platform (AMP) is the most complex of all DMMS's components: it builds mashups to match supply and demand, and it implements the five market design components. We use the architecture in Fig. 2 to drive the description of how the AMS works.

The AMS receives a collection of WTP-functions from buyers specifying the data needs they have. Sellers share their datasets with the arbiter, expecting to profit from transactions that include their datasets. The AMS uses the **Mashup Builder** (top of the figure) to identify combinations of datasets (i.e., *mashups*) that satisfy buyers' needs. These are depicted as $[m_1, m_2, ..., m_n]$ in the figure.

The next step is to evaluate the degree of satisfaction that each mashup achieves for each buyer's WTP-function. This task is conducted by the **WTP-Evaluator**. The WTP-Evaluator first runs the WTP-function code on each mashup and measures the degree of satisfaction achieved. With the degree of satisfaction, it then computes the amount of money (or other incentives) the buyer is willing to pay, wtp_i. The output of the WTP-Evaluator is a collection of pairs m_i, wtp_i indicating the amount of money that a buyer is willing to pay for each mashup that fits the needs indicated by their WTP-function.

The next step is to use the **Pricing Engine** to set a price for each m_i and choose a winner[1]. The **Transaction Support** component delivers m_i to the winning buyer and obtains the money, wtp_i. Finally, the **Revenue Allocation Engine** allocates wtp_i among the sellers that contributed datasets used to build m_i and the arbiter. At this point the transaction is completed.

Arbiter Services. Because the arbiter knows the supply and demand for datasets, it can use this information to offer additional services for buyers and sellers, perhaps for a fee. For example, the arbiter could recommend datasets to buyers based on what similar buyers have purchased before [83]. This kind of service, however, leaks information that was previously private to other buyers. This information leak affects the elicitation, allocation, and payment functions of the market design (see Section 3.1). To see why, consider how a buyer may change their bidding strategy if they knew the price at which a dataset was sold recently.

Negotiation Rounds. If the AMS cannot find mashups that fulfill the buyer's needs, it can describe the information it lacks and ask the sellers to complete it. Sellers are incentivized to add that information to receive a profit. For example, the AMS may ask the seller to explain how to transform an attribute so it joins with another one, or it may request information about how a dataset was obtained/measured, semantic annotations, mapping tables, etc. Sellers will be incentivized to help if that raises their prospect of profiting from the transaction. Similarly, buyers can request the arbiter for data context (provenance, how data was measured/sampled, how fresh it is, etc.) when they need it to use the data effectively.

4.2 Seller Management Platform

The SMP communicates with the AMS to share datasets and receive profit, to coordinate private data release procedures (as we see next), as well as to agree on changes to the dataset that may improve the seller's chances of participating in a profitable transaction. Next, we explain the key services we envision SMP offering sellers:

Statistical Database Privacy. Even if incentivized to sell data for money, sellers face a deterrent when their data may leak information—e.g., personally identifiable information (PII)—that should not be public. To assist sellers, the SMP must incorporate some support for the safe release of such sensitive datasets. And because datasets may leak information when combined with other datasets [69]—which is precisely what the arbiter will do as part of the mashup building process—the protection process must be coordinated between SMP and AMS. This component introduces opportunities to leverage the rich literature on differential privacy [38] and variants [59]. Applying statistical database privacy will reduce data's value for buyers who want to access precisely those records. It is an open area of research to understand how to price the externality that the loss in privacy introduces, a question other work has started exploring [62]. The challenge is on identifying a good balance between protection and profit.

Accountability. The SMP must allow sellers to track how their datasets are being sold in the market, e.g., as part of what mashups. When sellers update datasets in the platform, the SMP incrementally updates the information recorded about those datasets subject to an optional access quota established by the origin system. This permits the SMP to maintain fine-grained lineage information that is made available on demand.

Data Packaging. The SMP transforms datasets provided by sellers into a format interpretable by the arbiter. In addition, this feature allow sellers to share datasets in bulk by pointing to a data lake, cloud storage full of files, a databases, or data warehouse. This functionality is useful in internal data markets to unlock data silos.

[1] the market design may specify more than one winner, but we use one here to simplify the presentation

4.3 Buyer Management Platform

Data buyers must provide the arbiter with a willing-to-pay function (WTP-function) that indicates the price a buyer is willing to pay given the satisfaction achieved by a given dataset. Buyer management platforms (BMP) have the following requirements:

- Because manually describing a WTP function may be difficult, a BMP must help buyers define it through interfaces that permit descriptions of a multiplicity of tasks (see Section 3.2.2.1).
- Secure sharing of the WTP function with the arbiter, so the arbiter computes the level of satisfaction of different mashups and obtains the WTP price buyer bids for such a mashup.
- Finally, a communication channel enables buyer-arbiter exchange mashups, WTP-functions, as well as allow the arbiter to recommend alternative datasets to the buyer, e.g., when the arbiter knows of other similar buyers who have acquired such datasets.

4.4 Trust, Licensing, Transparency

Now we zoom out to the general architecture comprising AMS, BMS, and SMS and consider how differing degrees of trust, the existence of data licenses, as well as the need for transparency, introduce additional challenges for the design and implementation of a DMMS.

Trust. We have assumed so far that sellers and buyers trust the arbiter. Sellers trust that the arbiter will not share the data without sellers' consent, that it will implement the rules established by the market design faithfully, and that it will allocate revenue following those rules too. Buyers trust the arbiter with their code (that ships as part of the WTP-function), and similar to sellers, they trust the arbiter will enforce the agreed market rules. We think this trust is generally granted in the context of internal markets. In the context of external markets, although we think it is reasonable to assume trust in a third party—similar to how individuals and organizations trust the stock market—it is conceivable to imagine scenarios where trust is not granted. In this case, we need to consider techniques on privacy-preserving data management [38], processing over encrypted data [43], as well as decentralized, peer-to-peer markets and blockchain platforms [11, 68]. Using the above techniques it is conceivable to engineer the arbiter so it is not a logically centralized entity anymore, hence aiding buyers and sellers to gain trust and participate in the market. Introducing these techniques protects data owners at the cost of reducing data's value. Others have explored this tradeoff [20, 22, 62] making an explicit connection between privacy and data value. Finally, for situations when the chain of trust is broken, dispute management systems must be either embedded in or informed by the transactions that take place in the DMMS so the appropriate entities can intervene and resolve the situation.

Data licensing. Sellers can assign different licenses to the datasets they share that would confer different rights to the beneficiary. Similarly, buyers may be interested in obtaining datasets subject to licensing constraints. For example, a hedge fund may want to acquire a dataset with exclusive access, preventing perhaps other competitors to access the same data. The artificial scarcity generated by this license should cost more to buyers, who could be forced to pay a 'tax' so long they maintain the exclusivity access. Other types of licenses are those that transfer ownership completely, so buyers sell the datasets as soon as they have bought them (creating a market for arbitrageurs as we discuss in the next section), or licenses that prevent the beneficiaries from selling a previously acquired dataset. Supporting these licensing options affects both market design and DMMS system. Furthermore, it raises questions of legality and ethics that go beyond computer science and economics. Concretely, we are exploring software implementations of contextual integrity [71], which we believe may be an interesting vehicle to enable data licensing.

Transparency. Transparency may be required at many points of the market process. Sellers may need to know in what mashups their data is being sold and what aspects of their data (rows, columns, specific values) is more valuable. Similarly, buyers may request transparent access to the mashup building process to understand the original datasets that contribute to the mashup and decide whether to trust them or not. We do not discuss the implications of these requirements, we only highlight they have an impact on the engineering of a DMMS.

4.5 Markets of Many Data Types

We have presented the AMP, SMP, and BMP without focusing on a specific type of data to be exchanged. We envision markets to trade data of many types:

Multimedia Data. A variety of multimedia data such as text, web (i.e., a search engine market that does not depend on ads?), as well as images and video are likely targets for a data market platform. How to build DMMS platforms to reason about how to combine and prepare this data for buyers is a challenge.

Markets for Personal Data. Ultimately, we would like to be able to price a person's own information. If I knew how much the information I am giving an online service is worth, I could make a better decision on whether the exchange is really worth it or not. Because many times an individual's own data is not worth much in itself—but quickly raises its value when aggregated with other users—it is conceivable that coalitions of users would form who collectively would choose to relinquish/sell certain personal information to benefit together from their services. Some are advocating for these so-called *data trusts* [3, 32].

Embeddings and ML Models. Embeddings and vector data are growing fast because they are the input and output format of many ML pipelines. As data-driven companies keep building on their ML capabilities, we expect this data will only grow. Obtaining some of these embeddings incurs a high cost in compute resources, carbon footprint, and time. For example, the BERT pre-trained models produced by Google [35] take many compute hours to build. For this reason, we expect companies will rely on the exchange of pre-trained embeddings more and more, and hence our interest in supporting this format in our data market platforms. More generally, this motivates markets for data products—i.e., software, data, and services derived from data.

We focus initially on tabular data such as relations and spreadsheets because this data is sufficient to cover most business reporting, analytical, as well as many machine learning tasks. In the next section, we introduce a **Mashup Builder** specific to this type of data.

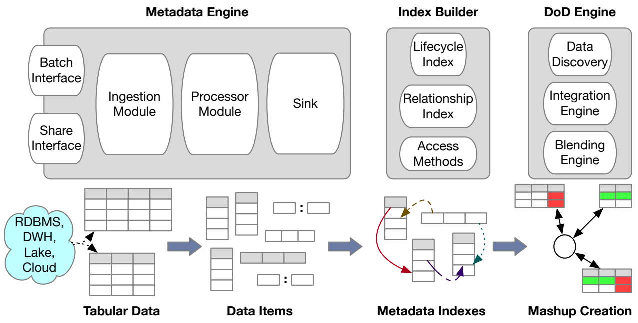

Figure 3: Architecture of Mashup Builder: metadata engine, index builder and DoD engine.

5. MATCHING SUPPLY AND DEMAND

The goal of the mashup builder is to generate a collection of mashups that satisfy a WTP-function. Key research goals of our vision are to understand the extent to which this process can be fully automated, and devise the best ways of involving humans when it is not possible (see Section 5.4). The architecture of the system we are building is depicted in Fig. 3 and is designed to address the following problems:

Data Discovery. The arbiter receives datasets from sellers, some of whom may be organizations with thousands of datasets. The goal of data discovery is to identify a *few* datasets that are relevant to a WTP-function among thousands of diverse heterogeneous datasets.

Data Integration and Blending. The goal of data integration and blending is to identify strategies to combine the datasets identified by the discovery component into mashups that satisfy the WTP-function. Those strategies consist of identifying mapping and transformation functions to join attributes as well as other preparation tasks such as value interpolation to join on different time granularities.

Because multiple similar datasets may contribute to the same or a small group of similar mashups, **data fusion** operations permit combining and contrasting the different combinations, keeping track of the origin of each data item, so consumers understand how data was assembled.

We bootstrap the implementation of the mashup builder with Aurum [19], a data discovery system that allows users to find relevant datasets and to combine them using join operations. To do that it extracts metadata from the input datasets, it organizes that metadata in an index and uses the index to identify datasets based on the criteria indicated in the WTP-function. The architecture of the Mashup Builder is shown in Fig. 3. We describe the components next:

5.1 Metadata Engine

The metadata engine's goal is to read and maintain the lifecycle of each input dataset. Datasets can be automatically read from a *source* in bulk (e.g., a relational database, a data lake, a repository of CSV files in the cloud) or they can be registered manually by a user who wants to share specific datasets. When datasets change in the sources, e.g., when users manually update them, the metadata engine registers and keeps track of these changes, maintaining version history. All these tasks are performed by the **ingestion module** through its batch and sharing interfaces as shown in the figure. Each dataset is divided conceptually into *data items*, which are the granularity of analysis of the engine. For example, a column data item can be used to extract the value distribution of that attribute. A row data item can be used to compute co-occurrences among values. A partial row data item can be used to compute correlations, among others. For each dataset, the metadata engine maintains a time-ordered list of context snapshots. A context snapshot captures the properties of each dataset's data item at each point in time. For example, signatures of its contents, a collection of human or machine owners (i.e., what code is using what data), as well as the security credentials. This is performed by the **Processor** component of the system.

Because data item information is not given directly at ingestion time, the engine must harness that information. Data market platforms aim to incentivize users to provide that information directly, but in certain scenarios this is not possible: e.g., a data steward pointing to a collection of databases in an internal organization. The output of the metadata engine is conceptually represented in a relational schema managed by the **Sink** component.

The metadata engine is a fully-incremental, always-on system that maintains the output schema as updated as possible while controlling the overhead incurred in the source systems and the precision of the output information.

5.2 Index Builder

The index builder processes the output schema produced by the metadata engine and shapes data so it can be consumed by the dataset-on-demand engine (DoD), which is the component in charge of integration and blending of mashups. Among other tasks, the index builder materializes join paths between files, and it identifies candidate functions to map attributes to each other; i.e., it facilitates the DoD's job. The index builder keeps indexes up-to-date as the output schema changes. This calls for efficient methods to leverage the signatures computed during the first stage.

5.3 DoD Engine

The DoD engine takes WTP-functions as input and produces mashups that fulfill the WTP-function requests as output. It uses the indexes built by the index builder, the output schema generated by the metadata engine, as well as the raw data.

The DoD relies on query reverse engineering and query-by-example techniques [91], as well as program-synthesis [6], among others, to produce the desired mashups.

Data Fusion. When there are many datasets available, DoD may find multiple alternatives to produce mashups. In certain cases, a buyer wants to see a contrast of mashups (this will be specified in the WTP-function). For example, consider a buyer who wants to access weather data and there are multiple sources that provide this information. A data fusion operator can align the differing values into a mashup that the buyer can explore manually. A specific fusion operator may select one value based on majority voting, for example, while other fusion operators will implement other strategies. Buyers may want to have access to all available signals to make up their own minds. As a consequence, buyers may want to use DoD's fusion operators to help combine the different sources into mashups.

5.4 Machines and People

Automatically assembling a mashup from individual datasets when only given a description of how the mashup should look is an ambitious goal. Our experience working on this problem for the last few years has taught us that in certain cases this may not be possible at all, such as when ambiguity makes it impossible to understand the right strategy to combine two datasets. We devise two strategies to tackle this problem.

Request additional input when automatic integration does not work. The first strategy is to have the AMS system interact with sellers to request additional information about the datasets they have shared that may help with the integration and blending process, e.g., a semantic annotation, a function to obtain an alternative representation, etc. Sellers willing to include the additional information can be incentivized to do so by obtaining a higher profit.

Involve humans in the loop. Another strategy is to directly incorporate humans-in-the-loop as part of the mashup builder's normal operation. This has been done to answer relational queries [41,42], and there are opportunities to extend those techniques to help with integration and blending operations as well. Because all this takes place in the context of a market, it becomes possible to compensate humans according to the value they are creating.

6. EVALUATION PLAN

In this section, we explain how we plan to evaluate market designs, as well as the DMMS implementation.

6.1 Simulation of Market Designs

A market design that is sound on paper may suffer unexpected setbacks in practice. This may happen because rationality assumptions made at design time may break in the wild. In the context of mechanism design/game theory, rationality is interpreted as players will play the best strategy available to them. Unfortunately, that does not account for risk-lover or ignorant players. Furthermore, some players may be adversarial in practice, forming coalitions with other players to game the market. Or less dramatic, a faulty piece of software may cause erratic behavior. Below, we explain how we plan to evaluate the effectiveness and efficiency of market design in practice.

Effectiveness. The mismatch between theory and practice calls for a framework to evaluate how resilient a market design is under adversarial, evil, and faulty processes. We plan to design a simulation platform where it is possible to implement different rules and change the behavior of players, and where it is possible to model adversarial, coalition-building, as well as risky and ignorant players (this is shown in (3) of Fig. 1). The simulation platform will test a market design's robustness before deployment.

Large-scale simulations introduce database challenges such as: i) supporting quick communication among many players (transaction processing); ii) modeling workloads to simulate different strategy distributions of players. Such a simulation framework will be of independent interest.

Efficiency. Market mechanisms are implemented with an algorithm. The fields of mechanism design and algorithmic game theory have contributed efficient approximation algorithms [70]. In databases, algorithms with high complexity are often used in practice for small problems, and conversely, sometimes algorithms with low complexity cannot be used practically because of the data size. We want to contribute empirical evaluations of these designs.

6.2 Building and Evaluating a DMMS

The vision is expansive and touches upon different disciplines. We think the database community is in a great position to refine, correct, expand, and contribute ideas towards our vision, hence the motivation for this vision paper. We layout next our research plan:

Market design. Because of the unique characteristics of data and the nature of the platform we propose, we need new theoretical designs that work in practice. We are in the process of engineering market designs for data.

Market platform. We consider the mashup builder a key component of our vision. We have experience building data discovery and integration systems and are using this experience to build this next generation of systems.

Market simulation. As explained above, we must have mechanisms to understand the properties of the markets we design before implementing them in a platform.

Among the multiple ways of creating a DMMS our choice is to start with internal markets. This will help us hone the interface with humans, understand the deployment context and its constraints better (e.g., issues of privacy, trust, licensing), as well as to conduct qualitative evaluations.

7. DATA MARKETS AND SOCIETY

The side effects of data markets span beyond computer science and economics. We plan to engage with the broader community of scholars at The University of Chicago and elsewhere to discuss and outline the challenges of data markets in a broader societal context. We outline some interesting aspects below.

7.1 Economic Opportunities

A well-functioning market generates economic opportunities for other players besides sellers and buyers:

Arbitrageurs. They play seller and buyer at the same time. Arbitrageurs buy certain datasets, transform them, perhaps combining them with certain information they possess, and sell them again to the market. The transaction generates a profit for them whenever the sold dataset is priced higher than the dataset they buy. Since we want to design mechanisms that price datasets based on supply and demand, it is conceivable that the participation of arbitrageurs in the market will rise data's value, because they will be incentivized to transform datasets into a shape that is desired by buyers.

Opportunistic data seller. Opportunistic data sellers may not own data, but they have time that they are willing to invest in collecting high-demand datasets. They obtain information about highly demanded datasets from the arbiter. For example, consider one more time the example of the introduction with the two sellers and the buyer. Consider a third seller, Seller 3, who does not own any dataset, but has time, and is willing to use that time to acquire/find data for profit. Because the arbiter knows that b_1 would benefit from attribute $\langle e \rangle$, which neither s_1 nor s_2 contain, the arbiter can ask Seller 3 to obtain a dataset $s_3 = \langle e \rangle$ for money. Because the arbiter knows supply and demand, not only does it help sellers and buyers, but it creates an ecosystem of economic opportunities for other entities.

Offloading tasks. As discussed above, when the arbiter does not know how to automatically assemble a mashup, it can schedule humans to help with the task and compensates them appropriately for their labor.

Data Insurance. Once data has a value and a price, it is possible to build an insurance market around it. Such an insurance market would be useful to reason about data breaches, for example. How liable is a company that suffers a data breach that results in leaking private customer information? Or, if a seller shares a dataset that is later de-anonymized by a third party, despite the best efforts from the arbiter to protect it, who is liable? Can/Should insurance cover these cases?

7.2 Legal and Ethical Dimension

Who owns a dataset? Throughout this paper, we have assumed that sellers owned the data they were sharing with the arbiter. Consider a seller who has collected a dataset through their manual effort and skill. In this case, does the seller own such a dataset? What if the records in the dataset correspond to users interacting with a service the seller has created? Do those users own part of the data too? A recent article from the New York Times [72] has illustrated in glaring detail how it is possible to determine with high precision the location of individuals and their daily activities from smartphone data traces. The data that permits that is routinely collected and sold by companies that profit from it. This leads to questions around what data is legal to possess, what does it mean to own data, and when it should be possible to trade data.

Market Failures. Markets sometimes fail and cause social havoc. Other times, markets work only for a few, causing or accentuating existing inequality. All markets are susceptible to these kinds of problems, including the ones we envision in this paper. The difference is that we haven't implemented our market yet, so we have a chance to study beforehand what the consequences of malfunctioning markets on society are and decide whether the tradeoffs are worth it. Forecasting the implications of different market designs is a key aspect of our vision; hence the simulation framework introduced in the previous section.

8. RELATED WORK

We propose the first comprehensive vision of end-to-end data market platforms that makes an explicit separation between design and implementation (DMMS). We start this section with a discussion of data markets (Section 8.1) and then focus on work related to the DMMS and the Mashup Builder in Section 8.3.

8.1 Markets of Data in the Wild

Existing Marketplaces of data. We use Dawex [31] as an illustrative example of platforms that refer to themselves as data markets. Others include OnAudience.com [74], BIG. Exchange [13], BuySellAds [17] for ad data, as well Qlik Datamarket [79], Xignite [99], WorldQuant [98], DataBroker DAO [27], Snowflake's Data Exchange [86], among others. In Dawex, sellers offer datasets that buyers can obtain for a fixed price after seeing a sample of the data. Dawex acts as a sharing platform but does not solve the discovery, integration, or pricing problems. Buyers need to commit to pay a price before truly knowing the value of the dataset. These characteristics are typical of today's data markets.

Data is traded today, everywhere. Data trade is pervasive. Consider the barter exchange in which users of platforms such as Facebook, Twitter, Google, or many others take part. Users give away their data in exchange of the service provided by the companies. Health institutions such as hospitals routinely share data to improve patient care and treatment [25, 51]. Consider the complex economy of data brokers [81, 85] who, albeit not directly connected to everyday consumers, trade data with the large corporations to profit. In many of these cases, the users who contribute their data are not aware of how it is being used behind the scenes [2, 87]. Recently, the concept of a data trust [32] has been proposed to treat data as labor and let users gain control of their data by pooling it together with other users. The data markets we propose make data trading explicit, and measuring data's externality is a component of our vision. We think these two characteristics bring transparency to an otherwise opaque economy.

8.2 Theoretical Data Markets

We discuss theoretical designs related to the components of a market design we discussed in Section 3.

Allocation and Payment functions. The marketplace for data proposal [4] models a market that solves the the allocation and payment problem in a static scenario with 1 buyer and multiple sellers. In [66], the authors propose an end-to-end market design that considers buyers and sellers arriving in a streaming fashion. This has been an active area of research modeled by work in dynamic mechanism design [76], revenue management [23], and algorithmic mechanism design. In the latter, the work on online auctions [10,15,47] for digital goods started an interesting line of research that has contributed results to ad auctions, among others. We are building on top of this rich literature with an emphasis for the trade of data when players are strategic over time and with the ability to construct mashups, a key component to avoid thin markets, where insufficient number of participants make trade inefficient.

Revenue allocation. A recent line of work has modeled certain machine learning settings as coalitions of players contributing (training) data to a model [4, 44, 56]. To assign credit to the input datasets, they use the Shapley value [84]. Other work suggests using a different metric, the core [102] which is also apt for coalitional games. Due to the complexity of computing the Shapley value, the contributions of these papers are usually approximations with good performance guarantees.

Query Pricing. There is a long and principled line of work coming from the database community around the problem of how to price queries [20, 22, 61, 62]. In this setting, a dataset has a set price. The problem is how to price relational queries on that dataset in such a way that arbitrage opportunities (obtaining the same data through a different and cheaper combination of queries) are not possible. Recent work in this line [20] also considers how to maximize revenue for the broker under the same pricing model as above. If all datasets of a market are thought of as views over a single relation, then the setting of this work resembles ours. However, many data integration tasks require arbitrary data transformations, and many buyers want to buy fused datasets that contain diverging opinions, for example. This line of work is complementary to our vision and we plan to include these ideas as part of our design.

Value of Data. An increasing amount of work from the economics literature focuses on understanding the value of data for a particular firm [9,16,58,94], an entire economy [39, 57]. This work is complementary to ours and relevant to understand, among others, how an individual or firm identifies their private valuation.

Privacy-Value Connection. This line of work makes a connection between data value and privacy [20, 22, 62]. The buyer can specify a level of privacy associated with a query, in such a way that the higher the privacy level, the less the dataset is perturbed, meaning the dataset will be of higher quality. Therefore, the higher the privacy level, the higher the price of the dataset.

In our vision we want to directly link market design with software platforms (DMMS) to provide an end-to-end market environment with rules governing every aspect and participant. We are interested in the engineering of plug'n'play platforms that can accept different market designs tailored to different scenarios, e.g., internal vs external markets. Although we expect to benefit from many of the past ideas, the database community faces unique challenges to build practical data markets.

8.3 DMMS Related Work

We discuss theory, algorithms, and systems for discovery and integration that are related to the Mashup Builder.

Data Sharing Platforms. The datahub system [12] introduced a data version control system implemented on a software platform that allows members of a team to collaborate. OrpheusDB [100] similarly offers teams the ability to collaborate over a relational system and capture how data evolves. Outside the database community, there are many sharing systems such as TIND [90], KOHA [60], as well as online repositories such as the Harvard Dataverse [29] or the ICPSR [54] at the University of Michigan, geared towards sharing data across the social sciences. Within organizations, data warehouses and lakes [33, 80] play the role of central hubs that facilitate data sharing.

AnyLog. The AnyLog system [1] proposes a platform to pool Internet-of-Things data into a logically decentralized repository. The paper emphasizes two key design decisions that are aligned with our data markets vision. First, participants are incentivized to share their data in exchange for rewards. Second, market forces guide data owners to curate their data in a way that is desired by data consumers. Dealing with the integration problem at the source is simpler than downstream. This idea is related to the *Negotiation Rounds* between arbiter and sellers we described in Section 4.1. We believe many of the ideas we proposed in this vision paper will complement efforts such as AnyLog and the DMMS we are building.

Data Discovery. Data discovery systems such as Infogather [101], Google Goods [52] and Dataset search [49], define a specific task and focus on how to build indexes to solve that task. There is also a line of work on data catalogs, with Amundsen [7], WhereHows [97], Databook [26] as open-source examples and Alation [5], Azure's data catalog [8], and Informatica's data catalog [55] as some commercial examples. A more general approach to data discovery is Aurum [19], which provides most of the functionality required to implement the systems above.

Data Integration. Relevant work in data integration is query reverse engineering [89,91], and query-by-example interfaces to data integration such as S4 [78]. Modern data integration systems such as Civilizer [34] and BigGorilla [21] assume the existence and participation of a human expert that needs to build DAGs of integration operators during the integration activity. Before these platforms, the *Dataspaces* [53] vision outlined many of the challenges and opportunities that we still demand of an integration system. We borrowed the term data mashup from the Yahoo Pipes system [77]. Related to creating mashups given many different datasets, some work [37] has studied the diminishing returns of integrating datasets.

Data Fusion and Truth Discovery. Data fusion refers to the ability to combine multiple sources of information to improve the quality of the end result. In our vision, we consider data fusion operators that permit combining multiple (possibly diverging) datasets and offer the result to users. This can be useful, among others, for truth discovery [64]: the process of identifying the real value for a specific variable. The database community has contributed results to these areas [36, 63, 65, 88]. We are building on top of this work to design fusion operators that can be incorporated into the DMMS architecture.

The DMMS systems we envision aim to incentivize buyers and sellers to solve the lack of information and incentives problem that keeps data siloed within and across organizations. At the same time, all the work above is relevant to build the mashup builder, which is one piece of the larger class of DMMS systems we envision.

9. DISCUSSION

In this paper, we presented a vision for data market platforms that focus on the problems of data sharing, discovery, and integration. These problems are a main hurdle to organizations' ability to exploit data.

Understanding data. While data and artificial intelligence are driving many changes to our economic, social, political, financial, and legal systems, we know surprisingly little about their foundations and governing dynamics. Furthermore, to an extent unseen in previous economic upheavals, the rapid pace of technological and social innovation is straining the ability of policy and economic practice to keep up. Moreover, while the recombination and integration of diverse data creates vast new value, we currently have neither theory for how data can be combined nor industrial policy for how to protect against the personal exposures and abuses that grow in proportion. We remain stuck with old models for understanding these new phenomena and antiquated heuristics for making decisions in the face of change. The data markets we propose are a vehicle to initiate the study of theory and systems to address this challenge.

We expect that the insights, algorithms, and systems we will produce will inform the design of future data market platforms. We expect that the different systems, simulators, and approaches proposed will pose interesting research questions for the database community.

10. REFERENCES

[1] D. Abadi, O. Arden, F. Nawab, and M. Shadmon. Anylog: a grand unification of the internet of things. In *CIDR*, 2020.

[2] A. Acquisti, C. Taylor, and L. Wagman. The economics of privacy. *Journal of economic Literature*, 54(2):442–92, 2016.

[3] T. D. F. Act. The data freedom act. `https://www.radicalxchange.org/wp-content/uploads/2020/03/DFA.pdf`, 2020.

[4] A. Agarwal, M. Dahleh, and T. Sarkar. A marketplace for data: An algorithmic solution. In *Proceedings of the 2019 ACM Conference on Economics and Computation*, EC '19, pages 701–726, New York, NY, USA, 2019. ACM.

[5] Alation Data Catalog: A Single Source of Reference. https://www.alation.com/.

[6] R. Alur, R. Singh, D. Fisman, and A. Solar-Lezama. Search-based program synthesis. *Commun. ACM*, 61(12):84–93, Nov. 2018.

[7] Amundsen — Lyft's data discovery & metadata engine. `https://eng.lyft.com/amundsen-lyfts-data-discovery-metadata-\`
`\engine-62d27254fbb9`, 2020.

[8] Microsoft Azure-Data Catalog: Get more value from your enterprise data assets. https://azure.microsoft.com/en-us/services/data-catalog/.

[9] P. Bajari, V. Chernozhukov, A. Hortaçsu, and J. Suzuki. The impact of big data on firm performance: An empirical investigation. Working Paper 24334, National Bureau of Economic Research, February 2018.

[10] Z. Bar-Yossef, K. Hildrum, and F. Wu. Incentive-compatible online auctions for digital goods. In *Proceedings of the thirteenth annual ACM-SIAM symposium on Discrete algorithms*, pages 964–970. Society for Industrial and Applied Mathematics, 2002.

[11] R. Beck, J. Stenum Czepluch, N. Lollike, and S. Malone. Blockchain–the gateway to trust-free cryptographic transactions. In *ECIS*, 2016.

[12] A. Bhardwaj, A. Deshpande, A. J. Elmore, D. Karger, S. Madden, A. Parameswaran, H. Subramanyam, E. Wu, and R. Zhang. Collaborative data analytics with datahub. *PVLDB*, 8(12):1916–1919, Aug. 2015.

[13] Big.exchange. https://big.exchange.

[14] A. Blum, V. Kumar, A. Rudra, and F. Wu. Online learning in online auctions. *Theoretical Computer Science*, 324(2-3):137–146, 2004.

[15] A. Blum, V. Kumar, A. Rudra, and F. Wu. Online learning in online auctions. *Theoretical Computer Science*, 324(2-3):137–146, 2004.

[16] E. Brynjolfsson, X. Hui, and M. Liu. Does machine translation affect international trade? evidence from a large digital platform. *Management Science*, 65(12):5449–5460, 2019.

[17] Buysellads. https://www.buysellads.com.

[18] M. Y. Carriere-Swallow and M. V. Haksar. *The economics and implications of data: an integrated perspective*. International Monetary Fund, 2019.

[19] R. Castro Fernandez, Z. Abedjan, F. Koko, G. Yuan, S. Madden, and M. Stonebraker. Aurum: A data discovery system. In *2018 IEEE 34th International Conference on Data Engineering (ICDE)*, pages 1001–1012, April 2018.

[20] S. Chawla, S. Deep, P. Koutrisw, and Y. Teng. Revenue maximization for query pricing. *PVLDB*, 13(1):1–14, Sept. 2019.

[21] C. Chen, B. Golshan, A. Y. Halevy, W. C. Tan, and A. Doan. Biggorilla: An open-source ecosystem for data preparation and integration. *IEEE Data Eng. Bull.*, 41:10–22, 2018.

[22] L. Chen, P. Koutris, and A. Kumar. Towards model-based pricing for machine learning in a data marketplace. In *Proceedings of the 2019 International Conference on Management of Data*, SIGMOD '19, pages 1535–1552, New York, NY, USA, 2019. ACM.

[23] Y. Chen, V. F. Farias, and N. Trichakis. On the efficacy of static prices for revenue management in the face of strategic customers. *Management Science*, 65(12):5535–5555, 2019.

[24] R. H. Coase. The nature of the firm. In *Essential readings in economics*, pages 37–54. Springer, 1995.

[25] N. O. Data. Nhs open data. `https://www.england.nhs.uk/ourwork/tsd/data-info/open-data/`, 2020.

[26] Databook: Turning Big Data into Knowledge with Metadata at Uber. https://eng.uber.com/databook/.

[27] Databroker dao. https://databrokerdao.com/.

[28] Data.gov. data.gov. `https://www.data.gov`, 2020.

[29] Harvard dataverse. https://dataverse.harvard.edu/.

[30] S. B. Davidson and J. Freire. Provenance and scientific workflows: Challenges and opportunities. In *Proceedings of the 2008 ACM SIGMOD International Conference on Management of Data*, SIGMOD '08, page 1345–1350, New York, NY, USA, 2008. Association for Computing Machinery.

[31] Dawex: Sell, buy and share data. https://www.dawex.com/en/.

[32] S. Delacroix and N. D. Lawrence. Bottom-up data Trusts: disturbing the 'one size fits all' approach to data governance. *International Data Privacy Law*, 9(4):236–252, 10 2019.

[33] Delta lake. https://delta.io.

[34] D. Deng, R. C. Fernandez, Z. Abedjan, S. Wang, M. Stonebraker, A. K. Elmagarmid, I. F. Ilyas, S. Madden, M. Ouzzani, and N. Tang. The data civilizer system. In *CIDR*, 2017.

[35] J. Devlin, M.-W. Chang, K. Lee, and K. Toutanova. Bert: Pre-training of deep bidirectional transformers for language understanding. *arXiv preprint arXiv:1810.04805*, 2018.

[36] X. L. Dong, L. Berti-Equille, and D. Srivastava. Integrating conflicting data: The role of source dependence. *PVLDB*, 2(1):550–561, Aug. 2009.

[37] X. L. Dong, B. Saha, and D. Srivastava. Less is more: selecting sources wisely for integration. In *Proceedings of the 39th international conference on Very Large Data Bases*, PVLDB, pages 37–48. VLDB Endowment, 2013.

[38] C. Dwork and A. Roth. The algorithmic foundations of differential privacy. *Found. Trends Theor. Comput.*

Sci., 9(3&#8211;4):211–407, Aug. 2014.

[39] M. Farboodi, R. Mihet, T. Philippon, and L. Veldkamp. Big data and firm dynamics. In *AEA papers and proceedings*, volume 109, pages 38–42, 2019.

[40] R. C. Fernandez, N. Tang, M. Ouzzani, M. Stonebraker, and S. Madden. Dataset-on-demand: Automatic view search and presentation for data discovery, 2019.

[41] M. J. Franklin, D. Kossmann, T. Kraska, S. Ramesh, and R. Xin. Crowddb: Answering queries with crowdsourcing. In *Proceedings of the 2011 ACM SIGMOD International Conference on Management of Data*, SIGMOD '11, page 61–72, New York, NY, USA, 2011. Association for Computing Machinery.

[42] M. J. Franklin, B. Trushkowsky, P. Sarkar, and T. Kraska. Crowdsourced enumeration queries. In *Proceedings of the 2013 IEEE International Conference on Data Engineering (ICDE 2013)*, ICDE '13, page 673–684, USA, 2013. IEEE Computer Society.

[43] C. Gentry and D. Boneh. *A fully homomorphic encryption scheme*, volume 20. Stanford University Stanford, 2009.

[44] A. Ghorbani and J. Zou. Data Shapley: Equitable Valuation of Data for Machine Learning. In K. Chaudhuri and R. Salakhutdinov, editors, *Proceedings of the 36th International Conference on Machine Learning*, volume 97 of *Proceedings of Machine Learning Research*, pages 2242–2251, Long Beach, California, USA, 09–15 Jun 2019. PMLR.

[45] A. V. Goldberg and J. D. Hartline. Competitive auctions for multiple digital goods. In *Proceedings of the 9th Annual European Symposium on Algorithms*, ESA '01, page 416–427, Berlin, Heidelberg, 2001. Springer-Verlag.

[46] A. V. Goldberg and J. D. Hartline. Envy-free auctions for digital goods. In *Proceedings of the 4th ACM Conference on Electronic Commerce*, EC '03, page 29–35, New York, NY, USA, 2003. Association for Computing Machinery.

[47] A. V. Goldberg, J. D. Hartline, A. R. Karlin, M. Saks, and A. Wright. Competitive auctions. *Games and Economic Behavior*, 55(2):242–269, 2006.

[48] Google. About the ad auction. `https://support.google.com/adsense/answer/160525?hl=en`, 2020.

[49] Google dataset search. https://toolbox.google.com/datasetsearch.

[50] T. J. Green, G. Karvounarakis, and V. Tannen. Provenance semirings. In *Proceedings of the Twenty-Sixth ACM SIGMOD-SIGACT-SIGART Symposium on Principles of Database Systems*, PODS '07, page 31–40, New York, NY, USA, 2007. Association for Computing Machinery.

[51] J. M. Grossman, T. S. Bodenheimer, and K. McKenzie. Hospital-physician portals: the role of competition in driving clinical data exchange. *Health Affairs*, 25(6):1629–1636, 2006.

[52] A. Halevy et al. Goods: Organizing Google's Datasets. In *SIGMOD*, 2016.

[53] A. Halevy, M. Franklin, and D. Maier. Principles of dataspace systems. In *Proceedings of the twenty-fifth ACM SIGMOD-SIGACT-SIGART symposium on Principles of database systems*, pages 1–9, 2006.

[54] ICPSR: Sharing data to advance science. https://www.icpsr.umich.edu/icpsrweb/.

[55] Informatica-Enterprise Data Catalog: Discover and inventory data assets across your organization. https://www.informatica.com/products/data-catalog/enterprise-data-catalog.html.

[56] R. Jia, D. Dao, B. Wang, F. A. Hubis, N. M. Gurel, B. Li, C. Zhang, C. Spanos, and D. Song. Efficient task-specific data valuation for nearest neighbor algorithms. *PVLDB*, 12(11):1610–1623, July 2019.

[57] C. I. Jones and C. Tonetti. Nonrivalry and the economics of data. Technical report, National Bureau of Economic Research, 2019.

[58] E. Junqué de Fortuny, D. Martens, and F. Provost. Predictive modeling with big data: Is bigger really better? *Big Data*, 1(4):215–226, 2013. PMID: 27447254.

[59] D. Kifer and A. Machanavajjhala. Pufferfish: A framework for mathematical privacy definitions. *ACM Trans. Database Syst.*, 39(1), Jan. 2014.

[60] Koha library software. https://koha-community.org/.

[61] P. Koutris, P. Upadhyaya, M. Balazinska, B. Howe, and D. Suciu. Query-based data pricing. *J. ACM*, 62(5):43:1–43:44, Nov. 2015.

[62] C. Li, D. Y. Li, G. Miklau, and D. Suciu. A theory of pricing private data. *ACM Trans. Database Syst.*, 39(4):34:1–34:28, Dec. 2014.

[63] X. Li, X. L. Dong, K. Lyons, W. Meng, and D. Srivastava. Truth finding on the deep web: Is the problem solved? *PVLDB*, 6(2):97–108, Dec. 2012.

[64] Y. Li, J. Gao, C. Meng, Q. Li, L. Su, B. Zhao, W. Fan, and J. Han. A survey on truth discovery. *SIGKDD Explor. Newsl.*, 17(2):1–16, Feb. 2016.

[65] X. Lin and L. Chen. Domain-aware multi-truth discovery from conflicting sources. *PVLDB*, 11(5):635–647, Jan. 2018.

[66] D. Moor. Data markets with dynamic arrival of buyers and sellers. In *Proceedings of the 14th Workshop on the Economics of Networks, Systems and Computation*, NetEcon '19, New York, NY, USA, 2019. Association for Computing Machinery.

[67] R. B. Myerson. Optimal auction design. *Math. Oper. Res.*, 6(1):58–73, Feb. 1981.

[68] S. Nakamoto. Bitcoin: A peer-to-peer electronic cash system, 2009.

[69] A. Narayanan and V. Shmatikov. Robust de-anonymization of large sparse datasets. In *Proceedings of the 2008 IEEE Symposium on Security and Privacy*, SP '08, pages 111–125, Washington, DC, USA, 2008. IEEE Computer Society.

[70] N. Nisan, T. Roughgarden, E. Tardos, and V. V. Vazirani. *Algorithmic Game Theory*. Cambridge University Press, New York, NY, USA, 2007.

[71] H. Nissenbaum. Privacy as contextual integrity. *Wash. L. Rev.*, 79:119, 2004.

[72] One nation, tracked. `https://www.nytimes.com/interactive/2019/12/19/opinion/location-tracking-cell-phone.html`.

[73] The world's most valuable resource is no longer oil,

but data. https://www.economist.com/leaders/2017/05/06/the-worlds-most-valuable-resource-is-no-longer-oil-but-data.

[74] Onaudience.com. https://www.onaudience.com.

[75] Y. Park, B. Mozafari, J. Sorenson, and J. Wang. Verdictdb: Universalizing approximate query processing. In *SIGMOD*, pages 1461–1476, 2018.

[76] A. Pavan, I. Segal, and J. Toikka. Dynamic mechanism design: A myersonian approach. *Econometrica*, 82(2):601–653, 2014.

[77] Re-Live Yahoo Pipes: Get and Manipulate Data From the Open Web by Connecting Blocks. https://www.pipes.digital/.

[78] F. Psallidas, B. Ding, K. Chakrabarti, and S. Chaudhuri. S4: Top-k spreadsheet-style search for query discovery. In *Proceedings of the 2015 ACM SIGMOD International Conference on Management of Data*, SIGMOD '15, pages 2001–2016, New York, NY, USA, 2015. ACM.

[79] Qlik datamarket. https://www.qlik.com/us/products/qlik-data-market.

[80] R. Ramakrishnan, B. Sridharan, J. R. Douceur, P. Kasturi, B. Krishnamachari-Sampath, K. Krishnamoorthy, P. Li, M. Manu, S. Michaylov, R. Ramos, N. Sharman, Z. Xu, Y. Barakat, C. Douglas, R. Draves, S. S. Naidu, S. Shastry, A. Sikaria, S. Sun, and R. Venkatesan. Azure data lake store: A hyperscale distributed file service for big data analytics. In *Proceedings of the 2017 ACM International Conference on Management of Data*, SIGMOD '17, page 51–63. Association for Computing Machinery, 2017.

[81] D. B. Registry. Data broker registry. `https://oag.ca.gov/data-brokers`, 2020.

[82] P. A. Samuelson. Foundation of economic analysis. *Harvard Economic Studies*, 1947.

[83] B. Sarwar, G. Karypis, J. Konstan, and J. Riedl. Item-based collaborative filtering recommendation algorithms. In *Proceedings of the 10th International Conference on World Wide Web*, WWW '01, pages 285–295, New York, NY, USA, 2001. ACM.

[84] L. S. Shapley. A value for n-person games. *Santa Monica, CA: RAND Corporation*, 1952.

[85] N. Singer. A data broker offers a peek behind the curtain. *The New York Times*, 1:1, 2013.

[86] Snowflake's data exchange. https://www.snowflake.com/data-exchange/.

[87] S. Spiekermann, A. Acquisti, R. Böhme, and K.-L. Hui. The challenges of personal data markets and privacy. *Electronic markets*, 25(2):161–167, 2015.

[88] D. Srivastava and X. L. Dong. Big data integration. In *Proceedings of the 2013 IEEE International Conference on Data Engineering (ICDE 2013)*, ICDE '13, pages 1245–1248, Washington, DC, USA, 2013. IEEE Computer Society.

[89] W. C. Tan, M. Zhang, H. Elmeleegy, and D. Srivastava. Reverse engineering aggregation queries. *PVLDB*, 10(11):1394–1405, Aug. 2017.

[90] Tind - reimagining library technology. https://tind.io/.

[91] Q. T. Tran, C.-Y. Chan, and S. Parthasarathy. Query reverse engineering. *PVLDB*, 23(5):721–746, Oct. 2014.

[92] A. Tsymbal. The problem of concept drift: definitions and related work. *Computer Science Department, Trinity College Dublin*, 106(2):58, 2004.

[93] B. Ubaldi. Open government data. (22), 2013.

[94] H. Varian. Artificial intelligence, economics, and industrial organization. Technical report, National Bureau of Economic Research, 2018.

[95] H. R. Varian. Versioning information goods, 1997.

[96] Versioning: The smart way to sell information. https://hbr.org/1998/11/versioning-the-smart-way-to-sell-information.

[97] WhereHows: Data Discovery and Lineage for Big Data Ecosystem. https://github.com/linkedin/WhereHows.

[98] Worldquant. https://data.worldquant.com.

[99] Xignite. https://aws.amazon.com/solutionspace/financial-services/solutions/xignite-market-data-cloud-platform/.

[100] L. Xu, S. Huang, S. Hui, A. J. Elmore, and A. Parameswaran. OrpheusDB: A Lightweight Approach to Relational Dataset Versioning. In *SIGMOD*, 2017.

[101] M. Yakout et al. InfoGather: Entity Augmentation and Attribute Discovery by Holistic Matching with Web Tables. In *SIGMOD*, 2012.

[102] T. Yan and A. D. Procaccia. If you like shapley then you'll love the core. *Manuscript*.