The Missing Value of Data*

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Abstract

Data assets are increasingly vital in modern economies, yet macroeconomic measurement is not well-adapted to capturing their value. Part of the problem is that data is an intangible asset: investments in data are missed in national accounts, and depreciation losses are missed in firms' balance sheets. Another part, unique to data, is that it serves as a means of payment in the modern economy: consumption bartered for data is also omitted from national accounts. We propose an output-based approach to measure the missing value of data. We treat data as an asset, measure its volume based on the quality of firms' revenue forecasts, and endogenously determine its depreciation. We then capitalize the data value and explore what the measured GDP would be if the data were treated and transacted similarly to a physical asset. Our findings suggest that the aggregate value of data is about 1.5% of GDP.

1 Introduction

In the digital economy, data has become one of firms' most valuable and essential assets. In the last few years, it has become particularly valuable because it is the fuel for artificial intelligence (AI). Not surprisingly, rapid advances in digital technologies have led to the conjecture that the value of data has grown immensely. Yet, despite its growing economic importance, measuring the aggregate value of firms' data and its evolution remains elusive. It is difficult to aggregate all revenues associated with data because data and the AI models

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it trains are used for so many different purposes. We provide a flexible approach to valuing firms' data. We then apply that methodology to correct measures of GDP.

Understanding the aggregate value of data assets can help policymakers design privacy, tax, and regulatory frameworks. Proper valuation of firms' data assets can improve financial market assessments and corporate valuation models. This is particularly relevant as data-driven business models become increasingly dominant, challenging conventional valuation techniques designed primarily for tangible capital and measured market transactions.

Data plays three distinct roles in modern economies: 1) Data is a factor of production. It is monetized through advertising or direct sales. These activities are measured with standard approaches. 2) Data is an asset that makes firms more productive by minimizing mistakes. This role of data is typically not captured. Since data requires costly investments and depreciates, it is similar to other intangible assets. 3) Data is bartered. Transactions generate data; hence, customers pay for goods and services partly with this data. This value, unique to data, distorts both national accounts and firm profits.

At its core, AI is a prediction technology fueled by data (Agrawal et al., 2018). Firms use data to predict demand, costs, inventories, and competitors' strategies (Goldfarb and Tucker, 2019). Since data is the fuel for predictive technologies, we place firms' predictions at the center of our analysis to quantify the value of data based on improvements in forecasting accuracy. We then leverage the estimated relationship between forecast errors and profits to infer this value, an approach that captures broader productivity benefits even when data is used for diverse strategic purposes beyond revenue forecasting. This methodology explicitly addresses the reverse-causality challenge of whether better predictions drive profits or whether profitable firms simply generate more data through higher transaction volumes. By embedding this two-way feedback in a recursive framework, we calibrate the model to isolate the fundamental value of data.

An important clarification is that we do not assume that firms' primary use of data is to

forecast revenues, nor that revenue forecasts themselves are the main source of data's value. Firms use data to make many revenue-relevant predictions: demand, marketing effectiveness, procurement needs, inventories, costs, and product-market conditions. These predictions are valuable because they guide production, pricing, sourcing, targeting, and other operational decisions. Our empirical strategy uses revenue forecast accuracy as an observable proxy for the precision of this broader set of predictions. The identifying assumption is that firms with data that allow them to predict these revenue-relevant variables more precisely will also tend to forecast revenues more precisely.

A key contribution of this paper is to capitalize the value of data as an investment flow (D_t) that accumulates into a productive stock of precision (Ω_t). When we capitalize this value and study its evolution, we find that the total volume of "missing" GDP is governed by two balancing forces: diminishing returns to information and endogenous depreciation. First, because expected squared prediction errors are bounded below by zero, the marginal utility of data in reducing forecast errors declines as the stock grows. Second, data depreciates endogenously; firms with the largest data stocks suffer more from depreciation because their highly precise forecasts are the most sensitive to shifts in the underlying economic state. Together, these forces explain why the aggregate value of missing data has remained a relatively stable yet substantial 1.5% of measured GDP over the last two decades.

These findings suggest that conventional accounting systematically underestimates the true value of internally generated data, which is often missed as an intangible investment and omitted as bartered consumption. Since national accounts fail to recognize data generated as a byproduct of own transactions as investments, its economic impact remains obscured in both firm valuations and GDP measurements. By providing a market-based approach to valuing data, our study contributes to ongoing debates on the role of intangible assets in economic growth and the necessity of adjusting national accounts for the unique role of data as a means of payment.

We also validate our approach based on the output of the data (forecasts) rather than the input data (labor costs of processing data) by conducting the following exercise. First, we show that increased employment of data workers is indeed correlated with forecast improvements. Second, we show that, unlike forecasts, which have a significant impact on profits, the use of data workers does not. This suggests that forecasts capture a more direct impact of data on profits than the inputs used to manage data, making them a better tool for measuring data value. This result supports the use of forecasts to capture the value of data in the economy.

The paper proceeds as follows: Section 2 presents a GDP accounting framework that establishes how the value of data, as both an intangible asset and a means of payment, should ideally be reflected in national accounts. Section 3 describes the framework we construct for measurement. Section 4 measures the data stock, its dynamics, and its decomposition into public data, undepreciated old data, and new data. We also show how to capitalize the flow of new data, per employee of the median firm, and extrapolate to the whole economy. Section 5 validates the pure output-based approach by comparing it with the more traditional input-based approach. Section 6 discusses directions for future research and policy implications before concluding.

Related literature Many papers have explored the value of data barter for free digital goods (Nakamura et al., 2017; Brynjolfsson et al., 2025), modeled mechanisms through which data can affect output and welfare (Farboodi and Veldkamp, 2021; Asriyan and Kohlhas, 2024; Eeckhout and Veldkamp, 2023; Jones and Tonetti, 2020), and estimated the increase in firm value attributable to data and AI adoption (Abis and Veldkamp, 2024; Eisfeldt et al., 2023). In contrast, this paper takes a national income accounting approach to simultaneously measure the value of data as a means of payment (data barter), as a firm asset that depreciates and needs to be capitalized, and as a means to increase firm productivity

and output. The result is an improved understanding of the observed trends in output and profits, as well as a strategy to improve firm valuation and GDP measurement that closely follows current practice for tangible assets.

The most closely related preceding papers are the following. Asriyan and Kohlhas (2024) measure firms' revenue forecast errors and show that these errors are reasonable measures of firms' data. They correlate with firms' profits and productivity. Jones and Tonetti (2020) explore the optimal amount of data sales. At the end of our paper, we value data sales, which may be far from optimal. Begenau et al. (2018) model the data of large and small firms, but with a focus on their financial data. We build on this work by distinguishing between internally generated data and purchased data, quantifying the value of data as a means of payment and capitalizing the data flow to value data as an asset.

The economic value of data has been a growing focus in recent research, with multiple strands of literature contributing to our understanding of its impact at the firm and macroeconomic levels. While prior studies have examined the role of intangible assets broadly (Crouzet et al., 2022; Eisfeldt et al., 2020) and proposed various methodologies to quantify the value of data, this paper introduces a novel approach: It recognizes that the data transferred from consumers to firms in the course of a transaction has value that should be counted as part of the transaction. This method contrasts with existing work because it acknowledges that not only is data a valuable asset, it is also a means of payment.

Data is a specific example of an intangible asset with its own mismeasurement literature. Crouzet and Eberly (2018) and Corrado et al. (2016) examine intangible assets as a broad class that includes brand equity, personal relationships, goodwill, and patents. Hulten and Hao (2008) explore how the mismeasurement of intangibles distorts economic indicators and propose methodologies to impute the value of software and R&D, an approach extended in Hulten and Nakamura (2020). However, data is distinct from these other assets because it is generated as a by-product of economic activity. As such, it is a good candidate for explaining

the strategic advantages of large firms that generate lots of data by participating in a large number of transactions. At the same time, data depreciates differently from other assets. This is at the heart of the trade-off we explore and is unique to data.

Many papers have noted the mismeasurement of GDP that arises from the digital economy and proposed remedies. Nakamura (2010) highlights that many data-related investments are expensed rather than capitalized, leading to an underestimate of GDP. He suggests imputing the value of free digital services based on consumer willingness to pay, an approach later extended by Brynjolfsson et al. (2019), who estimate the consumer surplus generated by digital goods. Their findings suggest that traditional GDP metrics significantly underestimate welfare gains in data-driven economies. However, these consumer-centric approaches do not address the firm-side valuation of data assets. Nakamura et al. (2017) advocate for developing satellite accounts to systematically track data-related investments, an approach that complements traditional national accounts. While such methodologies have been applied in pilot studies, they remain limited in scope and are not yet widely implemented. Syverson (2017) investigates whether digital services could explain the productivity slowdown but finds that the discrepancy would need to be implausibly large to account for observed trends. Finally, internal presentations by the Bureau of Economic Analysis have proposed data measures based on the cost of recording, organizing, and maintaining databases (Calderón and Rassier, 2022). However, since customers often provide data as a by-product of economic activity, a cost approach is likely to miss much of data's value.

A distinct body of work explores how data boosts firms' profits. Brynjolfsson and McAfee (2014) document significant productivity enhancements at the firm level due to data utilization. Their findings underscore the firm-level importance of data but do not provide an economy-wide valuation. Tambe et al. (2021) infer the value of data assets by analyzing hiring patterns and identifying the skills of data-complementary workers, offering an indirect approach to measuring data's impact on firms. Hulten (2010) provides a case study on Mi-

crosoft, demonstrating that the company's valuation is almost entirely driven by intangibles, likely including proprietary data.

2 GDP Accounting of Data

Data plays a unique dual role in modern economies: it is both a productive asset for firms and a means of payment for consumers. These two roles create two distinct channels through which standard measures of GDP fail to capture the full value of data. In this section, we describe these channels and show how properly accounting for data, as both an *intangible investment* and a *bartered good*, would affect measured GDP. The model developed in the following section will provide a method to identify the stock of data and decompose it into public data, old undepreciated data, and newly acquired data. We will also provide a new microfoundation for valuing data. The accounting arguments in this section stand independently of these details.

2.1 Expenditure Approach

Under the expenditure approach, GDP in period t is defined as,

$$\text{GDP}_{t|\text{exp}} = C_t + I_t + G_t + NX_t,$$

where C_t is total Consumption, I_t is Investment, G_t and $NX_t = X_t - M_t$ are Government Expenditures and Net Exports, respectively. These figures are measured by their market monetary prices. In a modern economy, however, firms often also obtain data in exchange for the value of the final good. Further, data is a form of intangible capital. Neither of these two sources of data value is explicitly captured in standard national accounts.

Consider the following thought experiment: Suppose some food, which is worth \$1, is transacted as pure barter in exchange for data about the preferences, tastes, and character-

istics of the buyer, also worth \$1. Imagine both are final goods. No money changes hands. What should this exchange add to GDP? If the food were sold first and the buyer paid \$1, and then the data were sold as a separate transaction, then the total price times quantity of both transactions would be \$2. That is the total value exchanged. Instead, there is no market transaction, and it is recorded as a value of \$0.

This, however, is not how GDP is measured in practice; instead, it is measured using the monetary prices of final goods. We define Y_t as the aggregate real output of the economy and D_t as the value of data gained by firms based on their transactions. The only good exchanged in the economy is the final good, for a market value of $Y_t - D_t$. Investment in data, on the other hand, is not recorded as a transaction for its full value D_t. Hence, the mismeasured value of data in GDP is $2D_t$. If customers were not compensated for the value of the data they provide, the value of the good would correctly be measured by its monetary value, and GDP would be mismeasured only by the omission of investment in missing data, D_t. The correct formulation of GDP *inclusive of data*, is:

$$\text{GDP}_{t|\text{exp}}^{\text{corrected}} = (C_t + D_t) + (I_t + D_t) + G_t + NX_t,$$

In a few words, GDP is undermeasured by $2D_t$ (the value of generated data), for two reasons. One is *consumption bartering*, under which the monetary value of consumption is D_t less than the true value. The other is *intangible investment*, as the investment in data with value D_t is not recorded as generated in the economy. This is an important distinction. If consumers were not compensated for data (no bartering), then only one D_t would be mismeasured, as is standard with intangibles.

Adjusting for market power: The formulation above assumes that to obtain data worth D_t, the firm must give a discount of D_t to consumers. However, with market power, the firm may be able to acquire the same data while offering a smaller discount. Suppose a firm charges a markup μ over marginal cost when selling goods, i.e., $P = \mu MC$, where P

is price, MC is marginal cost, and $\mu \in [1, \infty]$. The markup of $\mu = 1$ is the case of perfect competition (our benchmark), and higher values of μ reflect greater market power. Assume that the firm can obtain data at the same markdown – specifically, by offering a discount of D_t/μ instead of D_t. Incorporating this into the expenditure-side measurement, the correct GDP, inclusive of data, becomes

$$\text{GDP}_{t|\text{exp}}^{\text{corrected}} = \left(C_t + \frac{D_t}{\mu}\right) + (I_t + D_t) + G_t + NX_t.$$

Note that only the consumption component is adjusted, because the firm still receives data worth D_t; market power affects only the discount the firm must provide to acquire it, not the actual value of the data it receives. To see this clearly, let's return to the food example discussed above. Without market power, the firm trades \$1 worth of discount for \$1 worth of data. With market power, the firm obtains \$1 worth of data by discounting the price by only $1/\mu$, so the consumer pays $1 - 1/\mu$. The amount of GDP that goes unmeasured is therefore

$$2 - \left(1 - \frac{1}{\mu}\right) = 1 + \frac{1}{\mu}.$$

In general, when the value of data is D_t, the under-measured amount of GDP, after accounting for market power, equals

$$\left(1 + \frac{1}{\mu}\right) D_t.$$

When $\mu = 1$, the firm must fully compensate consumers for their data, and the missing data value corresponds to both intangible capital and consumption bartering. At the other extreme, when $\mu = \infty$, the firm does not compensate consumers for their data at all, and the missing value of data corresponds to just intangible capital.

2.2 Income Approach

Under the traditional income approach, GDP is defined as the sum of all factor payments plus allowances for capital consumption:

$$\text{GDP}_{t|\text{inc}} = w_t L_t + r_t K_t + \Pi_t + \delta_{t,K} K_t,$$

where $w_t L_t$ denotes labor compensation, $r_t K_t$ rental return to reproducible capital, Π_t pre-depreciation corporate profits, and $\delta_{t,K} K_t$ depreciation of fixed capital. Because firms report profits net of depreciation, adding back $\delta_{t,K} K_t$ simply yields gross profits.

The correct formulation of GDP using the income approach, *inclusive of data*, is:

$$\text{GDP}^{\text{corrected}}_{t|\text{inc}} = w_t L_t + r_t K_t + D_t + (\Pi_t + D_t - \delta_{t,D} S_{t-1}) + \delta_{t,K} K_t + \delta_{t,D} S_{t-1},$$

where $\delta_{t,D}$ is the depreciation rate of data and S_{t-1} is the value of total data stock in $t-1$. Notice that since data depreciation is both added and subtracted, it does not contribute to mismeasurement.

Just as before, we see that GDP is mismeasured for two reasons: First, due to bartering, firms fail to record the full value of their sales, which are higher by D_t than what is reported. The second reason D_t is mismeasured is by failing to record payments for data that consumers generate by transacting. This shows up as profits of consumer-owned, data-producing firms. These two terms correspond to *consumption bartering* and *intangible investment*. This is that important distinction arising again: If consumers were not compensated for data (no bartering), then only one D_t would be mismeasured, as is standard with intangible assets.

One might ask: If the firm needs to pay customers for data in the unbundled transaction, why isn't the cost of that data purchase subtracted from their profits? Think of this as if it were a firm buying a physical asset. In the income approach to GDP, the purchase cost of an asset is not subtracted from revenues. Instead, it is amortized, meaning its depreciation

is subtracted from gross profits in the future to arrive at net profits, and then added back. The idea is that purchasing an asset is not a loss of value. It is a transfer of a valuable asset from one party to another, in a way that does not affect GDP. Depreciation makes a firm less valuable. But it does not imply that less value of goods and services was produced. Thus, neither shows up in the national income accounting approach to GDP.

Similar arguments to those in the expenditure approach suggest that, with market power, the under-measured value of GDP would be $(1 + 1/\mu)D_t$.

Firms' Valuations: The previous discussion shows clearly that firms' values are mismeasured. However, the extent of bartering is critical in determining whether firms are over- or undervalued. When there is bartering, firms' values are undermeasured by $D_t - \delta_{t,D}S_{t-1}$, where D_t is the value of new data and S_{t-1} the value of data stock in the previous period. This is an issue only outside the steady state, since in the steady state $D_t = \delta_{t,D}S_{t-1}$. Firms are undervalued when data grow, and overvalued when they decline. If there is no bartering, however, firms are always overvalued, since firms report more profits than they should, also deducting the depreciation of data $\delta_{t,D}S_{t-1}$. In other words, as long as the firm monetizes the value of data (by capturing their value from consumers without compensation), profits are overvalued because they should also report data depreciation.

Implications for TFP mismeasurement: The two sources of data mismeasurement, investment in intangibles and barter transactions, induce biases in opposite directions. On the one hand, measuring data correctly as increasing intangible capital increases the measured input that generates a given output, reducing measured TFP. On the other hand, discounting correctly the bartered value of consumption implies more output given a set of inputs, increasing measured TFP. Evaluating the net effect on the mismeasurement of TFP over time involves modeling in more detail the production function and adding labor inputs, which is beyond the scope of this paper.

3 A Framework for Data Measurement

In this section, we propose a model to measure the value of new data D_t generated in the economy. At its heart, this is a forecasting model. It is not a production economy with equilibrium prices. It is simply a device to organize the measurement of the relationship between forecasts and profits and to help us distinguish and value various types of information. Since firm interactions are not our object of study, we begin by studying a single firm i. Later, we discuss aggregation.

3.1 Environment

Time is discrete and infinite. There is a continuum of competitive firms indexed by i. Each firm produces $y_{i,t}$ units of a final good using capital, according to the following production function

$$y_{i,t} = k_{i,t}^{\alpha}.$$

In each period t, there is an uncertain "state", which we denote by θ_t, that captures characteristics of the good that all customers value at time t (such as design, availability, adaptability, etc). We can then define a *state-adjusted unit of the good* as $A_{i,t}$, which we assume

$$A_{i,t} = A_i(1 + b\theta_t) \tag{1}$$

A low state θ_t is akin to customers valuing a "smaller product."

The firm can charge each unit of the good either "in cash" or "in data", $P_{i,t} = P_{i,t}^{\$} + P_{i,t}^{D}$. Cash payments are a standard form of monetary transaction. Payment-in-data is information the firm obtains from selling the product and can be useful for improving forecasts, but it is not compensated monetarily. The firm i's revenues can be written as

$$R_{i,t} = P_{i,t}A_{i,t}k_{i,t}^{\alpha} = P_{i,t}A_i(1 + b\theta_t)k_{i,t}^{\alpha}. \tag{2}$$

Since the model is for measurement, we want it to be flexible enough to use the data for multiple purposes. Therefore, we consider the possibility that production costs are also uncertain, and that data can be used to predict shocks that affect costs, such as input prices, production chains, etc. Cost also depends on the state θ_t.

We assume that the *per-unit cost of production* may depend on the price level, productivity, and a linear and quadratic term in the uncertain state θ_t:

$$c_{i,t} = P_{i,t}A_i(b\theta_t + \gamma(a_{i,t} - \theta_t)^2) + w \tag{3}$$

The unit cost depends on the realized characteristics valued by customers, with a higher state θ_t generating more revenue but also making production more costly (to fix ideas, think of the need to produce a larger product if θ_t is larger). Second, the cost depends on how well the firm targets such a state. When firms take actions that are not well-aligned with the state θ_t, the costs of producing the adjusted unit of the good are higher (again, setting up to produce a small product may be costly if the right size of production is large). Finally, each unit of production represents a transaction that brings data into the firm. We denote by w the cost (in terms of data labor) of turning the data generated by a unit of production (and transaction) into operational information that reduces future forecast errors, by cleaning, storing, interpreting, etc. Note that this per-unit cost does not include capital rental costs, which are typically included as an overhead expense.

Assuming the rental rate of capital is r_t, total costs are then

$$C_{i,t} = c_{i,t}k_{i,t}^{\alpha} + r_t k_{i,t}. \tag{4}$$

We assume that A_i, b, α, γ and w are known parameters. Since b is equivalent to normalizing units of variance and does not affect our estimates, we assume $b = 1$ henceforth. Finally, since we are interested in the price composition rather than price levels, we normalize the

price of the state-adjusted good to $P_{i,t} = 1$.

Deducting (4) from (2), total profits are,

$$\Pi_{i,t} \equiv R_{i,t} - C_{i,t} = \pi_{i,t} k_{i,t}^{\alpha} - r k_{i,t} \tag{5}$$

where variable unit gross profits (before capital cost) are,

$$\pi_{i,t} = A_i(1 - \gamma(a_{i,t} - \theta_t)^2) - w$$

The production structure appears more complex than in a standard production economy because the state θ_t appears in output and costs, in both linear and quadratic forms. Much of this is not essential to the model's functioning. However, the assumption that only fundamental θ_t affects revenues and only mistakes $(a_{i,t} - \theta_t)$ affect gross profits will prove extremely useful to separate the computation of the quantity of data (from forecast errors) and its monetary valuation (how forecast errors affect profits). This structure makes the point that, even if data is used to predict various types of uncertain outcomes, we can still capture the value of these predictions through the relationship between the firm's forecast accuracy and output.

Information sets For data to be useful in future periods, the state it predicts must persist and not be fully revealed at the end of each period. If either of these conditions fails, data fully depreciates at the end of each period, which is neither realistic nor interesting for data valuation. Therefore, we assume that the state is a hidden Markov process (i.e. a Kalman filter system). It is the combination of a "fundamental" component, $\widehat{\theta}_t$, which is forecastable, and a "transitory" component η_t, which is nonforecastable. More precisely, the state at time t is a noisy realization θ_t of an AR(1) process $\widehat{\theta}_t$ with normally-distributed innovations:

$$\theta_t = \widehat{\theta}_t + \eta_t, \qquad \eta_t \sim N(0, \sigma_\eta^2) \tag{6}$$

$$\widehat{\theta}_{t+1} \;=\; \rho\widehat{\theta}_t + \epsilon_{t+1}, \qquad \epsilon_{t+1} \sim N(0, \sigma_\epsilon^2), \tag{7}$$

for $0 < \rho < 1$. This structure implies that in each period t, the state is normally distributed: $\theta_t \sim N(0, \phi_t^{-1})$, where ϕ_t is a function of the parameters in (6) and (7).

We denote the firm's information set at time t as $\mathcal{I}_t$. This set contains *public* prior information about the distribution of θ_t, new data generated from current transactions, old undepreciated data, and, potentially, data acquired from outside parties. These sources of information help the firm to forecast the state $\hat{\theta}_t$. In other words, when combined optimally with an algorithm, this data can be used as a signal s_t about θ_t.

A solution to the model is a sequence of state-contingent production plans, given by capital renting $k_{i,t}$, and actions $a_{i,t}$ every period to maximize:

$$\sum_{t=0}^{\infty}(1+r)^{-t}\mathbb{E}\left[(A_i(1-\gamma\left(a_{i,t}-\theta_t\right)^2)-w)k_{i,t}^{\alpha}-rk_{i,t}|\mathcal{I}_t\right], \tag{8}$$

where beliefs are formed using Bayes' law, in each period t, given information sets $\mathcal{I}_t$.

3.2 Stock of Data and its Components

Since firms know their capital decision and other parameters, forecasting total revenues involves forecasting the state θ_t. First, we need to derive prior beliefs and variances for the dynamic model state using Bayes law. Given the linear revenue function, those are simply linear transforms of the mean and variance of θ_t.

We can define the stock of data based on forecast errors. The prior mean and variance of the state, which determine the expectation and variance of profits per unit of production, are $E[\theta_t|\mathcal{I}_t] = E[\hat{\theta}_t|\mathcal{I}_t]$ and $Var[\theta_t|\mathcal{I}_t] = Var[\widehat{\theta}_t|\mathcal{I}_t] + \sigma_\eta^2$. The expected squared forecast error is, by definition, a conditional variance. We define the stock of data in period t as the inverse of the conditional variance, so

$$\Omega_t \equiv Var^{-1}(\widehat{\theta}_t|\mathcal{I}_t), \tag{9}$$

This definition can be interpreted as a stock of data because lower variance, or more accurate estimates, imply that a firm has more data about $\widehat{\theta}_t$. The stock of data Ω_t in the aggregate corresponds to S_t in Section 2, except that Ω_t is in units of precision and S_t is measured in dollars.

The stock of data can be decomposed into four main components as follows:

$$\Omega_t = \phi_t + \tau_t(k_{t-1}) + \nu_t + (1 - \zeta_{t-1})(\Omega_{t-1} - \phi_{t-1}) \tag{10}$$

The first component is the *prior precision*, ϕ_t, which captures the quality of public data about the state and its dynamics. The second component is the precision of new data obtained from the firm's period transactions, τ_t, which depends on the production scale (i.e., the number of transactions) k_{t-1}. The third component is the precision of data purchased from external parties, ν_t. The fourth component is the undepreciated past private data stock, $(1 - \zeta_{t-1})(\Omega_{t-1} - \phi_{t-1})$, where the depreciation rate ζ_{t-1} is endogenous and time-varying.

Data Depreciation: Despite the properties that capital shares with data (the accumulation of transactions into a stock), we cannot assume an exogenous depreciation rate. To determine the depreciation of data, we first compute the forecast and variance of tomorrow's state, based on today's information set. Taking the mean and then the variance of both sides of (7) once combined with (6), we get

$$E[\hat{\theta}_{t+1}|\mathcal{I}_t] = \rho E[\hat{\theta}_t|\mathcal{I}_t], \tag{11}$$

$$Var[\hat{\theta}_{t+1}|\mathcal{I}_t] = \rho^2 Var[\hat{\theta}_t|\mathcal{I}_t] + \sigma_\epsilon^2. \tag{12}$$

This last conditional variance of the forecast of future state $\hat{\theta}_{t+1}$ is not a measure of the volatility of $\hat{\theta}_{t+1}$. Rather, it is a measure of uncertainty: the expected squared forecast error: $Var[\hat{\theta}_{t+1}|\mathcal{I}_t] := E[(\hat{\theta}_{t+1} - E[\hat{\theta}]_{t+1}|\mathcal{I}_t])^2|\mathcal{I}_t]$. In Bayesian terms, this is a prior variance of θ_{t+1}.

If new data is used to forecast $\hat{\theta}_{t+1}$ with normally-distributed noise, then Bayes' Law says that we can combine all data sources and represent it as a signal about tomorrow's state $s_t = \hat{\theta}_{t+1} + e_{st}$, with $e_{st} \sim N(0, \sigma_s^2)$. The firm will also observe time-t revenue at the end of period t. In other words, $\mathcal{I}_{t+1} = \{\mathcal{I}_t, \theta_t, s_t\}$. The information the agent will have to make decisions tomorrow is the information available today, plus the new revenue and the new data observed at the end of period t, and back out θ_t.

This construct assumes that the data are informative about θ_{t+1} but contain independent noise.[1] Note that observing θ_t is a signal about the unobserved state $\hat{\theta}_t$, with signal noise variance equal to σ_ϵ^2.

According to Bayes law for normal variables, the posterior precision of the estimate of $\hat{\theta}_{t+1}$ is the sum of the prior precision and the precision of both the new data and the revenue signal. In other words,

$$\Omega_{t+1} \equiv Var^{-1}(\hat{\theta}_{t+1}|\mathcal{I}_{t+1}) = \left[\rho^2 Var[\hat{\theta}_t|\mathcal{I}_t] \ + \sigma_\epsilon^2\right]^{-1} \ + \sigma_\eta^{-2} + \sigma_s^{-2}. \tag{13}$$

But the firm's profits do not depend on the conditional variance, or expected squared forecast error about $\hat{\theta}_t$, but about θ_t,

$$Var(\theta_{t+1}|\mathcal{I}_{t+1}) = \left[\left[\rho^2 Var[\hat{\theta}_t|\mathcal{I}_t] \ + \sigma_\epsilon^2\right]^{-1} \ + \sigma_\eta^{-2} + \sigma_s^{-2}\right]^{-1} + \sigma_\eta^2. \tag{14}$$

Rewriting equation (14) in terms of the stock of data, we get

$$Var(\theta_{t+1}|\mathcal{I}_{t+1}) = \left[\left[\rho^2 \Omega_t^{-1} \ + \sigma_\epsilon^2\right]^{-1} \ + \sigma_\eta^{-2} + \sigma_s^{-2}\right]^{-1} + \sigma_\eta^2 = \Omega_{t+1}^{-1} + \sigma_\eta^2,$$

which maps the time-t stock of data Ω_t, into the time-$t+1$ stock of data, Ω_{t+1}. This law of motion says that we take the stock Ω_t, depreciate it by transforming it into $(\rho^2\Omega_t^{-1} + \sigma_\epsilon^2)^{-1}$,

[1] If new data were correlated with old data, we could count only the part of the new data that constituted independent information. In a simple case, this might be accomplished by regressing new data on old data and using the residual to form s_t.

and then add on the flow of new data. New data is like a new investment in the data stock. This implies that $(1-\zeta_t)\Omega_t = \left[\rho^2 Var[\hat{\theta}_t|\mathcal{I}_t] \ + \sigma_\epsilon^2\right]^{-1}$. Hence, the depreciation rate is

$$\zeta_t = 1 - (\rho^2 + \sigma_\epsilon^2 \Omega_t)^{-1}. \tag{15}$$

This shows that the properties of data endogenize its depreciation rate. If the data stock is large, the data will depreciate more quickly.

3.3 A Recursive Representation

Conditional on the amount of data, Ω_{it}, the firm chooses the best production strategy, a_{it}, and the optimal scale of production k_{it}. It is clear that the action that maximizes the objective is $a_{i,t} = E(\theta_t|\mathcal{I}_t)$ each period. Thus, the objective consists of minimizing the expected squared forecast errors $\left(E(\theta_t|\mathcal{I}_t) - \theta_t\right)^2$ about the state θ_t.

By construction, the conditional variance of θ_t has two components: the variance of the forecastable component, $Var[\hat{\theta}_t|\mathcal{I}_t] = \Omega_{i,t}^{-1}$, which the firm can reduce by acquiring more data, and the variance of the transitory shock, σ_η^2, which is irreducible. Therefore

$$Var[\theta_t|\mathcal{I}_t] \ = \ \Omega_{i,t}^{-1} + \sigma_\eta^2.$$

Substituting this expression into the objective (8), the *expected per-period profit* from the objective can be written as an explicit function of the data stock as

$$\mathbb{E}\left[\left(A_i\left(1 - \gamma\left(\Omega_{it}^{-1} + \sigma_\eta^2\right)\right) - w\right) k_{i,t}^{\alpha} - r\, k_{i,t} \,\middle|\, \mathcal{I}_t\right].$$

The optimal sequence of capital investment $\{k_{i,t}\}$ solves the following recursive problem:

$$\mathbb{V}_i(\Omega_{i,t}^{-1}) = \max_{k_{i,t}} \Big\{ \underbrace{\big(A_i(1-\gamma\,(\Omega_{i,t}^{-1}+\sigma_\eta^2)) - w\big)}_{\equiv\ \pi_{i,t}(\Omega_{i,t}^{-1})}\, k_{i,t}^{\alpha} - r\,k_{i,t} + \beta\,\mathbb{E}_t\big[\,\mathbb{V}_i(\Omega_{i,t+1}^{-1})\,\big]\Big\}. \tag{16}$$

subject to equation (10) at $t+1$

$$\Omega_{i,t+1} = \phi_{t+1} + \tau_{i,t+1}(k_{i,t}) + \nu_{i,t+1} + (1-\zeta_{i,t}(\Omega_{i,t}))(\Omega_{i,t} - \phi_t) \tag{17}$$

where $\tau_{i,t+1}(k_{i,t})$ captures in general how new data is generated from the scale and operation of the firm, and $\zeta_{i,t}(\Omega_{i,t})$ is from equation (15). Note that σ_η^2 does not enter the state transition (17): the transitory shock is a feature of the data-generating process for θ_t, not of the stock of data the firm holds. We next characterize the solution in this general setting and discuss its properties. In the next sections, we calibrate it and numerically solve it. We solve for the deterministic steady state in Appendix A, and show it can be solved in closed-form when shutting down the reverse causality that $\tau_{i,t+1}(k_{i,t})$ generates.

Optimal Choices of Data and Scale By the envelope theorem applied to (16), fixing the value of $k_{i,t}$ at the argmax value,

$$\mathbb{V}'(\Omega_{i,t}^{-1}) = \frac{\partial \pi_{i,t}}{\partial \Omega_{i,t}^{-1}}\, k_{i,t}^{\alpha} + \beta\,\mathbb{E}_t\left[\mathbb{V}'(\Omega_{i,t+1}^{-1})\,\frac{\partial \Omega_{i,t+1}^{-1}}{\partial \Omega_{i,t}^{-1}}\right]. \tag{18}$$

From the period payoffs, and because σ_η^2 is exogenous to $\Omega_{i,t}^{-1}$,

$$\frac{\partial \pi_{i,t}}{\partial \Omega_{i,t}^{-1}}\, k_{i,t}^{\alpha} \;=\; -\gamma\, A_i\, \frac{\partial(\Omega_{i,t}^{-1}+\sigma_\eta^2)}{\partial \Omega_{i,t}^{-1}}\, k_{i,t}^{\alpha} \;=\; -\gamma\, A_i\, k_{i,t}^{\alpha}.$$

The marginal value of the forecastable component of variance is therefore unchanged from the case without transitory noise: only the level of the flow profit shifts.

Using the chain rule to determine the derivative of precision over time,

$$\frac{\partial \Omega_{i,t+1}^{-1}}{\partial \Omega_{i,t}^{-1}} = \frac{\partial \Omega_{i,t+1}^{-1}}{\partial \Omega_{i,t+1}} \cdot \frac{\partial \Omega_{i,t+1}}{\partial \Omega_{i,t}} \cdot \frac{\partial \Omega_{i,t}}{\partial \Omega_{i,t}^{-1}} = \left(- \Omega_{i,t+1}^{-2} \right) \cdot \frac{\partial \Omega_{i,t+1}}{\partial \Omega_{i,t}} \cdot \left(- \Omega_{i,t}^{2} \right) = \frac{\partial \Omega_{i,t+1}}{\partial \Omega_{i,t}} \left(\frac{\Omega_{i,t}}{\Omega_{i,t+1}} \right)^2 .$$

Differentiating (17) with respect to $\Omega_{i,t}$:

$$\frac{\partial \Omega_{i,t+1}}{\partial \Omega_{i,t}} = 1 - \zeta_{i,t}(\Omega_{i,t}) - \left(\Omega_{i,t} - \phi_{i,t} \right) \zeta_{i,t}'(\Omega_{i,t}) \quad \equiv \quad \Gamma_{i,t}(\Omega_{i,t}), \tag{19}$$

so that

$$\frac{\partial \Omega_{i,t+1}^{-1}}{\partial \Omega_{i,t}^{-1}} = \Gamma_{i,t} \left(\frac{\Omega_{i,t}}{\Omega_{i,t+1}} \right)^2 .$$

Since σ_η^2 does not enter (17), both the chain rule above and the definition of $\Gamma_{i,t}$ are identical to the case without transitory noise.

Hence, we can rewrite the envelope condition in (18) as

$$\mathbb{V}'(\Omega_{i,t}^{-1}) = - \gamma \, A_i \, k_{i,t}^{\alpha} + \beta \, \mathbb{E}_t \left[\mathbb{V}'(\Omega_{i,t+1}^{-1}) \, \Gamma_{i,t} \left(\frac{\Omega_{i,t}}{\Omega_{i,t+1}} \right)^2 \right] . \tag{20}$$

This condition determines the evolution of the value function given the optimal choice of $k_{i,t}$. It shows that more data affects value both statically, by improving current production through reduced forecast errors, and dynamically, by the extent to which some of that data persists into the future and improves future forecasts and profits. The transitory variance σ_η^2 is irreducible: data acquisition affects only the forecastable variance $\Omega_{i,t}^{-1}$, so σ_η^2 shifts the level of the flow profit but does not enter the marginal value of data. Notice also that full depreciation of data would imply $\Gamma_{i,t} = 0$ from equation (19), and no dynamic benefit of data.

Now we can obtain the FOC that determines $k_{i,t}$:

$$\frac{\partial \pi_{i,t}}{\partial k_{i,t}} k_{i,t}^{\alpha} + \pi_{i,t}\, \alpha\, k_{i,t}^{\alpha-1} - r + \beta\, \mathbb{E}_t \left[\mathbb{V}'(\Omega_{i,t+1}^{-1})\, \frac{\partial \Omega_{i,t+1}^{-1}}{\partial k_{i,t}} \right] = 0, \tag{21}$$

where, since $\pi_{i,t}$ does not depend on $k_{i,t}$ directly,

$$\frac{\partial}{\partial k_{i,t}} \big[\pi_{i,t}\, k_{i,t}^{\alpha} \big] = \alpha \Big(A_i \big(1 - \gamma\, (\Omega_{i,t}^{-1} + \sigma_\eta^2) \big) - w \Big)\, k_{i,t}^{\alpha-1},$$

$$\frac{\partial \Omega_{i,t+1}^{-1}}{\partial k_{i,t}} = \frac{\partial \Omega_{i,t+1}^{-1}}{\partial \Omega_{i,t+1}} \cdot \frac{\partial \Omega_{i,t+1}}{\partial k_{i,t}} = \big(-\Omega_{i,t+1}^{-2} \big)\, \tau_{i,t+1}'(k_{i,t}).$$

Hence, the general Euler equation (21) can be written as:

$$\alpha \big(A_i \big(1 - \gamma\, (\Omega_{i,t}^{-1} + \sigma_\eta^2) \big) - w \big)\, k_{i,t}^{\alpha-1} - r \;-\; \beta\, \mathbb{E}_t \big[\mathbb{V}'(\Omega_{i,t+1}^{-1})\, \Omega_{i,t+1}^{-2}\, \tau_{i,t+1}'(k_{i,t}) \big] = 0. \tag{22}$$

This last equation constitutes a generalized Euler equation. The scale of production, $k_{i,t}$, not only equalizes the marginal product of capital with its cost, but also takes into account the future value of capital in generating data and reducing forecast errors that turn into future values (the third term). The transitory variance σ_η^2 appears in the static term as part of the level of profit per unit of capital, but not in the dynamic term, since acquiring more data does not affect the irreducible noise η_t.

Changing Data Technology There are two types of technological change in data. One collects more data points or extracts more data precision, and the other makes the same amount of forecast error more valuable. Both are captured by our measurement strategy. When technology enables more data collection, more data refinement, or more precise forecasting from the same data, as is the case with AI, this shows up as lower forecast error. We interpret this as more data. Even if the number of data points remains the same and more value is extracted from them, treating them as more data captures the additional revenue

this data generates for the firm. Data should be valued more highly when it leads to more accurate forecasts, and our method captures the increase in forecast accuracy. When technological progress allows firms to profit more from a given forecast accuracy, this is captured by an increase in the coefficient in the estimation of the relationship between forecast error variance and profits. In other words, both alternatives increase the total value of data; the first is captured as more units of data, the second as a higher value per unit.

4 Measuring Stock, Sources and Value of Firms' Data

The dollar value of new private data is the D_t that we are missing in the GDP accounting. Measuring this value requires several steps: 1) measure the total stock of available data for a representative firm across different periods, in precision units; 2) decompose this stock into public data, new private data, purchased data, and undepreciated old private data, and 3) capitalize the amount of *new private data* and map it into dollars. This last task is contaminated by a reverse causality problem: Do data and better forecasts lead to better outcomes, or do production and profit generate more data for the firm?

We use our model to implement these steps as follows. First, we describe the data we use. Then, we use the evolution of forecast errors to infer how the data stock has changed for a median firm in our data. From the fundamentals process, we back out *public data*, and from the endogenous depreciation computation in (15), we separate between *new private data* and *undepreciated private data*. In this exercise, we abstract from purchased data. In Appendix E, we propose a strategy to assess the importance of purchased data, showing that its precision exceeds that of public data, but it is about half that of the firm's private data and two-thirds that of newly acquired data. This is consistent with a firm's most valuable data being the one obtained from its own operations, which provide a more precise signal of the determinants of its profits. Precision is distinct from value: given the strong diminishing returns to data, bought data stacked on top of data firms obtained with own transactions

has a smaller value (about a quarter), even at the same precision.[2]

Once we have the evolution of the data stock and its components, we proceed to value it. We calibrate our model to heterogeneity across firms and to the relationship between forecast errors and profits to estimate the value of data for a public firm, controlling for reverse causality. Finally, we extrapolate this estimation to the whole economy.

4.1 Data Description

Our data is based on US public firms. For firms' fundamentals, we use Compustat North America for the years 2003-2022. Following the convention in the finance literature, we exclude utilities and financial firms. We also exclude firm-years with missing or negative values for revenue, employment, and capital. This leaves us with 65,988 firm-year observations. We adjust all nominal figures for inflation by using the CPIAUCSL series and report all figures in terms of December 2002 dollars.

We use revenue forecast errors not because revenue forecasting is the main use of firm data, but because it is an observable summary statistic for the precision of the broader information set firms use to predict revenue-relevant variables.

To compute forecast errors, a critical input for measuring data stock, we use management guidance data from I/B/E/S and assess the sales forecast accuracy of US public firms. Guidance refers to any forward-looking statement made by a company to offer insights into its future financial performance. I/B/E/S Guidance extracts quantitative company expectations from press releases and transcripts of corporate events.

We retrieved the annual sales guidance from I/B/E/S Guidance via the WRDS platform

[2]A promising avenue of research is to identify sources of information about data transactions from firms that specialize in that industry (such as Equifax, CoreLogic, Visa, etc). In the Appendix we exploit very limited data from Visa transactions as recorded in its SEC filings to infer ν. With more precise information, however, and under the right assumptions, it may be possible to use prices of data to identify the pace of technical change, as it has been explored for the transactions of capital and equipment. A challenge with data, however, is to identify what is a unit of data, the value per unit (which depends on accumulated data, as we will discuss below) and the cost of producing and processing it.

on February 19, 2025. We use the "Detail" table, which contains firms' generated financial forecasts (e.g., annual or quarterly sales or earnings). We keep only US firms (observations with "usfirm"=1), available from 2002 to 2021. We focus on annual revenue forecasts, as these account for the largest share of firms' forecasts.[3]

After merging with Compustat data and retaining only firm-year observations with one-year-ahead revenue forecasts, we are left with 12,525 firm-year observations. We compare firms' sales guidance with realized sales data (retrieved from Compustat North America) and define the squared relative forecast error as in Equation (24). We winsorize the relative forecast error at the one percent level on the right tail.

4.2 Stock of Data: Dynamics and Components

Recall that our model for the evolution of the underlying state is given by

$$\theta_t = \widehat{\theta}_t + \eta_t, \qquad \eta_t \sim N(0, \sigma_\eta^2)$$

$$\widehat{\theta}_{t+1} \;=\; \rho\widehat{\theta}_t + \epsilon_{t+1}, \qquad \epsilon_{t+1} \sim N(0, \sigma_\epsilon^2),$$

for $0 < \rho < 1$, and we have defined the stock of data as the inverse of the conditional variance of the forecastable component ($\hat{\theta}$). With $\tilde{\theta}_{it} = \log(\text{Revenue}_{it}/\text{Assets}_{it})$ as a proxy for the state θ, we estimate ρ, σ_ϵ^2, and σ_η^2 from the data using a state-space model estimated via maximum likelihood with a Kalman filter and get the following results. Details of the estimation can be found in Appendix C. We use $\hat{\sigma}_\epsilon^2$ as the estimate of the prior conditional variance of $\hat{\theta}$[4].

[3]Firms revise and update their annual sales guidance over the course of the fiscal year as realized quarterly sales data comes in. Since our analysis focuses on firms' ability to forecast annual sales, we use only the forecast made in the first quarter of the financial year, which is not affected by subsequent realized quarterly data. When the sales forecast is expressed as a range, we take the midpoint.

[4]Note that $\hat{\sigma}_\epsilon^2$ is a lower bound for the conditional prior variance of $\hat{\theta}_t$ given the observation of θ_{t-1}. This is a conservative approximation and a reasonably good one in the current context as $\hat{\sigma}_\epsilon^2 \gg \hat{\sigma}_\eta^2$

Parameter	Estimate
$\hat{\rho}$	0.815
$\hat{\sigma}^2_\epsilon$	0.0562
$\hat{\sigma}^2_\eta$	0.00467

Table 1: Estimated parameters for the state-space model

With the estimate of σ^2_η in hand, we can estimate the conditional variance of $\hat{\theta}$ as

$$Var(\widehat{\theta}_t|\mathcal{I}_t) = Var(\theta_t|\mathcal{I}_t) - \sigma^2_\eta. \tag{23}$$

Therefore, we need an estimate for the conditional variance of θ, which can be measured as the *expected squared relative forecast errors*. Using firms' forecasts of future revenue and the realized revenue, we compute squared relative forecast errors (FE)

$$\text{FE}^{post} = \left| \frac{\text{Forecasted Revenue} - \text{Actual Revenue}}{(\text{Forecasted Revenue} + \text{Actual Revenue})/2} \right|^2. \tag{24}$$

One of the interesting observations from looking at the distribution of forecast errors is that it has a very heavy right skew. We plot the distribution of FE^{post} in Figure 1. The mean value of FE^{post} is 0.0205, and the median value is 0.0023, a tenfold difference. The mean squared relative forecast error in our sample is 0.0205. Combined with our estimate of σ^2_η, we obtain $Var(\widehat{\theta}_t|\mathcal{I}_t) = 0.0205 - 0.00467 = 0.0158$.

To make sure our analysis is representative of a median firm, we convert all the values obtained above to corresponding estimates for a median firm. We first construct an empirical proxy for the firm's prior forecast errors FE^{prior} using the parameters of our estimated state-space model. For each observation, the predicted value $\text{Pred}(\tilde{\theta}_{i,t})$ combines the Best Linear Unbiased Predictor of the firm-specific level with the AR(1) one-step-ahead projection from the observed lag $\tilde{\theta}_{i,t-1}$, and we set

$$\text{FE}^{prior} = |\tilde{\theta} - \text{Pred}(\tilde{\theta})|^2.$$

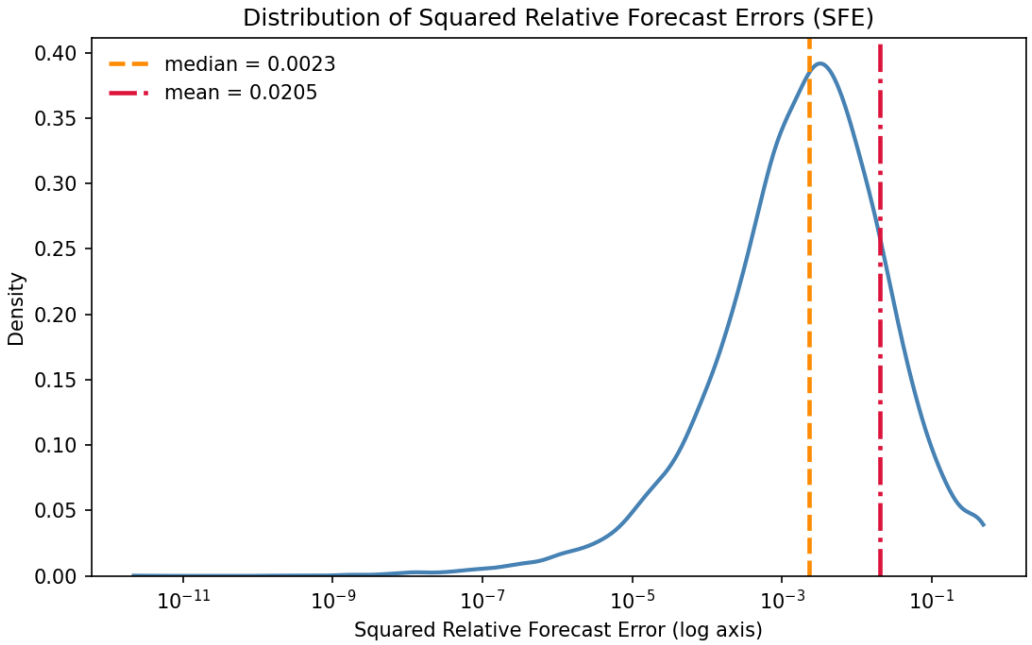

Figure 1: Distribution of Squared Relative Forecast Errors

As we are using log(Rev/Assets), this is a good approximation of the squared relative forecast error we use for revenue forecasts. We then assume that the right skew affects prior and posterior forecast errors in a similar way, so a single multiplicative correction maps mean-space variances to median-firm analogs. We compute this scaling factor as the ratio of the median empirical FE^{prior} in our sample to the theoretical mean prior variance $\hat{\sigma}_\epsilon^2 + \hat{\sigma}_\eta^2$,[5]

$$SF \;=\; \frac{\widetilde{\text{FE}}^{prior}}{\hat{\sigma}_\epsilon^2 + \hat{\sigma}_\eta^2} \;=\; \frac{0.0068}{0.0608} \;\approx\; 0.112.$$

This yields the following estimates for the prior and posterior variance of the forecastable component for the median firm.

$$Var_{med}^{prior}(\widehat{\theta}_t|\mathcal{I}_t) = 0.0063, \qquad Var_{med}^{post}(\widehat{\theta}_t|\mathcal{I}_t) = 0.0018$$

[5]Again note that this is a lower bound but both conservative and reasonably accurate when $\hat{\sigma}_\epsilon^2 \gg \hat{\sigma}_\eta^2$, which is the case here.

The inverse constitutes our measure of *data stock*, which is $\bar{\Omega} = 563$ for the posterior precision of a median firm-year observation in the sample. Similarly, the prior precision turns out to be $\bar{\phi} = 159$. The dynamics of these measures are plotted in Figure 2. This analysis immediately

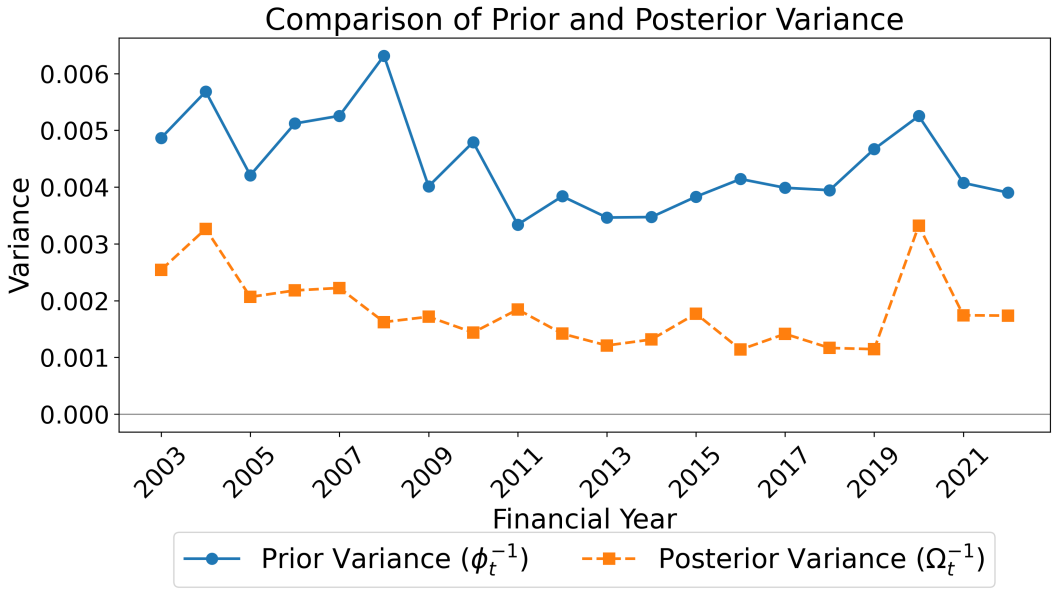

Figure 2: Prior and Posterior Variance

implies that the amount of private data, both new and undepreciated old data, is the residual. Hence *the average stock of private data* is $\bar{\Omega} - \bar{\phi} = 404$.

This is the first insight: *The precision of private data is more than twice that of public information based on prior realizations.* We now decompose the stock of data into public data, newly obtained private data, and undepreciated old data. From (9), the stock of data for firm i in period t is given by $\Omega_{i,t} = Var^{-1}(\widehat{\theta}_t|\mathcal{I}_t)$. Using $FE_{i,t}^{prior}$, $FE_{i,t}^{post}$ and our estimates of the variance of transitory component $\hat{\sigma}_\eta^2$, we back out the quantity of newly obtained data ($\tau_{i,t}$) using the recursive law of motion for the data stock (10) and the endogenous depreciation rate (15). Further details of this construction are provided in Appendix C.

The key question in this dynamic decomposition is how quickly data depreciates. Data about yesterday's state is less relevant to today's state because the state is changing. That decline in relevance is the source of data depreciation. While previous studies have estimated

depreciation rates, we derive the depreciation rate from our model and estimate it using firm revenue data. The model implies that data obtained in one period has value for multiple future periods, as long as $\rho > 0$. We find that the persistence coefficient is estimated to be $\rho = 0.815$, which we can now use in equation (15) to back out yearly depreciation. Figure 3

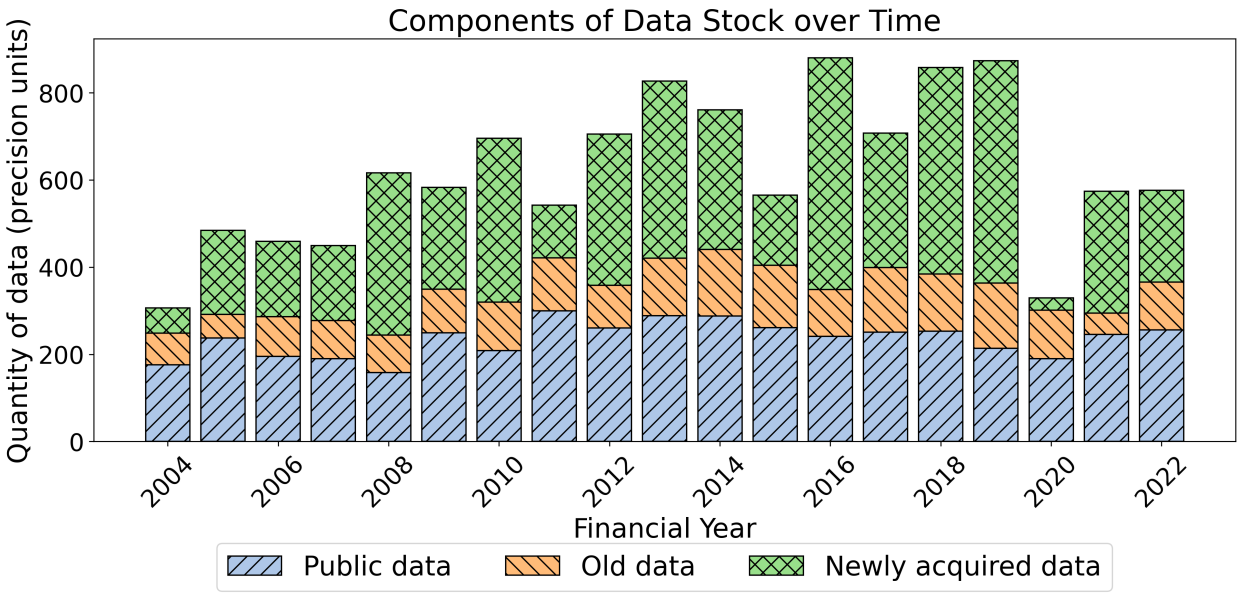

Figure 3: Data Stock and its Components: Public, Old and New Data (median firm)
Old data refers to the data carried over from the previous period after depreciation. For details of the three components, see equation (10)

decomposes the data stock into components that come from prior knowledge, which we call public data ϕ_t, newly obtained data from own operations τ_t, and the depreciated data stock carried over from the previous period. We find that most of the precision comes from new data inflows. Notice that two insights stand out from looking at the plot. First, both the total data stock as well as the flow of new data increases gradually. This is consistent with increasing adoption of cloud computing, big data, and mobile dominance. Second, the year 2020 looks quite different. This reflects the higher uncertainty in the COVID-19 period. It shows up as almost no new data flow. The fact that earnings variance in this period was high shows up as a lower value of prior information or public data. One might think of this period as marked by a relatively large depreciation shock to prior knowledge, as the business

environment changed rapidly.

4.3 Value of Data

So far, we have dealt with the data stock ($\Omega_{i,t}$). To capture the mismeasurement of GDP we need to assign monetary value to the present discounted value of new data generated in a given year, hence the importance of identifying the main components of the stock of data, as we did in the previous section. This involves expressing the marginal value of an improvement in forecast errors arising from new data, while correcting for reverse causality. To make progress on this task, we calibrate the model. Here we explain the main elements and results. The full simulation procedure and solution method are provided in Appendix B.

Model Implementation: Each firm i is characterized by a permanent productivity draw A_i, a stock of data precision $\Omega_{i,t}$, and a choice of capital $k_{i,t}$. Recall that in our model, the per-period profit of firm i, gross of capital rental costs, is given by

$$\Pi^g_{i,t} = \Big[(1 - \gamma\psi^2_{i,t})A_i - w\Big]k^\alpha_{i,t},$$

where $\psi_{i,t} \sim \mathcal{N}(0, \Omega^{-1}_{i,t} + \sigma^2_\eta)$ denotes the forecast error. We refer to $\Pi^g_{i,t}$ as gross profit hereafter.

The stock of data evolves according to equation (17), and we have to take a stand on the functional form of $\tau_{i,t+1}(k_{i,t})$: how new data depends on the previous period scale of production. Since we calibrate the model to the median firm in the sample, we assume that

$$\tau_{i,t+1}(k_{i,t}) = \tau_{t+1} + \chi \ln\left(\frac{\Pi^g_{i,t}}{\Pi^g_{M,t}}\right) \tag{25}$$

where $\Pi^g_{M,t}$ denotes gross profit for the median firm, τ_{t+1} is the baseline new data obtained by

the median firm, and χ captures the slope: how data changes with changes in scale relative to the median firm.

We obtain the policy functions that solve (16) using value function iteration (VFI) on discretized grids for productivity, precision, and capital. The productivity grid is constructed from quantiles of a log-normal distribution, the precision grid spans a geometric sequence covering the feasible range implied by the law of motion, and the capital grid spans a geometric sequence covering the feasible range implied by the optimal choice of capital from the Bellman equation (16) for all reasonable combinations of productivity and precision.

Calibration Strategy: To calibrate the model, we *i*) fix some parameters outside the model and *ii*) simulate a panel of 1000 firms for 100 time periods and match the model's moments with data moments.

First, on parameters that we calibrate through external measures, public data ϕ is set to $\bar{\phi} = 159$ to match prior precision, and baseline private data τ is set to 308, which jointly with ϕ and depreciation matches the posterior precision of the median firm in steady state. Notice that this is consistent with our previously discussed private data (see section 4.2), both new and undepreciated, on average. Such estimation was $\bar{\Omega} - \bar{\phi} = 404$, with new data τ coming from the decomposition in Figure 3 of around 75% on average. The persistence of the state variable, $\rho = 0.815$, and the mean variance of the non-forecastable component of the state, $\sigma_\eta^2 = 0.00467$, are obtained from state-space estimation of revenues normalized by assets as discussed previously. The capital share is set to $\alpha = 1/3$ and the rental rate of capital to $r = 0.04$, consistent with standard values in the literature (Table 2). Second, on parameters that we calibrate through simulating the model, each firm draws a permanent productivity A_i from a log-normal distribution with mean $\mu_{\ln A}$ and standard deviation $\sigma_{\ln A}$. The panel is then generated period by period: firms optimally choose capital based on the policy function, forecast errors are computed, revenue shocks are realized (which imply forecast errors), and precision is updated according to the data's law of motion. We calibrate $\mu_{\ln A}$, $\sigma_{\ln A}$, γ, χ,

Table 2: Parameters Calibrated Outside the Simulation

Parameter	Value	Strategy
ϕ	159	Match Prior Precision
τ	308	Match Posterior Precision
ρ	0.815	Match Persistence of State in Data
σ_η^2	4.67×10^{-3}	Match Transitory Variance of State
α	1/3	Standard Capital Share in Literature
r	0.04	Standard Rental Rate of Capital

and w to minimize the sum of squared percentage deviations between targeted empirical moments and the corresponding simulated moments.

Although all five parameters ($\mu_{\ln A}$, $\sigma_{\ln A}$, γ, χ, w) are calibrated jointly to match the five targeted moments, different moments load more heavily on specific parameters. The distributional moments of log gross profit (mean 5.77 and standard deviation 1.62) are most sensitive to $\mu_{\ln A}$ and $\sigma_{\ln A}$. The cost parameter w is primarily disciplined by the empirical share of gross profit paid to data workers for the median firm—0.4 percent, based on Occupational Employment and Wage Statistics (OEWS) data from the U.S. Bureau of Labor Statistics (BLS).

To obtain the moments that discipline γ and χ, we simulate a panel of 1000 firms for 100 time periods and run the following regressions on both simulated and empirical data:

1. To discipline how forecast errors translate into gross profit (γ), we run the following *gross profit regression*:

$$\ln(\Pi_{i,t}^g) = \beta_0 + \beta_1 \ln(FE_{i,t}) + \mathbf{X}_{i,t}'\boldsymbol{\beta} + \epsilon_{i,t}. \tag{26}$$

   where $\mathbf{X}_{i,t}$ is a vector of controls. In the data, we construct gross profit as the difference between revenue and cost of goods sold (Compustat variables `sale` and `cogs`, respectively).[6]

[6]Approximately 2% of firm-year observations in our sample have negative gross profit. We exclude these observations from this analysis.

Table 3 shows the results, Column (1) without any controls and Column (2) controlling for the log of the number of employees (ln(Emp)), which serves as a proxy for firm size in the data. As the model does not explicitly include total employment, we proxy for firm size in the simulated data using $\ln(A_i)$. Column (3) shows the results with Industry and Year fixed effects while also controlling for firm-size. The results we use for our calibration come from column (4) which has the most restrictive set of controls - firm and year fixed effects along with ln(Emp).

For our calibration, we use the result from column (4), which shows that a 1% decrease in Forecast errors is associated with a 0.011% increase in gross profits. This is sizable. Our estimates show that the median firm has a prior variance of 0.0063 and posterior variance of 0.0018 implying a 71% decline in forecast error from prior to posterior. Hence, the log gross profit for the median firm increases by approximately $|0.011 \times \ln(1 - 0.71)| \approx 0.014$, or approximately 1.4%.

Table 3: Effect of Forecast Error on Gross Profits

	(1) log(GP)	(2) log(GP)	(3) log(GP)	(4) log(GP)
log(FE)	-0.138***	-0.033***	-0.022***	-0.011***
	(0.006)	(0.003)	(0.003)	(0.001)
log(Emp)		0.772***	0.884***	0.759***
		(0.005)	(0.022)	(0.029)
Observations	12279	12279	12179	11543
Fixed effects	None	None	Industry, Year	Firm, Year
SE clustered at	None	None	Industry	Firm

Standard errors in parentheses.
Standard Errors in columns (1) and (2) are heteroskedasticity-consistent.
Standard errors in column (3) clustered by industry identifier.
Standard errors in column (4) clustered by firm identifier.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

2. To discipline how gross profits translate into new data available next period (captured

by χ), we run the following *Forecast error regression:*

$$\ln(FE_{i,t}) = \beta_0 + \beta_1 \ln(\Pi^g_{i,t-1}) + \mathbf{X}'_{i,t}\boldsymbol{\beta} + \epsilon_{i,t}. \tag{27}$$

where $\mathbf{X}_{i,t}$ is a vector of controls. Table 4 shows the results. Column (1) does not use any controls, whereas column (2) controls for industry and year fixed effects. For our calibration, we use the result from column (3), which has the most restrictive controls: firm and year fixed effects. It shows that a 1% increase in last year's gross profit is associated with a 0.428% decrease in forecast errors for the current year. The standard deviation of the lagged $\log(\Pi^g)$ in our data is 1.66. Therefore, a one-standard-deviation increase in $\log(\Pi^g)$ is associated with a change of 0.71 in $\log(FE)$. Since the standard deviation of $\log(FE)$ is 2.7, a one-standard-deviation increase in $\log(\Pi^g)$ is associated with a 0.26 standard deviation decrease in $\log(FE)$ in the next year.

Table 4: Forecast Error vs. Lagged Gross Profit

	(1) log(FE)	(2) log(FE)	(3) log(FE)
log (GP(t-1))	-0.349***	-0.386***	-0.428***
	(0.014)	(0.022)	(0.061)
Observations	12257	12156	11528
Fixed effects	None	Industry, Year	Firm, Year
SE clustered at	None	Industry	Firm

Standard errors in parentheses.
Standard Errors in column (1) are heteroskedasticity-consistent.
Standard errors in column (2) clustered by industry identifier.
Standard errors in column (3) clustered by firm identifier.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5 shows the fit of our calibration relative to the empirical moments. Table 6 reports the corresponding parameter values.

Given our previous estimates of data stock and its components for the median firm over 2003-2022, we can now use this calibration, which maps forecast errors into gross profits

Table 5: Calibration Results (Simulation): Targeted vs. Model Moments

Moment	**Target**	**Model**
Mean log Π^g	5.77	5.80
SD log Π^g	1.62	1.51
$\beta_{\ln(FE)}$ in ln Π^g	-0.011	-0.010
$\beta_{\ln(\Pi^g_{t-1})}$ in ln FE	-0.428	-0.346
Fraction of gross profit paid to data workers	0.004	0.004

Table 6: Parameter Values calibrated through simulation

Parameter	**Value**
$\mu_{\ln A}$	3.2
$\sigma_{\ln A}$	1.0
γ	5.2
χ	130
w	0.08

while controlling for reverse causality, to value each firm's data stock. Using the calibrated model, we can back out the value of data obtained by firm i at time t as

$$D_{i,t} = \mathbb{V}_i\left(\Omega_{i,t}^{-1}\right) - \mathbb{V}_i\left(\left[\Omega_{i,t} - \tau_{i,t}\right]^{-1}\right)$$

The expression above obtains the value of newly acquired data as the difference between the value of the firm with stock of data $\Omega_{i,t}$ and the value of the firm without new data at t.

Normalizing newly acquired data by the median firm's number of employees, we obtain an estimate of the value of data per employee for that firm. Figure 4 shows how this value has evolved over the past two decades. Despite the growth of data, its value per employee remains stable for most years around $700 a year (in December 2002 dollars).

4.4 Scaling Up: From the Median Firm to GDP

Here we scale up the model-implied value of data for the median firm to the whole economy, and obtain three estimates of the associated GDP mismeasurement. We briefly describe the process below; more details are available in Appendix D.

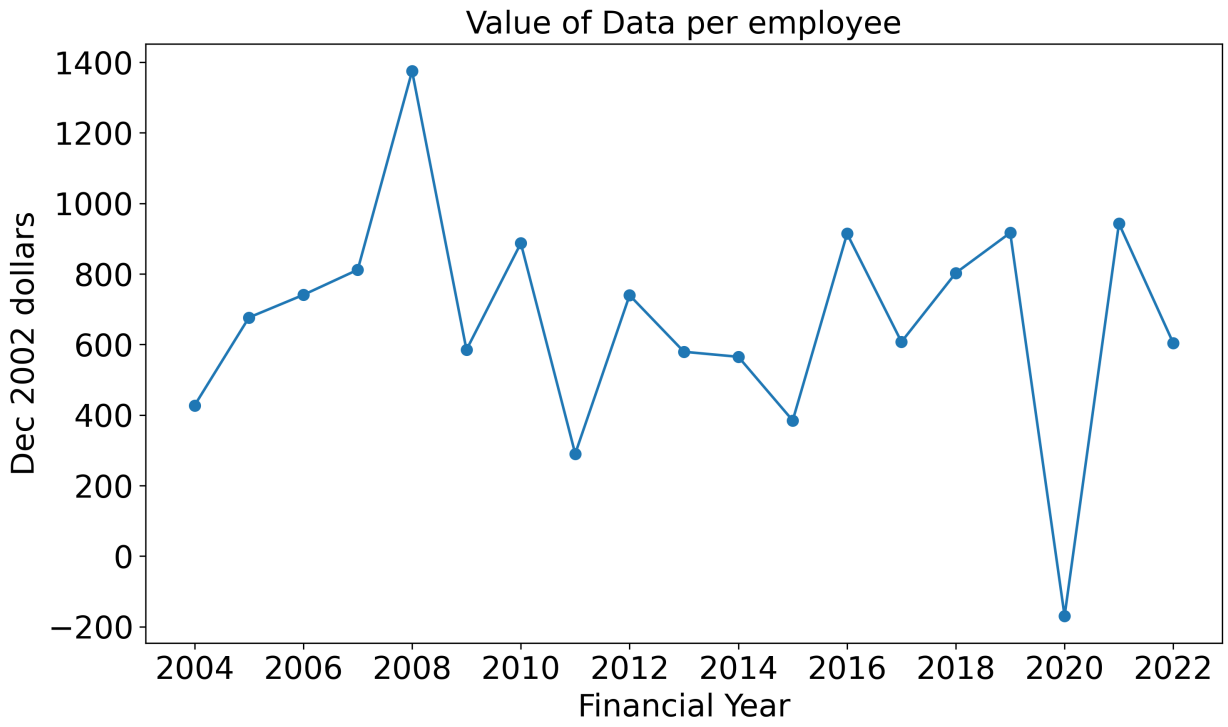

Figure 4: Estimate of the value of data per employee for the median firm in our sample

The first projection is a clear lower bound. It assumes that only the firms in our sample possess valuable data. Under this assumption, missing GDP equals $2D_t$ for each firm, where D_t is the value of data in period t, and as explained, it is counted twice because of two sources of mismeasurement, as intangible capital and as bartered consumption. We therefore take twice the value of data per employee for the median firm in our sample and multiply it by the total employment of all *firms in the sample*. Under this approach, the implied missing GDP averages about 0.1% of measured GDP.

The second projection uses the same logic but scales the calculation to the entire economy, assuming all firms obtain and value data in the same way as the firms in our sample. Specifically, we take twice the value of data per employee for the median firm and multiply it by total U.S. employment. Under this approach, the implied missing GDP averages about 1.5% of measured GDP.[7]

[7]Of course, public companies that forecast revenue are different from the average U.S. firm. While we cannot fully correct for this bias, one might use the smallest firms in our sample as a more comparable

Both of these projections assume that firms must fully compensate consumers for the data they obtain. However, if firms have market power, they may only need to offer a discount of D_t/μ rather than D_t to acquire data worth D_t. In this case, the amount of GDP missing from national accounts reduces to $(1 + 1/\mu)D_t$, given the lower impact of missing bartering. We set $\mu = 1.26$, following Edmond et al. (2023), who show that after 1990 the cost-weighted average markup for U.S. public firms remained within the range 1.2–1.26. Because our sample covers 2003–2022, this estimate applies directly to our setting. This yields our third projection, which adjusts the missing GDP estimate for market power, and reduces the estimated missing GDP merely by 0.1% on average.

The estimates of missing GDP from all three methods are presented in Figure 5. Three interesting patterns emerge.

First, the missing value of data remained remarkably stable at around 1.5% of GDP for most of the sample. This is in contrast to the rough doubling in the flow of new data we documented in Figure 3. The reason is that the value of new data is, intuitively, determined by the prediction improvement relative to the prior without new data. When the firm already has accumulated a lot of data (either public or undepreciated data) then the same amount of new data is not that valuable, as it does not improve prediction much further. As can also be seen in Figure 3, not only new data increased, but also the accumulated data did, which reduced the value per unit of new data. These two effects seem to counterbalance each other, and maintain the total value of data stable in the last couple of decades.

Second, there was a pronounced decline during the COVID-19 pandemic. This drop aligns with the sharp increase in forecast errors documented in Figure 2, driven primarily by a collapse in newly acquired data, as shown in Figure 3. This result suggests that the loss in GDP during the pandemic was likely underestimated.

benchmark to the firms outside our sample. When we used the data-per-worker of smallest quintile of firms in the sample to project to the whole economy, we found an aggregate data value that is higher than what we report here. Thus, we kept the simpler procedure with the more conservative answer. Results available on request.

Finally, the missing value of data increased substantially during the 2008 financial crisis. Interestingly, as shown in Figure 2, forecast errors declined slightly despite the sharp rise in prior variance. In more intuitive terms, the heightened uncertainty of that period appears to have been offset by a surge in new data generation, consistent with the patterns observed in Figure 3. This points to a substantial expansion in information production during that turbulent year. If accounted for, that could have raised the measured value of GDP during the financial crisis. Together, the 2008 and 2020 episodes illustrate that the value of firms' data responds differently to different types of recessions: a financial crisis like 2008 raises it by sharpening the payoff to accurate forecasting, while a broad structural shock like the 2020 pandemic lowers it by eroding the informational content of historical data.

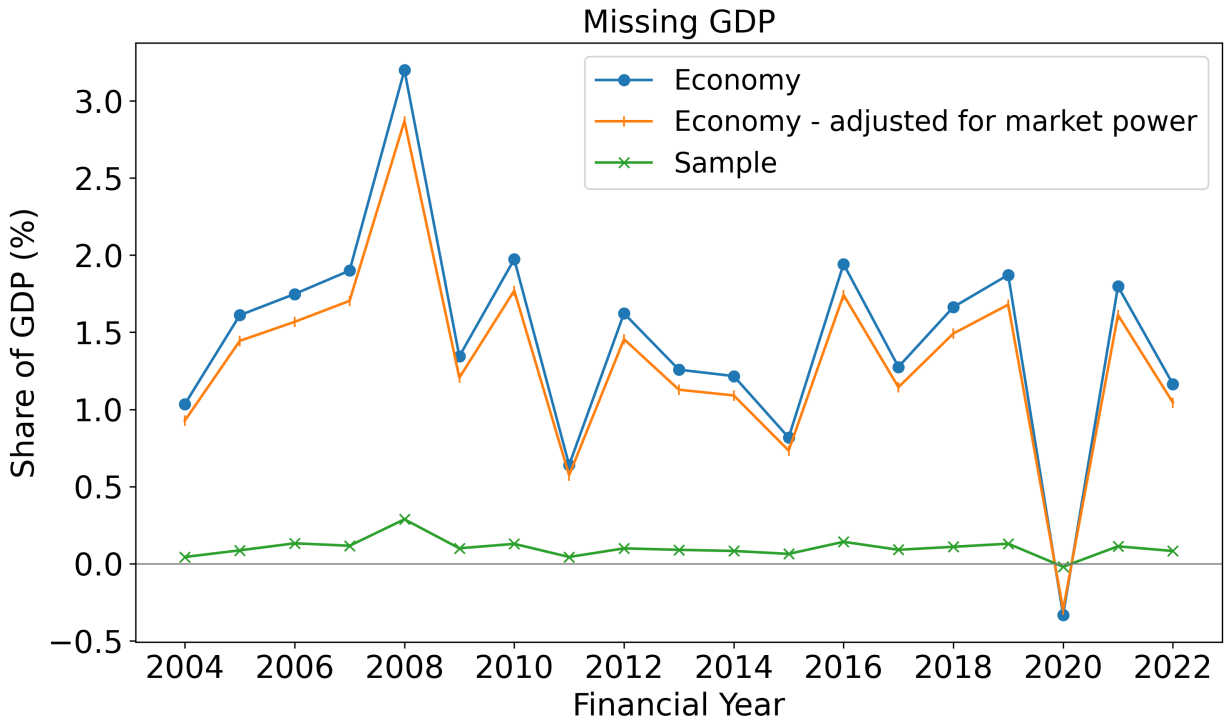

Figure 5: Estimates of missing data GDP measure with three methods.
The first series scales the median firm's data value to the employment in our sample, the second extends this scaling to the entire U.S. workforce, and the third adjusts the implied missing GDP for market power using $(1 + 1/\mu)D_t$ with $\mu = 1.26$.

Remark about Business Stealing: An important concern in assigning value to data is whether it is used to improve forecast errors that allow for better and more production, or

if it is just used to steal resources from other firms, hence rendering its value not conducive to increase value added in the economy. Our strategy partially mitigates within-sample business stealing because it comes fundamentally from the mapping between forecast errors and profits. If two firms in our sample use their new data to steal business from each other, the role of lower forecast errors on aggregate profits within the sample would be muted in the regressions. Hence, business stealing among firms in our sample is partially captured in our regressions when assigning a value to data. As long as the use of data is not unique to publicly listed firms, then the extrapolation to the whole economy also captures the role of new data on value added.

5 Validation of Forecast-Based Approach

In this paper, we value data with an *output approach*: we use the evolution of forecast errors, and their impact on firm outcomes, as the observable output of data. To validate our exercise here, we explore the relation between forecast errors and the labor that in principle makes data valuable, such as data workers: an *input approach*. This is the most explored approach, and examples include Abis and Veldkamp (2024), Crouzet et al. (2022), and Calderón and Rassier (2022).

To obtain a proxy for the number of workers engaged in data work, we use the Occupational Employment and Wage Statistics (OEWS) program of the U.S. Bureau of Labor Statistics (BLS). The OEWS reports employment shares and wages for detailed occupations within each NAICS industry, with consistent coverage starting in 2012. We focus on the occupational category Database and Network Administrators and Architects[8] as our proxy for Data Workers. For each firm–year observation, we assign the employment share of Data Workers in the firm's four-digit NAICS industry, defined as the percentage of total workers in

[8]We use this broader category rather than more granular codes to avoid breaks across years when detailed occupation definitions change or are subject to sampling limitations.

that industry who are classified as Data Workers. If four-digit industry data are unavailable, we use the corresponding three-digit industry average; if still unavailable, we use two-digit industry. Observations that remain unmatched are assigned an employment share of zero.[9]

Using this proxy, we regress our measure of squared forecast errors (FE) on the employment share of Data workers (DataEmp) using the following specification:

$$FE_{i,t} = \alpha + \beta \times DataEmp_{i,t} + \upsilon \times emp_{i,t} + \delta_i + \xi_t + \epsilon_{i,t} \tag{28}$$

where $FE_{i,t}$ denotes the squared forecast error for firm i in year t, $DataEmp_{i,t}$ is the employment share of Data workers in the industry of firm i, $emp_{i,t}$ is the log of firm i's total employment, and δ_i and ξ_t represent firm and year fixed effects.

Table 7 reports the results. We find a statistically and economically significant negative relationship between the share of Data Workers and the magnitude of forecast errors. Column (1) presents the specification without controlling for firm size, while Column (2) includes log employment. The estimate in Column (2) implies that a one-percentage-point increase in the employment share of Data Workers reduces squared forecast error by 0.005 percentage points. To gauge economic significance, note that the standard deviations of FE and DataEmp are 0.019 and 1.829, respectively. Thus, a one-standard-deviation increase in Data worker employment share is associated with a 0.48-standard-deviation decline in forecast errors.

Columns (3) and (4) repeat the analysis using the wage-bill share of Data workers (DataWage), defined as the percentage of the total wage bill paid to Data workers. Column (4) shows that DataWage is also significantly negatively associated with squared forecast errors, after controlling for firm size and including firm- and year-fixed effects.

Next, we examine whether the employment of Data workers, while strongly associated with lower squared forecast errors, also has a significant effect on gross profit. Column (1)

[9]Results are robust to excluding these unmatched observations.

Table 7: Forecast Errors regressed on employment of Data workers

	(1) FE	(2) FE	(3) FE	(4) FE
DataEmp	-0.004^{+}	-0.005*		
	(0.002)	(0.002)		
DataWage			-0.003^{+}	-0.004*
			(0.002)	(0.002)
emp		-0.015*		-0.015*
		(0.006)		(0.006)
Constant	0.022***	0.045***	0.022***	0.046***
	(0.002)	(0.009)	(0.003)	(0.009)
Observations	6431	6431	6431	6431

Standard errors in parentheses.
Standard errors are clustered by firm identifier.
$^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

of Table 8 reports results from the following specification:

$$\ln \Pi^{g}_{i,t} = \alpha + \beta \times DataEmp_{i,t} + \upsilon \times emp_{i,t} + \delta_i + \xi_t + \epsilon_{i,t} \tag{29}$$

where $\Pi^{g}_{i,t}$ is the gross profit for firm i in year t, and the remaining terms are defined as in Equation 28. To gauge economic significance, note that the standard deviations of log gross profit and DataEmp are 1.6 and 1.8, respectively. A one-standard-deviation increase in the employment share of Data workers is associated with a 0.05-standard-deviation decrease in log gross profit. Likewise, the standard deviation of the wage-bill share is 2.1. A one-standard-deviation increase in this measure is also associated with just a 0.05-standard-deviation decrease in log (Π^{g}). These results suggest that the presence of data workers, while statistically significant, has limited direct effect on gross profit.

Lastly, Table 9 reports results using the employment share (ESM) and wage-bill share (WSM) of Mathematical Professions, instead of Data workers. None of the measures shows a strong relationship with squared forecast errors. This placebo test reinforces our conclusion

Table 8: Log Gross Profits regressed on employment of data workers

	(1) log (Π^g)	(2) log (Π^g)
DataEmp	-0.046**	
	(0.016)	
DataWage		-0.038**
		(0.012)
emp	0.746***	0.745***
	(0.042)	(0.042)
Constant	5.267***	5.270***
	(0.072)	(0.072)
Observations	6340	6340

Standard errors in parentheses.
Standard errors are clustered by firm identifier.
$^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

that the labor input most relevant for reducing forecast errors is captured by the employment of Data workers in the category *Database and Network Administrators and Architects*, but, in general, it is difficult to identify which inputs map to data outputs.

We take these results to imply that, while the input that firms use to manage data clearly affects the output of that data (in terms of reducing forecast errors), it is not as clearly related to the profit implications of that improvement. This result gives us confidence that, in order to value data, it is more natural and precise to directly study the relevance of data through predictions than to study the indirect use of data through processing inputs.

6 Conclusion and Next Steps

This paper presents a novel framework for computing the value of firms' data that is missing in standard measures of GDP. Our approach recognizes data as both a productive asset and a means of payment. By quantifying data's value through its impact on firms' forecasting accuracy, we demonstrate that traditional measures of investment underestimate firms' true

Table 9: Forecast Errors regressed on employment of workers in mathematical occupations

	(1) FE	(2) FE	(3) FE	(4) FE
ESM	0.008	0.011		
	(0.008)	(0.008)		
WSM			0.009	0.012^{+}
			(0.006)	(0.006)
emp		-0.015*		-0.015*
		(0.006)		(0.006)
Constant	0.015***	0.036***	0.014***	0.036***
	(0.002)	(0.009)	(0.002)	(0.009)
Observations	6431	6431	6431	6431

Standard errors in parentheses.

Standard errors are clustered by firm identifier.

$^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

asset base. We argue that our *output-based* approach to measuring the value of data complements and extends the more standard *input-based* approach advanced in the literature.

Our approach allows us to answer several questions about the role of data in modern economies. First, the extent of reverse causality. Does data induce firm growth, or does firm growth induce data? We show that data is indeed quite powerful in improving outcomes. Second, the extent to which data is obtained in day-to-day operations, undepreciated old data, or purchased from external parties. We show that the most important source of data is the one obtained from day-to-day operations. Finally, future work could explore the degree of heterogeneity in the value of data across firms.

Addressing these measurement gaps is essential for policymakers, economists, and corporate decision-makers. More accurate valuation of data assets can improve financial market assessments, guide policy on data governance, and refine taxation frameworks for intangible investments. By incorporating a rigorous, market-based approach to data valuation, this research contributes to ongoing debates about the role of intangible assets in economic growth and firm productivity. Future work should explore refinements to our methodology, including

sector-specific variations in data value, firm-level heterogeneity, and alternative approaches to estimating data depreciation. Ultimately, recognizing and properly accounting for firms' data assets will provide a more comprehensive and accurate understanding of the digital economy's impact on productivity, investment, and innovation.

An important consideration for future work is accounting for market power. When equating the value of the data barter discount to the value firms extract from data, we assume perfect competition. This assumption assigns all data surplus to customers. While perfect competition is a natural starting point, it surely overestimates the size of the data barter. We have explored robustness using estimations of product market power for data market power. A fruitful research agenda involves measuring and disciplining the extent to which firms can extract rents from customers when buying data, which is likely quite different than the extent to which they can extract rents from selling products.

We hope this novel methodology to measure the aggregate value of data opens the doors to including other potentially relevant aspects of data. First, we have assumed the effects of forecast errors on profits are symmetric, but it may be the case that a mistake is more costly than an accurate prediction. Second, there may be a complement between reducing forecast errors, and the role of data on facilitating automation, becoming part of the production function, or inducing better sorting and matching in the aggregate, hence characterized by externalities to other firms.

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Online Appendix

A Steady State

Assume a deterministic steady state with time-invariant primitives $\{\phi, \nu, \tau(\cdot), \zeta(\cdot)\}$ and $\Omega_{t+1} = \Omega_t = \Omega$, $k_{t+1} = k_t = k$. The steady-state equation follows from (17) with $\Omega_{t+1} = \Omega_t = \Omega$:

$$\Omega \;=\; \phi + \tau(k) + \nu + \big(1 - \zeta(\Omega)\big)\big(\Omega - \phi\big). \tag{30}$$

Equations (19) and (20) collapse to

$$V'(\Omega^{-1}) = -\,\gamma\, A\, k^{\alpha} + \beta\, \Gamma(\Omega)\, V'(\Omega^{-1}), \qquad \Gamma(\Omega) \equiv 1 - \zeta(\Omega) - (\Omega - \phi)\, \zeta'(\Omega),$$

so

$$V'(\Omega^{-1}) \;=\; \frac{-\,\gamma\, A\, k^{\alpha}}{1 - \beta\, \Gamma(\Omega)}\,.$$

So, the steady-state Euler equation is:

$$\alpha\left(A\left(1 - \gamma\left(\frac{1}{\Omega} + \sigma_\eta^2\right)\right) - w\right) k^{\alpha-1} - r \;+\; \frac{\beta\, \gamma\, A\, k^{\alpha}\, \tau'(k)}{\big(1 - \beta\, \Gamma(\Omega)\big)\, \Omega^2} = 0. \tag{31}$$

Equations (30) and (31) jointly determine steady state levels of scale k^*, and data Ω^*.

A.1 Steady-State System when depreciation is endogenous.

As we discussed, depreciation depends on the stock of data as follows

$$(1 - \zeta(\Omega)) = (\rho^2 + \sigma_\epsilon^2 \Omega)^{-1}$$

Hence, equation (30) of the state steady state becomes a quadratic in the stock of data

$$\Omega \;=\; \phi + \tau(k) + \nu \;+\; \frac{\Omega - \phi}{\rho^2 + \sigma_\epsilon^2\, \Omega}. \tag{32}$$

Similarly, the definition $\Gamma(\Omega)$ in equation (19), which enters into the steady state Euler in equation (31) becomes

$$\Gamma(\Omega) = 1 - \zeta(\Omega) - (\Omega - \phi)\, \zeta'(\Omega) = \frac{1}{\rho^2 + \sigma_\epsilon^2 \Omega} - \frac{\sigma_\epsilon^2 (\Omega - \phi)}{(\rho^2 + \sigma_\epsilon^2 \Omega)^2} = \frac{\rho^2 + \sigma_\epsilon^2 \phi}{\big(\rho^2 + \sigma_\epsilon^2 \Omega\big)^2}. \tag{33}$$

In this case, the steady state is characterized by scale k^* and data Ω^*. These jointly solve the modified state steady-state equation (32) and the steady-state Euler equation (31), with $\Gamma(\Omega)$ given by (33).

A.2 Steady State without reverse causality

When there is no reverse causality, i.e., when scale depends on data (k depends on Ω) but data does not depend on scale (Ω does not depend on k), the deterministic steady state solution is analytic, even when depreciation is endogenous.

In our setting, this is the same as assuming $\tau(k) = \tau$. Define the total exogenous signals as $S \equiv \phi + \tau + \nu$. The state fixed point is then given by

$$\Omega \;=\; S \;+\; \frac{\Omega - \phi}{\rho^2 + \sigma_\epsilon^2\,\Omega}.$$

Equivalently, the quadratic in Ω:

$$\sigma_\epsilon^2\,\Omega^2 + \Big(\rho^2 - 1 - \sigma_\epsilon^2 S\Big)\Omega + \phi - \rho^2 S \;=\; 0.$$

Hence, in closed-form:

$$\Omega^* = \frac{-B \;\pm\; \sqrt{B^2 - 4\,\sigma_\epsilon^2\,C}}{2\,\sigma_\epsilon^2}, \qquad B \equiv \rho^2 - 1 - \sigma_\epsilon^2 S, \quad C \equiv \phi - \rho^2 S. \tag{34}$$

which is well-defined if the root is economically admissible: $\Omega^* > 0$ and $\rho^2 + \sigma_\epsilon^2 \Omega^* > 0$.

Since $\tau'(k) = 0$, the continuation term vanishes and the steady-state FOC reduces to

$$\alpha\left(A\left(1 - \gamma\left(\frac{1}{\Omega^*} + \sigma_\eta^2\right)\right) - w\right)\,(k^*)^{\alpha-1} \;=\; r,$$

Hence,

$$k^* \;=\; \left[\frac{\alpha\big(A\big(1 - \gamma\big(\frac{1}{\Omega^*} + \sigma_\eta^2\big)\big) - w\big)}{r}\right]^{\frac{1}{1-\alpha}}. \tag{35}$$

B Model Simulation and Calibration

This appendix describes the simulation framework used to discipline the relationship between firm-level revenues, forecast errors, and data accumulation. The objective is to generate model-implied moments that can be compared to their empirical counterparts, thereby guiding the calibration of key parameters.

B.1 Value Function Iteration

Firms choose capital to maximize the present discounted value of revenues net of capital costs, taking into account the evolution of precision. The Bellman equation, which carries the irreducible transitory variance σ_η^2 alongside the forecastable-component variance $\Omega_{i,t}^{-1}$ in the flow profit, is:

$$\mathbb{V}_i(\Omega_{i,t}^{-1}) = \max_{k_{i,t}} \left\{ \left[(1 - \gamma\,(\Omega_{i,t}^{-1} + \sigma_\eta^2))A_i - w\right] k_{i,t}^{\alpha} - r k_{i,t} + \beta\,\mathbb{E}[\mathbb{V}_i(\Omega_{i,t+1}^{-1})] \right\}.$$

To accommodate the fact that different firms face different levels of irreducible transitory uncertainty while keeping the calibration tractable, we assume that the transitory variance σ_η^2 is perfectly correlated with the forecastable-component variance Ω^{-1} across firms — that is, the two are proportional. The proportionality constant is pinned down by the ratio of σ_η^2 to $Var^{post}(\widehat{\theta}|\mathcal{I})$ evaluated at the median firm. The relationship therefore holds exactly for the median observation, and for non-median firms it is an assumed extrapolation across the rest of the grid.

The solution proceeds as follows:

1. **Grids.**
   - The productivity grid for A_i is constructed from 51 quantiles of a log-normal distribution with mean $\mu_{\ln A}$ and variance $\sigma^2_{\ln A}$.
   - The precision-state grid for Ω^{-1} is a geometric sequence of 500 points covering the range 10^{-6} to 0.5, chosen wide enough that the firm's dynamics rarely visit the boundary.
   - The capital grid for k is 80 points over a geometric sequence. The endpoints of the range are chosen so the optimal choice of k implied by VFI does not bind at either edge.
2. **Flow Payoffs.** For each point on the grids (A, Ω^{-1}, k), the flow gross profit net of capital costs implied by the Bellman is computed.
3. **Continuation Values.** Given current gross profit, the Bayesian law of motion in the main paper yields the next-period precision. The continuation value is then obtained by linear interpolation of $V(\cdot)$ on the Ω^{-1} grid. We impose a soft floor on the next-period posterior precision at 10% of the prior precision of the median firm ($P \geq 0.1\,\bar{\phi} \approx 16$), which keeps the dynamics in the well-resolved part of the grid; this is a numerical convenience and does not change the substantive Bayesian recursion away from the floor.
4. **Optimal Capital Choice.** For each state (A, Ω^{-1}), the capital choice k^* is obtained numerically by maximizing the sum of current flow payoffs and discounted continuation values over the capital grid.
5. **Iteration.** The value function is updated iteratively until the supremum norm between successive iterations falls below a pre-specified tolerance.

B.2 Simulation of a Firm Panel

After solving for the value and policy functions, a panel of 1,000 firms is simulated and allowed to run for 100 periods.

1. **Initialization.** Each firm draws a permanent productivity A_i from the calibrated log-normal distribution. Initial precision is set at the median value of the Ω^{-1} grid.

2. **Evolution.** For each period and firm:

   - The policy function yields the optimal capital given $(A_i, \Omega_{i,t}^{-1})$.
   - A realized forecast error $\psi_{i,t}$ is drawn from a normal distribution with mean zero and variance equal to the firm's total conditional variance, $\Omega_{i,t}^{-1} + \sigma_\eta^2$ (the sum of the forecastable component and the transitory shock).
   - Realized gross profit (using $\psi_{i,t}^2$ in place of its expectation) and the forecast error itself are recorded.
   - Precision is updated according to the Bayesian law of motion described in the main paper.

3. **Output.** The simulated panel contains firm-year observations of gross profits, forecast errors, capital, and precision, along with the underlying productivity draw.

B.3 Calibration

Our model has 11 parameters in total as described in section 3. We calibrate 6 of them outside the simulation and the remaining 5 are calibrated to match 5 targeted moments observed in the data.

We start with the parameters chosen outside the simulation. The rental rate of capital $r = 0.04$ and the capital share $\alpha = 1/3$ are standard values from the literature.

The persistence parameter ρ and the variances σ_ϵ^2 (forecastable innovation) and σ_η^2 (transitory shock) are estimated from a pooled state-space model fit to the log revenue-to-assets ratio $\tilde{\theta}_{i,t}$, treated as a proxy for the latent state. Because forecast guidance is not required here, we estimate on each firm's contiguous Compustat panel from its first to last year in the main sample, which provides a gap-free series for the Kalman filter. The model is specified as follows:

$$\begin{aligned} \tilde{\theta}_{i,t} &= \mu + \alpha_i + \widehat{\theta}_{i,t} + \eta_{i,t}, \\ \widehat{\theta}_{i,t+1} &= \rho\, \widehat{\theta}_{i,t} + \epsilon_{i,t+1}, \end{aligned}$$

with $\eta_{i,t} \sim N(0, \sigma_\eta^2)$, $\epsilon_{i,t+1} \sim N(0, \sigma_\epsilon^2)$, and $\alpha_i \sim N(0, \sigma_\alpha^2)$ all independent. Here μ is the panel grand mean of $\tilde{\theta}$ and α_i captures permanent firm-level deviations from μ. The four parameters $(\rho, \sigma_\epsilon^2, \sigma_\eta^2, \sigma_\alpha^2)$ are estimated jointly by maximum likelihood, integrating α_i out as a Gaussian random effect rather than estimating it as a fixed effect.[10] The obtained estimates are reported in Table 1 of the main paper: $\rho = 0.815$, $\hat{\sigma}_\epsilon^2 = 0.0562$, $\hat{\sigma}_\eta^2 = 0.00467$, $\hat{\sigma}_\alpha^2 = 0.3535$.

Constructing predicted-$\tilde{\theta}$ and FE^{prior}: To construct the model-implied prior forecast errors used downstream, we predict each firm-year's state from its prior history. For each firm i, we run an augmented-state forward Kalman filter and a backward smoother on the demeaned series $\tilde{\theta}_{i,t} - \mu$, which delivers a time-invariant Best Linear Unbiased Predictor

[10] With only 10–15 observations per firm on average in our panel, treating α_i as a free fixed effect would yield noisy firm-level intercepts and biased variance estimates; the random-effects assumption pools information across firms and delivers consistent identification of $(\rho, \sigma_\epsilon^2, \sigma_\eta^2, \sigma_\alpha^2)$.

(BLUP) $\tilde{\alpha}_i$ of the firm-specific intercept. Given $\tilde{\alpha}_i$, the one-step-ahead prediction at time t combines the BLUP intercept with an AR(1) projection from the observable lagged value:

$$\text{Pred}(\tilde{\theta}_{i,t}) = \mu + \tilde{\alpha}_i + \rho \cdot \big(\tilde{\theta}_{i,t-1} - \mu - \tilde{\alpha}_i\big).$$

The prior forecast error is given by

$$FE_{i,t}^{prior} \;=\; |\tilde{\theta}_{i,t} - \text{Pred}(\tilde{\theta}_{i,t})|^2.$$

The empirical median across firm-years is $\widetilde{FE}^{prior} \approx 0.0068$. As with the posterior forecast errors, we winsorize the prior forecast errors at the one percent level on the right tail.

Scaling factor and median-scale σ_η^2. The MLE returns $\hat{\sigma}_\eta^2$ as a population mean across all firm-years. Because the FE distribution has a heavy right skew, the mean and median variances across our sample differ by roughly an order of magnitude, so $\hat{\sigma}_\eta^2$ cannot be substituted directly into formulas targeting the median firm-year observation. We therefore define a single scaling factor as the ratio of the median empirical prior FE to the theoretical mean prior variance,

$$SF \;=\; \frac{\widetilde{FE}^{prior}}{\hat{\sigma}_\epsilon^2 + \hat{\sigma}_\eta^2} \;\approx\; \frac{0.0068}{0.0608} \;\approx\; 0.112,$$

and apply this same factor to map any estimates of the mean variance to the corresponding estimates for a median observation in our sample.

The remaining two pre-simulation parameters are ϕ, the prior precision of public information, and τ, the baseline new-data inflow for the median firm. We already have the mean estimate for prior variance as $\hat{\sigma}_\epsilon^2$. To get the mean estimate of the variance of new-data inflow, we first need to obtain the estimate for the posterior variance of the forecastable component and the depreciation rate. To get the posterior variance, we subtract the transitory variance $\hat{\sigma}_\eta^2$ from the mean value of Squared Relative Forecast Errors and then use the scaling factor SF to get the median posterior variance of the forecastable component. This yields the following estimates for the median prior and posterior variances of the forecastable component:

$$\phi = \frac{1}{Var_{med}^{prior}(\widehat{\theta}_t|\mathcal{I}_t)} \approx 159, \qquad \Omega = \frac{1}{Var_{med}^{post}(\widehat{\theta}_t|\mathcal{I}_t)} \approx 563.$$

Substituting into the steady-state depreciation identity,

$$\zeta = 1 - \left(\rho^2 + \frac{\Omega}{\phi}\right)^{-1},$$

gives a median depreciation rate $\zeta \approx 0.76$ where we have used the fact that ϕ is the inverse of prior variance. Using the steady-state data-accumulation expression $\zeta(\Omega - \phi) = \tau$, we obtain $\bar{\tau} \approx 308$. This completes the calibration of the six pre-simulation parameters $(r, \alpha, \rho, \bar{\phi}, \bar{\tau}, \sigma_\eta^2)$, summarized in Table 2 in the main paper.

With these parameters in place, we now calibrate the remaining five parameters $(\gamma, \chi, \mu_{\ln A}, \sigma_{\ln A}, w)$ to match five targeted moments. Specifically:

1. β_1 from the regression

$$\ln(\Pi^g_{i,t}) = \beta_0 + \beta_1 \ln(FE_{i,t}) + \xi \ln A_i + \epsilon_{i,t}$$

where $\Pi^g_{i,t}$ is gross profit (revenue minus cost of goods sold). Empirical target: $\beta_1 = -0.011$.

2. β_1 from the regression

$$\ln(FE_{i,t}) = \beta_0 + \beta_1 \ln(\Pi^g_{i,t-1}) + \epsilon_{i,t}.$$

Empirical target: $\beta_1 = -0.428$.

3. Mean of log gross profit (in millions of December 2002 USD): 5.77.

4. Standard deviation of log gross profit: 1.62.

5. Fraction of the median firm's gross profit paid as wages to data workers, estimated as 0.4% from Occupational Employment and Wage Statistics (OEWS) data.

We run the same regressions on the simulated panel as on the empirical sample. The calibration minimizes a loss function defined as the sum of squared percentage deviations between model-implied and empirical moments, with the minimum located by grid search over a fine grid of the five free parameters.

These moments and results are summarized in Tables 5 and 6 in the manuscript.

C Measuring the Evolution of Data Stock

The previous section described how we obtain estimates of the prior and posterior precision for the median firm in the full sample. We apply the same procedure year by year to construct a per-year series of the prior precision ϕ_t, posterior precision Ω_t, depreciation rate ζ_t, and new-data precision τ_t for the median firm.

Per-year prior and posterior precisions. For each year $t \in \{2003, \ldots, 2022\}$, we aggregate the firm-level prior and posterior forecast errors $FE^{prior}_{i,t}$ and $FE^{post}_{i,t}$ across the sample to obtain mean values, and subtract the transitory variance $\hat{\sigma}^2_\eta$ to isolate the forecastable component. Multiplying by SF at the end and taking reciprocal yields the median-firm prior and posterior precisions ϕ_t and Ω_t.

Depreciation rate and new-data inflow. Given ϕ_t and Ω_t, the depreciation rate follows directly from the Bayesian update,

$$\zeta_t \;=\; 1 - \frac{1}{\rho^2 + \Omega_t/\phi_t}.$$

The new-data inflow τ_t then follows by inverting the law of motion in equation (17):

$$\tau_t \;=\; \Omega_t - \phi_t - (1 - \zeta_{t-1})(\Omega_{t-1} - \phi_{t-1}).$$

For the first period (Year 2003, t=1), we assume that the firm starts with no private data, so $\Omega_0 = \phi_0$ and the expression collapses to $\tau_1 = \Omega_1 - \phi_1$. For each subsequent year, τ_t is computed using the previous year's ζ_{t-1}, Ω_{t-1}, and ϕ_{t-1}.

This yields a complete per-year series $\{\phi_t, \Omega_t, \zeta_t, \tau_t\}$ for the median firm, which feeds the per-year value-of-data computations. We use these annual estimates and the value function calibrated in the previous section to obtain the value of data for the median firm as

$$D_{M,t} = \mathbb{V}_M\left(\Omega_{M,t}^{-1}\right) - \mathbb{V}_M\left([\Omega_{M,t} - \tau_{M,t}]^{-1}\right)$$

where subscript M denotes the median firm. Because the model calibration uses pooled data, we rescale $D_{M,t}$ by the ratio of year-t median revenue to the pooled-sample median revenue.

D Extrapolation of GDP (Mis)measurement

As discussed in the paper, GDP mis-measurement at the firm level is given by $2 \times D_t$. Note that because many firms do not provide guidance consistently every year, we cannot calculate the value of data at the firm level for all firms. To get around this, we calculate the value of data per employee for the median firm in our sample and use the employment count at different levels of aggregation to extrapolate the value of data (and GDP mis-measurement).

$$\text{Missing-GDP} = 2 \times \text{Value of data per employee} \times \text{Total number of workers}$$

To get the number of workers in the economy, we use the Employment Level series (CE16OV) provided by the Federal Reserve Bank of St. Louis.[11]

The estimate above does not take into account the fact that firms with market power may not have to compensate the consumer fully for the data. To adjust this estimate for a firm's market power, we assume that if a firm charges a markup of μ over its marginal cost in the goods market, it can apply a symmetric markdown μ when giving a discount to the consumer for data. Therefore, the missing-GDP after accounting for market power takes the form

$$\text{Missing-GDP} = \left(1 + \frac{1}{\mu}\right) \times \text{Value of data per employee} \times \text{Total number of workers}$$

Edmond et al. (2023) show that after 1990, the cost-weighted average markup has stayed roughly stable between the range 1.2 - 1.26. To get a conservative estimate of missing GDP, we use the maximum value of 1.26 for μ in our calculations.

E Data Purchase

There is a market for data that explicitly assigns value to data in national accounts when measuring GDP. Several platforms collect and sell data directly or with prior processing and

[11] U.S. Bureau of Labor Statistics, *Employment Level* [CE16OV], retrieved from FRED, Federal Reserve Bank of St. Louis, https://fred.stlouisfed.org/series/CE16OV, accessed June 16, 2025.

advisory services. This ranges from general data (such as Snowflake, Google or Amazon), to financial data (Bloomberg, Refinitiv, or Quandl), consumer data (Eagle, SafeGraph or Experian), healthcare (IQVIA, HealthVerity or Komodo), real estate (Zillow, CoreLogic) or labor and tech (LinkedIn, Crunchbase or PitchBook).

From the model, we obtain the following estimate for the median firm in our data

$$\frac{\partial \mathbb{V}_M(\Omega^{-1})}{\partial \Omega^{-1}}\Big|_{\Omega=\Omega_M} = -\$3460$$

which tells us that a unit decrease in Forecast errors is associated with an increase of $3460 million in terms of December 2024 dollars.

For this exercise we use information from a platform in particular, Visa Inc. Visa is a major player in the global payments industry, processing substantial transaction volumes annually. According to its 2024 10-K earnings statement, "Visa's total payments and cash volume was $16 trillion, and the Visa network processed 234 billion total transactions — 639 million transactions every day." This volume is larger than the main competitors like Mastercard (handling 171 billion transactions a year) or American Express (with $1.5 trillion in total payments).

This volume of transactions uniquely positions Visa as an intermediary of data and data analytics. According to its 2024 10-K earnings statement, "we have continued to expand our services beyond Visa transactions to non-Visa transactions and non-payment services.....For example, in Advisory Services alone, we delivered more than 3,000 consulting engagements during 2024, up nearly 50 percent from last year, and we estimate that we helped clients realize over $5 billion in incremental revenue as a result."

This last statement implies that by selling analytics based on unique data from transactions across the board, Visa generates $1.67m additional revenues per firm, which constitutes the value of Visa's data to those firms. If we interpret this amount as the present discounted value of all future additional revenue, then we can use this to estimate the value of data bought by the median firm as follows:

$$1.67 = \frac{\partial \mathbb{V}_M(\Omega^{-1})}{\partial \Omega^{-1}}\Big|_{\Omega_M} \times \Delta\Omega^{-1} = 3460\left(\frac{1}{\Omega_M} - \frac{1}{\Omega_M + \nu}\right)$$

This reduces to

$$\frac{1}{\Omega_M + \nu} = \frac{1}{\Omega_M} - \frac{1.67}{3460} = 0.0013$$

This implies that bought data has precision $\nu = 210$, larger than public data ($\phi = 159$) but nearly half that of the firm's private data ($\Omega - \phi = 404$) and two-thirds that of newly acquired data ($\tau = 308$). Moreover, given the strong diminishing returns to data, bought data stacked on top of data already acquired through transactions would add much less value even at the same precision. For comparison, the estimated value of data generated through transactions for the median firm-year is approximately $7.3 million (December 2024 dollars), which places externally bought data at about a quarter (1.67/7.3) of the value of data generated through transactions.