Price Rigidities and the Granular Origins of Aggregate Fluctuations*

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Abstract

We study the ability of sectoral shocks to generate aggregate fluctuations in a multi-sector New Keynesian model featuring sectoral heterogeneity in price stickiness, sector size, and input-output linkages. Both theoretically and empirically, the cross-sectional distribution of price rigidity is central for sectoral shocks to generate aggregate fluctuations. Heterogeneity in price rigidities (i) generates sizable GDP volatility from sectoral shocks relative to aggregate productivity shocks, (ii) may amplify both the "granular" and the "network" effects, (iii) alters the identity and relative contributions of the most important sectors for aggregate fluctuations, (iv) can change the sign of fluctuations, (v) invalidates the Hulten (1978) Theorem, and (vi) generates a "frictional" origin of aggregate fluctuations. We calibrate a 341 sector version of the model to the United States to reach these conclusions.

JEL classification: E31, E32, O40

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I Introduction

Identifying aggregate shocks that drive business cycles might be difficult (Cochrane (1994)). A recent literature advances the possibility that shocks to a few "granular" firms or economic sectors may drive aggregate fluctuations. This view stands in contrast to the "diversification argument" of Lucas (1977), which conjectures microeconomic shocks average out through disaggregation.[1] Gabaix (2011) instead argues the diversification argument does not readily apply when the firm-size distribution is fat-tailed, which is the empirically relevant case for the United States. Intuitively, shocks to disproportionately large firms do not cancel out with shocks to smaller firms. In a similar vein, Acemoglu, Carvalho, Ozdaglar, and Tahbaz-Salehi (2012) focus on input-output relationships across sectors and show granularity arises when measures of sector centrality follow a fat-tailed distribution. Thus, either through asymmetry in the firm-size distribution or network centrality, microeconomic shocks to small numbers of firms or sectors may drive aggregate fluctuations.[2]

Prices are the key transmission mechanism of sectoral technology shocks to the economy in the recent literature. But this prior work assumes prices are flexible which might not be an innocuous assumption. We argue fat tails of the firm-size distribution as in Gabaix (2011) or measures of network centrality as in Acemoglu et al. (2012) are neither necessary nor sufficient for microeconomic shocks to generate aggregate fluctuations, because the responsiveness of prices to shocks is heterogeneous across sectors. Many reasons exist why prices respond differently to shocks, but we focus on nominal rigidities for several reasons. First, a large literature suggests prices might respond sluggishly to shocks with substantial heterogeneity across economic sectors (see Bils and Klenow (2004); Klenow and Kryvtsov (2008); Nakamura and Steinsson (2008)). Second, we can measure moments of price rigidities at highly disaggregated levels for quantitative assessments. Third, prices are the central propagation mechanism of idiosyncratic shocks and nominal price stickiness illustrates well the channels affecting aggregate fluctuations independently of the frictions that result in incomplete pass-through of shocks into prices.

To fix ideas, consider a multi-sector economy without linkages across sectors and a positive productivity shock to one sector. Marginal costs in the shocked sector decrease and output prices fall in a frictionless economy. But consider what happens if prices do not react to the

[1] Dupor (1999) takes a perspective similar to Lucas (1977) and implicitly anyone who models aggregate shocks driving aggregate fluctuations.

[2] A fast-growing literature has followed. Some recent examples are Acemoglu, Akcigit, and Kerr (2016); Acemoglu, Ozdaglar, and Tahbaz-Salehi (2017); Atalay (2015); Baqaee (2016); Bigio and La'O (2016); Caliendo, Parro, Rossi-Hansberg, and Sarte (2014); Carvalho and Gabaix (2013); Carvalho and Grassi (2015); Di Giovanni, Levchenko, and Méjean (2014); Di Giovanni, Levchenko, and Méjean (2016); Foerster, Sarte, and Watson (2011); Ozdagli and Weber (2016); Grassi (2017); and Baqaee and Farhi (2017).

shock. Demand for goods of the shocked sector remains unchanged, so production remains unchanged. Therefore, regardless of the size of the sector, the effect of its shocks to GDP is zero (except for some small general equilibrium effects).[3] A similar logic applies to input-output networks. Following a positive productivity shock, a price cut in the shocked sector propagates downstream by decreasing production costs, and upstream through demand for inputs. This, in turn, triggers price cuts in other sectors. But, if prices do not change in the shocked sector, marginal costs of downstream firms and demand for inputs of upstream firms remain unchanged. Then, there is no propagation to GDP regardless of the centrality of the shocked sector (except for the same general equilibrium effects).

The example above assumes fully rigid prices for illustration. More generally, we want to understand how nominal price rigidity, which is heterogeneous across sectors, interacts with the sector-size distribution as in Gabaix (2011) or network centrality as in Acemoglu et al. (2012) in affecting the power of microeconomic shocks to generate sizable aggregate fluctuations. Can heterogeneous price rigidity by itself generate a frictional origin of aggregate fluctuations? Do price rigidities distort the identity of sectors that drive aggregate fluctuations?

To answer these questions, we develop a multi-sector New Keynesian model in which firms produce output using labor and intermediate inputs. Sectoral productivity shocks are the only source of variation. To build intuition, we first study a simplified economy in which random firms have to set prices before shocks are realized. The simplifying assumptions allow us to solve the model in closed form nesting the core results in Gabaix (2011) and Acemoglu et al. (2012) as special cases. We then move to a quantitative assessment with firms adjusting prices to shocks following Calvo. We calibrate our model at the most disaggregate level for U.S. data (341 sectors, roughly 6-digit industry disaggregation), to match sectoral GDP and input-output tables from the Bureau of Economic Analysis (BEA) and the industry-average frequency of price adjustments from the microdata underlying the Producer Price Index (PPI) at the Bureau of Labor Statistics (BLS).

Our answers are "yes" and "yes." Heterogeneity in price rigidities changes the identity of sectors from which aggregate fluctuations originate, and generates GDP volatility from sectoral shocks independent of the sector-size distribution and network centrality, that is, a "frictional" origin of granularity exists conceptually different from size or network centrality. Thus, depending on the cross-sectional distribution of price rigidities, sectoral shocks may become an alternative to aggregate shocks as origin of aggregate fluctuations even when all sectors have equal size or the production network is perfectly symmetric. It is also possible

[3] The shocked firms demand fewer inputs and transfer more profits to households. However, these effects are small up to a first-order approximation.

the "diversification argument" of Lucas (1977) holds in an economy with nominal rigidities, while the granular hypothesis holds in a frictionless economy, or that the frictional, size and network sources of granularity reinforce each other. Our calibrations suggest heterogeneity in price stickiness reinforces size and network channels of aggregate fluctuations. We also find the identity of the most important sectors for aggregate fluctuations from sectoral shocks changes substantially relative to a frictionless economy.

Using our simplified model, we show analytically the multiplier of sectoral shocks to GDP volatility is up to a first-order approximation a function of its steady-state GDP share, its steady-state input-output linkages, and the whole distribution of price rigidity. We decompose the effect of price rigidity into three channels.

First, the interaction of price rigidity with sectoral GDP. In a frictionless economy without intermediate inputs, the multiplier of sectoral shocks depends only on the GDP share. Thus, the granular hypothesis of Gabaix (2011) holds when sector size (here, sectoral GDP) follows a fat-tailed Pareto distribution. When we add heterogeneous price rigidity, multipliers depend on the convolution of GDP shares and price rigidity. Sectors more flexible than the average sector are *effectively* larger than their GDP shares implies. Hence, sectoral multipliers can be more or less fat-tailed than sectoral GDP shares, or not be fat-tailed at all, depending on the price flexibility of the largest sectors. If all sectors have equal size, the fat-tailedness of multipliers depends solely on the distribution of price rigidities.

Second, the interaction between price rigidity and input-output linkages. When prices are flexible and all sectors have equal GDP shares, multipliers are exactly as in Acemoglu et al. (2012). Granularity holds when measures of sector centrality follow fat-tailed distributions: large suppliers of intermediate inputs (first-order interconnection) and/ or large suppliers to large suppliers of intermediate inputs (second-order interconnection) are important for GDP volatility. Once we introduce heterogeneous price rigidity across sectors, the most flexible sectors among large suppliers of intermediate inputs and/ or the most flexible sectors among large suppliers to the most flexible large intermediate input suppliers are now the most important sectors for GDP. Thus, the sectoral multipliers may be more or less fat-tailed than the distribution of sector centrality. Crucially, not only the price rigidity of the shocked sector matters, but through input-output linkages the whole distribution of price rigidity. As a result, granularity might arise even when the input-output network is perfectly symmetric.

Third, a scale effect depending on the average price rigidity in the economy. This channel mutes GDP volatility from productivity shocks regardless of whether shocks are aggregate or sectoral and whether or not production requires intermediate inputs. This scale effect is mostly irrelevant for the questions we pose in this paper, because it affects equally the propagation of sectoral and aggregate shocks. We also show active monetary policy can largely offset the scale effect.

In practice, total sales determines total sectoral size, that is, the sum of sales of final goods (GDP) and intermediate inputs. Thus, these two channels also interact. In this regard, we also find heterogeneity in price rigidity invalidates the Hulten (1978) result that holds in Gabaix (2011) and Acemoglu et al. (2012), stating that sectoral (or firm) total sales are a sufficient statistic for the importance of sectors (or firms) for GDP.

In our calibrations, we use variations of our full model to isolate the importance of the different channels of how heterogeneity in price rigidities affect the power of idiosycnratic shocks to drive aggregate fluctuations. To abstract from the scale effect of the average price rigidity, we base our discussion on relative multipliers, that is, multipliers of sectoral productivity shocks on GDP volatility relative to the multiplier of an aggregate TFP shock on GDP volatility. We confirm active monetary policy almost perfectly eliminates this scale effect.

In our first experiment, we match sectoral GDP shares but assume equal input-output linkages across sectors, so heterogeneity in sectoral size depends only on GDP shares. The relative multiplier of sectoral productivity shocks on GDP volatility increases from 11% when prices are flexible to 33.7% when the frequency of price changes in the model matches the empirical distribution. This large increase in multipliers is remarkable, because the correlation between sectoral GDP and the frequency of price changes in the data is zero across all firms but 9.8% in the upper 20% of the size distribution. This result highlights the importance of price rigidities of the largest sectors, rather than the overall distribution of price rigidity across sectors.

In the second experiment, we match input-output linkages to the U.S. but assume equal GDP shares across sectors. Now, the relative multiplier increases from 8% with flexible prices to 13.2%; the correlation between statistics of network centrality and the frequency of price changes is about 20% in the upper 20% tail.

In a third experiment, differences in the frequency of price changes are the only source of heterogeneity across sectors. The relative multiplier of sectoral shocks is now 12.4%, more than twice as large as the multiplier in a frictionless economy with complete symmetry in size and linkages. The multiplier is also larger than the pure "size" and "network" multipliers suggesting a "frictional" origin of aggregate fluctuations.

Overall, when we match GDP shares and input-output linkages in the U.S., the multiplier under flexible prices is 17% – almost identical to the one reported by Gabaix (2011). When we also match the empirical distribution of the frequency of price changes, the relative multiplier on GDP volatility increases to 32%. The multiplier is almost six times larger than in an economy with complete symmetry across sectors and flexible prices. The six-fold increase of the relative multiplier underscores the potential of microeconomic shocks for aggregate fluctuations as an alternative source to aggregate shocks, and shows heterogeneities in sector size, input-output structure, and price rigidity are intricately linked and reinforce each other.

But price rigidity does not only contribute to the importance of microeconomic shocks for aggregate volatility. Differences in price rigidity across sectors also have strong effects on the identity and contribution of sectors driving aggregate fluctuations. For instance, the identity of the two most important sectors for aggregate volatility from sectoral shocks shifts from "Real Estate," and "Wholesale Trading" under flexible prices to "Oil and Gas Extraction" and "Dairy cattle and milk production" under heterogeneous price stickiness when we only consider network effects. When we also allow for sectoral heterogeneity in sector size, the two most important sectors under flexible prices are "Retail trade" and "Real Estate" but "Monetary authorities and depository credit intermediation" and "Wholesale Trading" under sticky prices. These results have important implications for the conduct of monetary policy aiming to stabilize aggregate fluctuations. A central bank aiming to stabilize the prices of large or central sectors might make systematic policy mistakes when it ignores the sectoral heterogeneity in price rigidity.

This paper uses two simple forms of modeling price rigidity, but both are similarly informative to study the interaction of price rigidity with the size and network sources of granularity. In particular, on impact, the simplified pricing friction we use for our analytical results yields quantitatively similar effect as the Calvo friction. In addition, we argue the Calvo friction yields results similar to menu cost models. In quantitative menu cost models, good-level shocks mainly drive the frequency of price changes rather than sectoral shocks. Thus, a menu cost model would create only a weak link between the volatility of sectoral shocks, which we model, and the frequency of price adjustment. If a positive link existed, our analytical results suggest it would strengthen our findings. For our purposes, the main difference between a Calvo model and menu cost models is we only need the frequency of price changes from the data to discipline price rigidity in case of the former, while we might also require higher moments of prices changes in case of the latter. Of course, menu cost models would also be computationally unsolvable at the level of disaggregation we study.

At an abstract level, our analysis does not only show the size or centrality of nodes in the network matters for the macro effect of micro shocks, but also the frictions that affect the capacity of nodes to pass through shocks. The frictional origin of fluctuations goes beyond production networks in a closed economy; it applies to all networks with heterogeneous effects of frictions across nodes, for example, in international trade networks, financial networks, or social networks. Hence, our work relates to an extensive literature that we do not attempt to summarize here; instead, we only highlight the most closely related papers below.

A. Literature review

Long and Plosser (1983) pioneer the microeconomic origin of aggregate fluctuations, and Horvath (1998) and Horvath (2000) push this literature forward. Dupor (1999) argues microeconomic shocks matter only due to poor disaggregation. Gabaix (2011) invokes the firm size-distribution, and Acemoglu et al. (2012) assert the sectoral network structure of the economy to document convincingly the importance of microeconomic shocks for macroeconomic fluctuations: under empirically plausible assumptions, microeconomic shocks do matter. Barrot and Sauvagnat (2016), Acemoglu et al. (2016), and Carvalho, Nirei, Saito, and Tahbaz-Salehi (2016) provide empirical evidence for the importance of idiosyncratic shocks for aggregate fluctuations, and Carvalho (2014) synthesizes this literature.

The distortionary role of frictions, and price rigidity in particular, is at the core of the business-cycle literature that conceptualizes aggregate shocks as the driver of aggregate fluctuations, including the New Keynesian literature. However, to the best of our knowledge, our paper is the first study the distortionary role of frictions when aggregate fluctuations have microeconomic origins. That said, a few recent papers include frictions in their analyses. Baqaee (2016) shows entry and exit of firms coupled with CES preferences may amplify the aggregate effect of microeconomic shocks. Carvalho and Grassi (2015) study the effect of large firms in a quantitative business-cycle model with entry and exit. Bigio and La'O (2016) study the aggregate effects of the tightening of financial frictions in a production network. Despite a different focus, we share our finding with Baqaee (2016) and Bigio and La'O (2016) that the Hulten theorem does not apply in economies with frictions. Farhi and Baqaee (2017) relates to our analysis by decomposing the effect of shocks into "direct" and "allocative" effects for various frictions.

Our model shares building blocks with previous work studying pricing frictions in production networks. Basu (1995) shows frictions introduce misallocation resulting in nominal demand shocks looking like aggregate productivity shocks. Carvalho and Lee (2011) develop a New Keynesian model in which firms' prices respond slowly to aggregate shocks and quickly to idiosyncratic shocks, rationalizing the findings in Boivin et al. (2009). We build on their work to answer different questions and relax assumptions regarding the production structure to quantitatively study the interactions of different heterogeneities.

Nakamura and Steinsson (2010), Midrigan (2011), and Alvarez, Le Bihan, and Lippi (2016), among many others, endogenize price rigidity to study monetary non-neutrality in multi-sector menu-cost models. Computational burden and calibration issues make such an approach infeasible in our highly disaggregated model which is why we study the effect of disaggregation on monetary non-neutrality in a multi-sector Calvo model in a companion paper (Pasten, Schoenle, and Weber (2016)). In addition to feasibility, we see our work as a first-order approximation that we argue is informative for the purposes of this paper. This is because, through the lens of a menu-cost model, a higher frequency of price changes is mostly related to higher volatility of heterogeneous good-specific shocks and not so much to sector-specific volatility. Bouakez, Cardia, and Ruge-Murcia (2014) estimate a Calvo model with production networks, using data for 30 sectors, and find heterogeneous responses of sectoral inflation to monetary policy shocks, but do not study the questions we pose in this paper.

Other recent applications of networks in different areas of macroeconomics and finance are Gofman (2011), who studies how intermediation in over-the-counter markets affects the efficiency of resource allocation, Di Maggio and Tahbaz-Salehi (2015), who study the fragility of the interbank market, Ozdagli and Weber (2016), who show empirically that input-output linkages are a key propagation channel of monetary policy shocks to the stock market, and Kelly, Lustig, and Van Nieuwerburgh (2013), who study the joined dynamics of the firm-size distribution and stock return volatilities. Herskovic, Kelly, Lustig, and Van Nieuwerburgh (2016) and Herskovic (2015) study the asset-pricing implications of production networks.

II Model

Our multi-sector model has households supplying labor and demanding goods for final consumption, firms operating under oligopolistic competition producing varieties of goods using labor and intermediate inputs, and a monetary authority setting nominal interest rates according to a Taylor rule. Sectors are heterogeneous in three dimensions: the amount of final goods they produce, input-output linkages, and the frequency of price adjustment.

A. Households

The representative household solves

$$\max_{\{C_t, L_{kt}\}_{t=0}^{\infty}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\sigma} - 1}{1-\sigma} - \sum_{k=1}^{K} g_k \frac{L_{kt}^{1+\varphi}}{1+\varphi} \right),$$

subject to

$$\begin{aligned}\sum_{k=1}^{K} W_{kt}L_{kt} + \sum_{k=1}^{K}\Pi_{kt} + I_{t-1}B_{t-1} - B_t &= P_t^c C_t \\ \sum_{k=1}^{K} L_{kt} &\leq 1,\end{aligned}$$

where C_t and P_t^c are aggregate consumption and aggregate prices, respectively. L_{kt} and W_{kt} are labor employed and wages paid in sector $k = 1, ..., K$. Households own firms and receive net income, Π_{kt}, as dividends. Bonds, B_{t-1}, pay a nominal gross interest rate of I_{t-1}. Total labor supply is normalized to 1.

Household demand of final goods, C_t, and goods produced in sector k, C_{kt}, are

$$C_t \equiv \left[\sum_{k=1}^{K} \omega_{ck}^{\frac{1}{\eta}} C_{kt}^{1-\frac{1}{\eta}}\right]^{\frac{\eta}{\eta-1}}, \tag{1}$$

$$C_{kt} \equiv \left[n_k^{-1/\theta}\int_{\Im_k} C_{jkt}^{1-\frac{1}{\theta}} dj\right]^{\frac{\theta}{\theta-1}}. \tag{2}$$

A continuum of goods indexed by $j \in [0,1]$ exists with total measure 1. Each good belongs to one of the K sectors in the economy. Mathematically, the set of goods is partitioned into K subsets $\{\Im_k\}_{k=1}^{K}$ with associated measures $\{n_k\}_{k=1}^{K}$ such that $\sum_{k=1}^{K} n_k = 1$.[4] We allow the elasticity of substitution across sectors η to differ from the elasticity of substitution within sectors θ.

The first key ingredient of our model is the vector of weights $\Omega_c \equiv [\omega_{c1}, ..., \omega_{cK}]$ in equation (1). This vector summarizes heterogeneity in size. These weights show up in household sectoral demand

$$C_{kt} = \omega_{ck}\left(\frac{P_{kt}}{P_t^c}\right)^{-\eta} C_t. \tag{3}$$

All prices are identical in steady state, so $\omega_{ck} \equiv \frac{C_k}{C}$, where variables without a time subscript are steady-state quantities. In our economy, C_t represents the total production of final goods, that is, GDP. The vector Ω_c represents steady-state sectoral GDP shares satisfying $\Omega_c'\iota = 1$ where ι denotes a column-vector of 1s. Away from the steady state, sectoral GDP shares depend on the gap between sectoral prices and the aggregate price index, P_t^c

$$P_t^c = \left[\sum_{k=1}^{K} \omega_{ck} P_{kt}^{1-\eta}\right]^{\frac{1}{1-\eta}}. \tag{4}$$

[4] The sectoral subindex is redundant, but it clarifies exposition. We can interpret n_k as the sectoral share in gross output.

We can interpret P_t^c as GDP deflator. Household demand for goods within a sector is given by

$$C_{jkt} = \frac{1}{n_k}\left(\frac{P_{jkt}}{P_{kt}}\right)^{-\theta} C_{kt} \text{ for } k = 1, ..., K. \tag{5}$$

Goods within a sector share sectoral consumption equally in steady state. Away from steady state, the gap betwen a firm's price, P_{kt}, and the sectoral price distorts the demand for goods within a sector

$$P_{kt} = \left[\frac{1}{n_k}\int_{\Im_k} P_{jkt}^{1-\theta} dj\right]^{\frac{1}{1-\theta}} \text{ for } k = 1, ..., K. \tag{6}$$

The household first-order conditions determine labor supply and the Euler equation

$$\frac{W_{kt}}{P_t^c} = g_k L_{kt}^{\varphi} C_t^{\sigma} \text{ for all } k, j, \tag{7}$$

$$1 = \mathbb{E}_t\left[\beta\left(\frac{C_{t+1}}{C_t}\right)^{-\sigma} I_t \frac{P_t^c}{P_{t+1}^c}\right]. \tag{8}$$

We implicitly assume sectoral segmentation of labor markets, so labor supply in equation (7) holds for a sector-specific wage $\{W_{kt}\}_{k=1}^K$. We choose the parameters $\{g_k\}_{k=1}^K$ to ensure a symmetric steady state across all firms.

B. Firms

A continuum of monopolistically competitive firms exists in the economy operating in different sectors. We index firms by their sector, $k = 1, ...K$, and by $j \in [0, 1]$. The production function is

$$Y_{jkt} = e^{a_{kt}} L_{jkt}^{1-\delta} Z_{jkt}^{\delta}, \tag{9}$$

where a_{kt} is an i.i.d. productivity shock to sector k with $\mathbb{E}[a_{kt}] = 0$ and $\mathbb{V}[a_{kt}] = v^2$ for all k, L_{jkt} is labor, and Z_{jkt} is an aggregator of intermediate inputs

$$Z_{jkt} \equiv \left[\sum_{k'=1}^{K} \omega_{kk'}^{\frac{1}{\eta}} Z_{jk}\left(k'\right)^{1-\frac{1}{\eta}}\right]^{\frac{\eta}{\eta-1}}. \tag{10}$$

$Z_{kjt}(r)$ is the amount of goods firm j in sector k uses in period t as intermediate inputs from sector r.

The second key ingredient of our model is heterogeneity in aggregator weights $\{\omega_{kk'}\}_{k,k'}$. We denote these weights in matrix notation as Ω, satisfying $\Omega\iota = \iota$. The demand of firm jk for goods produced in sector k' is given by

$$Z_{jkt}\left(k'\right) = \omega_{kk'} \left(\frac{P_{k't}}{P_t^k}\right)^{-\eta} Z_{jkt}. \tag{11}$$

We can interpret $\omega_{kk'}$ as the steady-state share of goods from sector k' in the intermediate input use of sector k, which determines the input-output linkages across sectors in steady state. Away from the steady state, the gap between the price of goods in sector k' and the aggregate price relevant for a firm in sector k, P_t^k, distorts input-output linkages

$$P_t^k = \left[\sum_{k'=1}^{K} \omega_{kk'} P_{k't}^{1-\eta}\right]^{\frac{1}{1-\eta}} \text{ for } k = 1, ..., K. \tag{12}$$

P_t^k uses the sector-specific steady-state input-output linkages to aggregate sectoral prices.

The aggregator $Z_{jk}\left(k'\right)$ gives the demand of firm jk for goods in sector k'

$$Z_{jk}\left(k'\right) \equiv \left[n_{k'}^{-1/\theta} \int_{\Im_{k'}} Z_{jkt}\left(j', k'\right)^{1-\frac{1}{\theta}} dj'\right]^{\frac{\theta}{\theta-1}}. \tag{13}$$

Firm jk's demand for an arbitrary good j' from sector k' is

$$Z_{jkt}\left(j', k'\right) = \frac{1}{n_{k'}} \left(\frac{P_{j'k't}}{P_{k't}}\right)^{-\theta} Z_{jk}\left(k'\right). \tag{14}$$

In steady state, all firms within a sector share the intermediate input demand of other sectors equally. Away from steady state, the gap between a firm's price and the price index of the sector it belongs to (see equation (6)) distorts the firm's share in the production of intermediate input. Our economy has $K+1$ different aggregate prices, one for the household sector and one for each of the K sectors. By contrast, the household sector and all sectors face unique sectoral prices.

The third key ingredient of our model is sectoral heterogeneity in price rigidity. Specifically, we model price rigidity à la Calvo with parameters $\{\alpha_k\}_{k=1}^K$ such that the pricing problem of firm jk is

$$\max_{P_{jkt}} \mathbb{E}_t \sum_{s=0}^{\infty} Q_{t,t+s} \alpha_k^\tau \left[P_{jkt} Y_{jkt+s} - MC_{kt+s} Y_{jkt+s}\right].$$

Marginal costs are $MC_{kt} = \frac{1}{1-\delta}\left(\frac{\delta}{1-\delta}\right)^{-\delta} e^{-a_{kt}} W_{kt}^{1-\delta}\left(P_t^k\right)^{\delta}$ in reduced form after imposing the optimal mix of labor and intermediate inputs

$$\delta W_{kt} L_{jkt} = (1-\delta) P_t^k Z_{jkt}, \tag{15}$$

and $Q_{t,t+s}$ is the stochastic discount factor between periods t and $t+s$.[5]

We assume the elasticities of substitution across and within sectors are the same for households and all firms. This assumption shuts down price discrimination among different customers, and firms choose a single price P_{kt}^*:

$$\sum_{\tau=0}^{\infty} Q_{t,t+\tau} \alpha_k^s Y_{jkt+\tau} \left[P_{kt}^* - \frac{\theta}{\theta-1} MC_{kt+\tau} \right] = 0, \tag{16}$$

where $Y_{jkt+\tau}$ is the total production of firm jk in period $t+\tau$.

We define idiosyncratic shocks $\{a_{kt}\}_{k=1}^K$ at the sectoral level, and it follows the optimal price, P_{kt}^*, is the same for all firms in a given sector. Thus, aggregating among all prices within sector yields

$$P_{kt} = \left[(1-\alpha_k) P_{kt}^{*1-\theta} + \alpha_k P_{kt-1}^{1-\theta} \right]^{\frac{1}{1-\theta}} \text{ for } k = 1, ..., K. \tag{17}$$

C. Monetary policy, equilibrium conditions, and definitions

The monetary authority sets nominal interest rates according to a Taylor rule:

$$I_t = \frac{1}{\beta} \left(\frac{P_t^c}{P_{t-1}^c} \right)^{\phi_\pi} \left(\frac{C_t}{C} \right)^{\phi_y}. \tag{18}$$

Monetary policy reacts to inflation, P_t^c/P_{t-1}^c, and deviations from steady state total value-added, C_t/C. We do not model monetary policy shocks.

Bonds are in zero net supply, $B_t = 0$, labor markets clear, and goods markets clear such that

$$Y_{jkt} = C_{jkt} + \sum_{k'=1}^{K} \int_{\Im_{k'}} Z_{j'k't}(j,k)\, dj', \tag{19}$$

implying a wedge between gross output Y_t and GDP C_t.

III Theoretical Results in a Simplified Model

We derive closed-form results for the importance of sectoral shocks for aggregate fluctuations in a simplified version of our model. Given the focus of the paper, we study log-linear deviations from

[5] We choose Calvo pricing merely as an expository tool, and for computational reasons. We discuss details of choosing an endogenous price adjustment technology at the end of the next section.

steady state GDP. The Online Appendix contains the steady-state solution, the full log-linear system, and solves for the equilibrium. All variables in lower cases denote log-linear deviations from steady state. We discuss at the end of the section implications of a variety of simplifying assumptions regarding the labor market, monetary policy, the pricing friction and additional forms of heterogeneity across sectors.

A. Simplifying Assumptions

We make the following simplifying assumptions:

(i) Households have log utility, $\sigma = 1$, and linear disutility of labor, $\varphi = 0$. Thus,

$$w_{kt} = p_t^c + c_t; \tag{20}$$

that is, the labor market is integrated and nominal wages are proportional to nominal GDP.

(ii) Monetary policy targets constant nominal GDP, so

$$p_t^c + c_t = 0. \tag{21}$$

(iii) We replace Calvo price stickiness by a simple form of price rigidity: all prices are flexible, but with probability λ_k, a firm in sector k has to set its price before observing shocks. Thus,

$$P_{jkt} = \begin{cases} \mathbb{E}_{t-1}\left[P_{jkt}^*\right] & \text{with probability } \lambda_k, \\ P_{jkt}^* & \text{with probability } 1-\lambda_k, \end{cases} \tag{22}$$

where $\mathbb{E}_{t-1}$ is the expectation operator conditional on the $t-1$ information set. This price setting technology is a simple form of modeling price rigidity because it implies the response of prices to shocks is only partial on impact.

Solution We show in the Online Appendix under assumptions (i), (ii), and (iii), GDP is given by

$$c_t = \chi' a_t, \tag{23}$$

where $\chi \equiv (\mathbb{I}-\Lambda)\left[\mathbb{I}-\delta\Omega'(\mathbb{I}-\Lambda)\right]-1\Omega_c$. Λ is a diagonal matrix with price-rigidity probabilities $[\lambda_1, ..., \lambda_K]$ as entries, and $a_t \equiv [a_{1t}, ..., a_{Kt}]'$ is a vector of sectoral productivity shocks. Recall Ω_c and Ω represent in steady state the sectoral GDP shares and intermediate-input shares.

A linear combination of sectoral shocks describes the log-deviation of GDP from its steady state up to a first-order approximation. Thus, aggregate GDP volatility is

$$v_c = v\sqrt{\sum_{k=1}^{K} \chi_k^2} = \|\chi\|_2 \, v, \tag{24}$$

because all sectoral shocks have the same volatility; that is, $\mathbb{V}[a_{kt}] = v^2$ for all k. $\|\chi\|_2$ denotes the Euclidean norm of χ. The vector χ contains the multipliers of sectoral productivity shocks to GDP. We will refer to these multipliers as *sectoral multipliers* in the following.

Below, we study the effect of heterogeneous price rigidity on the scale of aggregate volatility v_c in an economy from two perspectives; first, in a cross-sectional sense for a given finite number of sectors K, and second, with respect to distributional properties as the economy becomes increasingly more disaggregated, $K \to \infty$.

We will use the following definition:

Definition 1 *A given random variable X follows a* ***power-law distribution with shape parameter*** *β when $\Pr(X > x) = (x/x_0)^{-\beta}$ for $x \geq x_0$ and $\beta > 0$.*

B. Price Rigidity and Sectoral GDP

The granular effect studies the role the firm-size distribution plays in generating aggregate volatility from microeconomic shocks. Gabaix (2011) measures firm size by total sales, which includes sales of final goods and intermediate inputs. By contrast, the setup of our model and data requirements have us study sectors instead of firms. However, this difference is only nominal.

To clarify exposition, we first shut down intermediate inputs, that is, $\delta = 0$. Then, sector size only depends on sales of final goods, or equivalently, sectoral GDP. This allows us to focus on the interaction between price rigidity and sectoral GDP, abstracting from its interaction with input-output linkages which we study separately below. This exposition also allows us to disentangle the source of granularity: sales of final goods or sales of intermediate inputs. We will make the same distinctions in our calibrations in the next section.

When we shut down the use of intermediate inputs ($\delta = 0$),

$$\chi = \left(\mathbb{I} - \Lambda'\right)\Omega_c, \tag{25}$$

or, simply, $\chi_k = (1 - \lambda_k)\,\omega_{ck}$ for all k. Also recall $\omega_{ck} = C_k / \sum_{k=1}^{K} C_k$. Hence, steady-state sectoral GDP shares fully determine sectoral multipliers only when prices are flexible ($\lambda_k = 0$). In general, sectoral multipliers also depend on the sectoral distribution of price rigidity. Sales of final goods is no longer a sufficient statistic for the importance of sectors for aggregate volatility. This fact breaks the Hulten (1978) result in the Gabaix (2011) framework.

The following lemma presents our first, cross-sectional result for homogeneous price stickiness across sectors.

Lemma 1 *When $\delta = 0$ and $\lambda_k = \lambda$ for all k, then*

$$v_c = \frac{(1-\lambda)\, v}{\overline{C}_k K^{1/2}} \sqrt{\mathbb{V}\left(C_k\right) + \overline{C}_k^2},$$

where $\overline{C}_k$ and $\mathbb{V}(\cdot)$ are the sample mean and sample variance of $\{C_k\}_{k=1}^{K}$.[6]

This lemma follows from equation (24) when we shut down the use of intermediate inputs. Adapting the results in Gabaix (2011) to sectoral shocks, the volatility of GDP in an economy with K sectors depends on the cross-sectional dispersion of sector size, here measured by $\mathbb{V}(C_k)$. Price rigidity which is equal across sectors only has a scale effect on volatility. This scale effect affects GDP volatility independently of the nature of shocks, whether sectoral or aggregate. We can directly see this result if we assume all sectoral shocks are perfectly correlated. In this case, $v_c = (1-\lambda)\, v$. Therefore, in most of the analysis below, we abstract from the scale effect, because it is irrelevant for the capacity of sectoral shocks to become a source of aggregate volatility. In addition, we show below active monetary policy can mute or even eliminate this scale effect.

Another way to characterize the effect of sectoral shocks on aggregate fluctuations is to consider the rate with which aggregate fluctuations dissipate. The next proposition determines the rate of decay of v_c as the economy becomes increasingly more disaggregated, $K \to \infty$, in the presence of homogeneous price stickiness.

Proposition 1 (Granular effect) *If $\delta = 0$, $\lambda_k = \lambda$ for all k, and $\{C_k\}_{k=1}^{K}$ follows a power-law distribution with shape parameter $\beta_c \geq 1$, then*

$$v_c \sim \begin{cases} \frac{u_0}{K^{\min\{1-1/\beta_c, 1/2\}}} v & \text{for } \beta_c > 1 \\ \frac{u_0}{\log K} & \text{for } \beta_c = 1, \end{cases}$$

where u_0 is a random variable independent of K and v.

Proof. See Online Appendix. ■

[6] We define $\mathbb{V}(X_k)$ of a sequence $\{X_k\}_{k=1}^{K}$ as $\mathbb{V}(X_k) \equiv \frac{1}{K} \sum_{k=1}^{K} \left(X_k - \overline{X}\right)^2$. The definition of the sample mean is standard.

Proposition 1 revisits the central idea of granularity: when the size distribution of sectors is fat-tailed, given by $\beta_c < 2$, aggregate volatility v_c converges to zero at a rate slower than the Central Limit Theorem implies, which is $K^{1/2}$. The rate of decay of v_c becomes slower as $\beta_c \to 1$. Intuitively, when the size distribution of sectors is fat-tailed, few sectors remain disproportionately large at any level of disaggregation. Gabaix (2011) documents a power-law distribution with a shape parameter close to 1 characterizes the upper tail of the empirical distribution of firm sizes.[7] Thus, contrary to Dupor (1999), sectoral shocks can generate sizable aggregate effects even if sectoral shocks are defined at a highly disaggregated level. Homogeneous price rigidity plays no role for this result, except for the scale effect presented in Lemma 1.

We next study the cross-sectional effect of heterogeneous price rigidity across sectors.

Lemma 2 *When $\delta = 0$ and price rigidity is heterogeneous across sectors, then*

$$v_c = \frac{v}{\overline{C}_k K^{1/2}} \sqrt{\mathbb{V}\left(\left(1-\lambda_k\right) C_k\right) + \left[\left(1-\overline{\lambda}\right)\overline{C}_k - \mathbb{COV}\left(\lambda_k, C_k\right)\right]^2},$$

where $\overline{\lambda}$ is the sample mean of $\{\lambda_k\}_{k=1}^K$ and $\mathbb{COV}(\cdot)$ is the sample covariance of $\{\lambda_k\}_{k=1}^K$ and $\{C_k\}_{k=1}^K$.[8]

For a fixed number of sectors K, Lemma 2 states the volatility of GDP depends on the sectoral dispersion of the convoluted variable $(1-\lambda_k)C_k$ as well as the covariance between sectoral price rigidity and sectoral GDP. Thus, heterogeneity of price rigidity has the power to increase GDP volatility relative to the case with homogeneous price rigidity. This result holds even when all sectors have equal size, measured by their sectoral GDP, which highlights the potential of heterogeneous price rigidity to become a "frictional" force that increases propagation of sectoral shocks to GDP volatility. Again, we find a level effect of price rigidity.

These results hold regardless of the exact relationship between price rigidity and sectoral GDP. For example, it does not matter whether or not price rigidity and size are independent across sectors. The exact relationship between price rigidity and sectoral GDP is, however, important for the rate of decay of v_c as $K \to \infty$.

Proposition 2 *If $\delta = 0$, λ_k and C_k are independently distributed, the distribution of λ_k satisfies*

$$\Pr\left[1-\lambda_k > y\right] = \frac{y^{-\beta_\lambda} - 1}{y_0^{-\beta_\lambda} - 1} \text{ for } y \in \left[y_0, 1\right], \beta_\lambda > 0,$$ [9]

[7] We find similar results with sectoral data.

[8] We define $\mathbb{COV}(X_k, Q_k)$ of sequences $\{X_k\}_{k=1}^K$ and $\{Q_k\}_{k=1}^K$ as $\mathbb{COV}(X_k, Q_k) \equiv \frac{1}{K}\sum_{k=1}^K \left(X_k - \overline{X}\right)\left(Q_k - \overline{Q}\right)$.

[9] We show in the Online appendix that this distributional assumption characterizes the empirical marginal distribution of sectoral frequencies well. The distribution is Pareto with a theoretically bounded support that is not binding in our sample of sectors.

and C_k follows a power-law distribution with shape parameter $\beta_c \geq 1$, then

$$v_c \sim \begin{cases} \frac{u_0}{K^{\min\{1-1/\beta_c, 1/2\}}} v & \text{for } \beta_c > 1 \\ \frac{u_0}{\log K} & \text{for } \beta_c = 1, \end{cases}$$

where u_0 is a random variable independent of K and v.

Proof. See Online Appendix. ■

Proposition 2 shows price rigidity does not affect the rate of decay of v_c as $K \to \infty$ when λ_k and C_k are independent. The independence assumption and the lower bound in the support of the distribution of the price rigidity, λ_k, explain this result. If λ_k were unbounded below, $(1 - \lambda_k) C_k$ would follow a Pareto distribution with shape parameter equal to the minimum of the shape parameters of the distributions of C_k and $1 - \lambda_k$. But under the assumptions of Proposition 2, the convoluted variable $(1 - \lambda_k) C_k$, follows a Pareto distribution with the shape parameter of the distribution of C_k.

Yet, price rigidity is still economically important despite its irrelevance for the rate of convergence. Lemma 2 implies price rigidity distorts the identity and the contribution of the most important sectors for the volatility of GDP. This distortion arising from price rigidity can be central for policy makers who aim to identify the microeconomic origin of aggregate fluctuations, for example, for stabilization purposes. A large sector can become effectively small if low price rigidity reduces its *effective* size through the convolution of $(1 - \lambda_k) C_k$.

We now move to the central result in this section.

Proposition 3 *Let $\delta = 0$. The distributions of λ_k and C_k are not independent such that the following relationships hold:*

$$\lambda_k = \max\left\{0, 1 - \phi C_k^{\mu}\right\} \text{ for some } \mu \in (-1, 1), \ \phi \in (0, x_0^{-\mu}), \tag{26}$$

and C_k follows a power-law distribution with shape parameter $\beta_c \geq 1$.

If $\mu < 0$,

$$v_c \sim \begin{cases} \frac{u_1}{K^{\min\{1-(1+\mu)/\beta_c, 1/2\}}} v & \text{for } \beta_c > 1 \\ \frac{u_2}{K^{\min\{-\mu, 1/2\}} \log K} v & \text{for } \beta_c = 1. \end{cases} \tag{27}$$

If $\mu > 0$,

$$v_c \sim \begin{cases} \frac{u_2}{K^{\min\left\{1 - \frac{1 + \mathbf{1}\{K \leq K^*\}\mu}{\beta_c}, \frac{1}{2}\right\}}} v & \text{for } \beta_c > 1 \\ \frac{u_2}{K^{-\mathbf{1}\{K \leq K^*\}\mu} \log K} v & \text{for } \beta_c = 1, \end{cases} \tag{28}$$

for $K^* \equiv x_0^{-\beta_c} \phi^{-\beta_c/\mu}$.

Proof. See Online Appendix. ■

Proposition 3 studies the implications of the interaction between sectoral GDP and price rigidity on the rate of decay of GDP volatility, v_c, as the economy becomes more disaggregated. First, consider the case in which $\mu < 0$, that is, when larger sectors have more rigid prices. When $\beta_c \in (\max\{1, 2(1+\mu)\}, 2)$, v_c decays at rate $K^{1/2}$. Yet, in general, when $\beta_c \in [1, 2)$, a positive relationship between sectoral size and price rigidity can still slow down the rate of decay of v_c despite the bounded support of the price-rigidity distribution.

Next, consider the case in which sectors with high GDP have more flexible prices ($\mu > 0$). The functional form assumption in Equation (26) and the bounded support of the degree of price rigidity now generate a kink: sectors with higher GDP than $\phi^{-1/\mu}$ have perfectly flexible prices. This kink also generates a kink in the rate of decay of aggregate volatility, v_c. First, if $\beta_c \in [1, 2)$, v_c decays at a rate slower than when sector GDP and price rigidity are independently distributed, as long as the number of sectors is weakly smaller than some K^*, $K \leq K^*$. Second, if the number of sectors is sufficiently large, price rigidity is irrelevant for the rate of decay of v_c, as in Proposition 2. Intuitively, sector GDP and price rigidity become independent when sector GDP is high. When the number of sectors is large enough, $K > K^*$, sectors with fully flexible prices dominate the upper tail of the sectoral GDP distribution, so the rate of decay of aggregate volatility is the same as in a frictionless economy.

A central question now becomes: what is a sufficiently large number of sectors empirically; that is, how large is the threshold K^*? We can answer this question within the context of Proposition 3. In the data we exploit for our quantitative exercises below, the finest degree of disaggregation available, 341 sectors, no sector has fully flexible prices. Hence, when sectors with higher GDP tend to have more flexible prices, the price-setting frictions slow down the rate of decay of aggregate volatility v_c for any level of disaggregation with at most 341 sectors. With no kink in the relationship between sectors' GDP and price rigidity, price rigidity always slows down the rate of decay of v_c for any level of disaggregation, just as in the case of $\mu < 0$.

For expositional convenience, we have assumed a deterministic relationship between sectoral GDP and price rigidity. However, if this relationship is stochastic, we trivially find price rigidity distorts the identity of the most important sectors for GDP volatility – even if price rigidity is irrelevant for the rate of decay of GDP volatility.

C. Price Rigidity and Input-Output Linkages

We now focus on the interaction between price rigidity and network centrality paralleling the main results in Acemoglu et al. (2012). We assume a positive intermediate input share, $\delta \in (0, 1)$, but shut down the heterogeneity of sectoral GDP shares, that is, $\Omega_c = \frac{1}{K}\iota$. The vector of multipliers mapping sectoral shocks into aggregate volatility now solves

$$\chi \equiv \frac{1}{K}(\mathbb{I}-\Lambda)\left[\mathbb{I}-\delta\Omega'(\mathbb{I}-\Lambda)\right]^{-1}\iota. \tag{29}$$

This expression nests the solution for the "influence vector" in Acemoglu et al. (2012) when prices are fully flexible, that is, $\lambda_k = 0$ for all $k = 1, ..., K$.[10]

In general, however, a non-trivial interaction between price rigidity and input-output linkages across sectors exists. To study this interaction, we follow Acemoglu et al. (2012) and use an approximation of the vector of multipliers truncating the effect of input-output linkages at second-order interconnection

$$\chi \simeq \frac{1}{K}(\mathbb{I}-\Lambda)\left[\mathbb{I}+\delta\Omega'(\mathbb{I}-\Lambda)+\delta^2\left[\Omega'(\mathbb{I}-\Lambda)\right]^2\right]\iota. \tag{30}$$

Let us first assume homogeneous price rigidity across sectors and focus on the scale effect of price rigidity on GDP volatility.

Lemma 3 *If $\delta \in (0,1)$, $\Omega_c = \frac{1}{K}\iota$, and $\lambda_k = \lambda$ for all k, then*

$$v_c \geq \frac{(1-\lambda)\,v}{K^{1/2}}\sqrt{\kappa+\delta'^2\mathbb{V}(d_k)+2\delta'^3\mathbb{COV}(d_k,q_k)+\delta'^4\mathbb{V}(q_k)}, \tag{31}$$

where $\kappa \equiv 1+2\delta'+3\delta'^2+2\delta'^3+\delta'^4$, $\delta' \equiv \delta(1-\lambda)$, $\mathbb{V}(\cdot)$ and $\mathbb{COV}(\cdot)$ are the sample variance and covariance statistics across sectors, and $\{d_k\}_{k=1}^K$ and $\{q_k\}_{k=1}^K$ are the *outdegrees* and *second-order outdegrees*, respectively, defined for all $k = 1, ..., K$ as

$$\begin{aligned} d_k &\equiv \sum_{k'=1}^{K}\omega_{k'k}, \\ q_k &\equiv \sum_{k'=1}^{K}d_{k'}\omega_{k'k}. \end{aligned}$$

Lemma 3 follows from equation (24), $d = \Omega'\iota$ and $q = \Omega'^2\iota$. We have an inequality, because the exact solution for the multipliers χ is strictly larger than the approximation. Acemoglu et al. (2012) coin the terms "outdegrees" and "second-order outdegrees" to measure the centrality of sectors in the production network. In particular, d_k is large when sector k is a large supplier of intermediate inputs. In turn, q_k is large when sector k is a large supplier of large suppliers of

[10] The only difference here is $\chi'\iota = 1/(1-\delta)$, because Acemoglu et al. (2012) normalize the scale of shocks such that the sum of the influence vector equals 1.

intermediate inputs. Upstream effects through demand of intermediate inputs do not play any role here due to our focus on GDP and due to our assumption of linear disutility of labor.

Similar to Lemma 1, homogeneous price rigidity across sectors has a scale effect on aggregate volatility for a given level of disaggregation. Thus, as in Acemoglu et al. (2012), aggregate volatility from idiosyncratic shocks is higher if the production network is more asymmetric, that is, if a higher dispersion of outdegrees and second-order outdegrees across sectors exists. The only new insight price rigidity adds is it penalizes more strongly the quantitative effect of heterogeneity in second-order outdegrees than in first-order outdegrees. This result is important because Acemoglu et al. (2012) stress second-order outdegrees contribute more to the aggregate impact of sectoral shocks in a frictionless economy than first-order outdegrees. In general, inter-connections of order τ are penalized by a factor $(1-\lambda)^{\tau}$.

The next proposition shows results for the rate of decay of v_c as $K \to \infty$, still under the assumption of homogeneous price rigidity.

Proposition 4 (Network effect) *If $\delta \in (0,1)$, $\lambda_k = \lambda$ for all k, $\Omega_c = \frac{1}{K}\iota$, the distribution of outdegrees $\{d_k\}$, second-order outdegrees $\{q_k\}$, and the product of outdegrees $\{d_k q_k\}$ follow power-law distributions with respective shape parameters $\beta_d, \beta_q, \beta_z > 1$ such that $\beta_z \geq \frac{1}{2}\min\{\beta_d, \beta_q\}$, then*

$$v_c \geq \begin{cases} \frac{u_3}{K^{1/2}} v & \text{for } \min\{\beta_d, \beta_q\} \geq 2, \\ \frac{u_3}{K^{1-1/\min\{\beta_d,\beta_q\}}} v & \text{for } \min\{\beta_d, \beta_q\} \in (1,2), \end{cases}$$

where u_3 is a random variable independent of K and v.

Proof. See Online Appendix. ■

Proposition 4 summarizes the network source of granularity: the rate of decay of aggregate volatility depends on the distribution of measures of network centrality and their interaction. Thus, if some sectors are disproportionately central in the production network, sectoral shocks have sizable effects on aggregate volatility even if sectors are defined at highly disaggregated levels. The fattest tail among the distributions of outdegrees and second-order outdegrees bounds the rate of decay of aggregate volatility, if the positive relation between outdegrees and second-order outdegrees is not too strong.[11]

Next, we study heterogeneous price rigidity across sectors.

[11] Acemoglu et al. (2012) document in the U.S. data that $\beta_d \approx 1.4$ and $\beta_q \approx 1.2$. We find slightly higher numbers in the data we use in our calibration. Given these numbers, we abstract from the case in which $\min\{\beta_d, \beta_q\} = 1$ in Proposition 4.

Lemma 4 *If $\delta \in (0,1)$, $\Omega_c = \frac{1}{K}\iota$, and price rigidity is heterogeneous across sectors, then*

$$v_c \geq \frac{v}{K^{1/2}} \left[\begin{array}{c} \left(\frac{1}{K}\sum_{k=1}^{K}(1-\lambda_k)^2\right)\left[\widetilde{\kappa} + \delta^2 \mathbb{V}\left(\widetilde{d}_k\right) + 2\delta'^3 \mathbb{COV}\left(\widetilde{d}_k, \widetilde{q}_k\right) + \delta'^4 \mathbb{V}\left(\widetilde{q}_k\right)\right] \\ -\left(\frac{1}{K}\sum_{k=1}^{K}(1-\lambda_k)^2\right)\left[2\delta^2\left(1+\widetilde{\delta}+\widetilde{\delta}^2\right)\mathbb{COV}\left(\lambda_k, \widetilde{d}_k\right) + \delta^4 \mathbb{COV}\left(\lambda_k, \widetilde{d}_k\right)^2\right] \\ +\mathbb{COV}\left((1-\lambda_k)^2, \left(1+\delta\widetilde{d}_k + \delta^2\widetilde{q}_k\right)^2\right) \end{array} \right]^{\frac{1}{2}}, \tag{32}$$

where $\widetilde{\kappa} \equiv 1+2\widetilde{\delta}+3\widetilde{\delta}+2\widetilde{\delta}+\widetilde{\delta}$, $\widetilde{\delta} \equiv \delta\left(1-\overline{\lambda}\right)$, $\overline{\lambda}$ is the sample mean of $\{\lambda_k\}_{k=1}^{K}$, $\mathbb{V}(\cdot)$ and $\mathbb{COV}(\cdot)$ are the sample variance and covariance statistics across sectors, and $\left\{\widetilde{d}_k\right\}_{k=1}^{K}$ and $\{\widetilde{q}_k\}_{k=1}^{K}$ are the **modified outdegrees** and **modified second-order outdegrees**, respectively, defined for all $k = 1, ..., K$ as

$$\begin{aligned} \widetilde{d}_k &\equiv \left(1-\overline{\lambda}\right)\sum_{k'=1}^{K}\left(\frac{1-\lambda_{k'}}{1-\overline{\lambda}}\right)\omega_{k'k}, \\ \widetilde{q}_k &\equiv \left(1-\overline{\lambda}\right)\sum_{k'=1}^{K}\left(\frac{1-\lambda_{k'}}{1-\overline{\lambda}}\right)\widetilde{d}_{k'}\omega_{k'k}. \end{aligned}$$

Lemma 4 follows from equation (24), $\widetilde{d} = \Omega'(\mathbb{I}-\Lambda)\,\iota$ and $\widetilde{q} = [\Omega'(\mathbb{I}-\Lambda)]^2\,\iota$. What matters now is the effective centrality of sectors in the production network – after adjusting nodes by their degree of price rigidity. In particular, $\widetilde{d}_k$ is high either when sector k is a large supplier of intermediate inputs and/ or when it is a large supplier of the most flexible sectors. Similarly, $\widetilde{q}_k$ is large when sector k is a large supplier of the most flexible sectors, which are in turn large suppliers of the most flexible sectors. Thus, depending on the cross-sectoral distribution of price rigidity, $\widetilde{d}$ and $\widetilde{q}$ may be heterogeneous across sectors even when the production network is perfectly symmetric.

In turn, the lower bound for v_c in Lemma 4 collapses to the one in Lemma 3 if price rigidity is homogeneous across sectors. How does cross-sectional GDP volatility change when we introduce heterogeneous price ridigities across sectors compared to homogeneous price rigidity? As in the case of heterogeneous sectoral GDP, the scale effect depends on the average degree of price rigidity in the economy. On top of this scale effect, the first line on the right-hand side of equation (32) is similar to the one in equation (31) in Lemma 3 with two differences. First, by Jensen's inequality,

$$\frac{1}{K}\sum_{k=1}^{K}(1-\lambda_k)^2 \geq \left(1-\overline{\lambda}\right)^2.$$

Thus, price rigidity mutes aggregate volatility by less if price rigidity is heterogeneous across sectors relative to an economy with $\lambda_k = \overline{\lambda}$ for all k.

Second, we now compute key statistics using modified outdegrees, that is, $\widetilde{d}$ and $\widetilde{q}$ instead of d and q. To see the implications, note

$$\begin{aligned}
\widetilde{d}_k &= \left(1-\overline{\lambda}\right) d_k - K\mathbb{COV}\left(\lambda_{k'}, \omega_{k'k}\right), \\
\widetilde{q}_k &= \left(1-\overline{\lambda}\right)^2 q_k - K\mathbb{COV}\left(\lambda_{k'}, \widetilde{d}_k\omega_{k'k}\right) - \left(1-\overline{\lambda}\right)\sum_{k'=1}^{K}\omega_{k'k}\mathbb{COV}\left(\lambda_s, \widetilde{d}_s\omega_{sk'}\right).
\end{aligned}$$

The dispersion of $\widetilde{d}$ is higher than the dispersion of $\left(1-\overline{\lambda}\right) d$ when $\mathbb{COV}\left(\lambda_{k'}, \omega_{k'k}\right)$ is more dispersed across sectors and when it is negatively correlated with d. In words, the dispersion of $\widetilde{d}$ is high when the intermediate input demand of the most flexible sectors is highly unequal across supplying sectors, and when large intermediate input-supplying sectors are also large suppliers to flexible sectors. Similarly, the dispersion of $\widetilde{q}$ is higher than the dispersion of $\left(1-\overline{\lambda}\right)^2 q$ when $\mathbb{COV}\left(\lambda_{k'}, \widetilde{d}_k\omega_{k'k}\right)$ is more dispersed and is negatively correlated with q.

The second and third lines on the right-hand side of the lower bound for v_c in of equation (32) capture new effects. In particular, volatility of GDP is higher when $\mathbb{COV}\left(\lambda_k, \widetilde{d}_k\right) < 0$, that is, if sectors with high modified outdegree, $\widetilde{d}_k$, are the most flexible sectors (second line), and if Jensen's inequality effect is stronger (third line).

Analyzing the effect of the heterogeneous price rigidity on the rate of decay of v_c as $K \to \infty$ is more intricate than in the case with no intermediate inputs ($\delta = 0$).

Proposition 5 *If $\delta \in (0,1)$, $\Omega_c = \frac{1}{K}\iota$, price rigidity is heterogeneous across sectors, the distribution of modified outdegrees $\left\{\widetilde{d}_k\right\}$, modified second-order outdegrees $\{\widetilde{q}_k\}$, and the product $\left\{\widetilde{d}_k\widetilde{q}_k\right\}$ follow power-law distributions with respective shape parameter $\widetilde{\beta}_d, \widetilde{\beta}_q, \widetilde{\beta}_z > 1$ such that $\widetilde{\beta}_z \geq \frac{1}{2}\min\left\{\widetilde{\beta}_d, \widetilde{\beta}_q\right\}$, then*

$$v_c \geq \begin{cases} \frac{u_4}{K^{1/2}} v & \text{for } \min\left\{\widetilde{\beta}_d, \widetilde{\beta}_q\right\} \geq 2, \\ \frac{u_4}{K^{1-1/\min\left\{\widetilde{\beta}_d, \widetilde{\beta}_q\right\}}} v & \text{for } \min\left\{\widetilde{\beta}_d, \widetilde{\beta}_q\right\} \in (1,2), \end{cases}$$

where u_4 is a random variable independent of K and v.

Proof. See Online Appendix. ■

Proposition 5 resembles Proposition 3 in the context of production networks. If sectors with the most rigid (flexible) prices are also the most central in the price-rigidity-adjusted production network such that $\min\left\{\widetilde{\beta}_d, \widetilde{\beta}_q\right\} > (<) \min\{\beta_d, \beta_q\}$, then GDP volatility decays at a faster (slower) rate than when price rigidity is homogeneous across sectors or is independent of network centrality. Also as before, regardless of the effect of price rigidity on the rate of decay of v_c, as $K \to \infty$, price rigidity distorts the identity of the most important sectors driving GDP volatility originating from idiosyncratic shocks through the network effect.

The details of the analysis here are different from the details in the preceding section, but the main message is identical: the inefficiency price rigidity introduces can dampen aggregate fluctuations just as in an economy with aggregate shocks. However, it also changes the sectoral origin of aggregate fluctuations. This change can affect the rate of decay of aggregate volatility, and individual sectoral multipliers may become larger or smaller.

Importantly, one can also think of these sectoral multipliers as relative weights to compute aggregate fluctuations, weighting the effect of sectoral shocks (see equation (23)). It is trivial to see that re-weighting sectoral shocks of potentially opposite signs can easily change the sign of business cycles, relative to a frictionless economy.

D. Relaxing Simplifying Assumptions

We now discuss the implications of relaxing the simplifying modeling assumptions we made above. We have made these assumptions for illustration and to directly relate our work with Gabaix (2011) and Acemoglu et al. (2012).

Non-linear Disutility of Labor When $\varphi > 0$, the labor market becomes segmented, so wages may differ across sectors. In addition, labor supply and demand now jointly determine wages and not only supply as in the simplified model. In particular,

$$w_{kt} = c_t + p_t^c + \varphi l_{kt} \tag{33}$$

becomes the log-linear counterpart to equation (7). Thus, with monetary policy targeting $c_t + p_t^c = 0$, it no longer holds sectoral productivity shocks have no effect on wages.[12]

We now describe these effects one by one and relegate an exploration of their quantitative importance to the calibration exercises below. First, the log-linear version of the production function implies

$$l_{kt}^d = y_{kt} - a_{kt} - \delta \left(w_{kt} - p_t^k \right). \tag{34}$$

Conditioning on sectors' gross output, shocks in sector k have direct effects on labor demand in sector k and indirect effects on all other sectors depending on their intensity of use of goods sector k produces (which are implicit in the sector-specific aggregate price of intermediate inputs, p_t^k).

[12] The Online Appendix contains details of the derivations.

Second, aggregating demand for goods by households and firms implies sectoral gross output depends on total gross output y_t and prices according to

$$y_{kt} = y_t - \eta \left(p_{kt} - \left[\left(1-\psi\right) p_t^c - \psi \widetilde{p}_t\right]\right). \tag{35}$$

Conditioning on total gross output, shocks in sector k affect sectoral gross output through the effects on the relative price between sectoral prices and the GDP deflator, p_t^c, and sectoral prices and the economy-wide aggregate price for intermediate goods, $\widetilde{p}_t$, given by

$$\widetilde{p}_t = \sum_{k'=1}^{K} \zeta_{k'} p_{k't}. \tag{36}$$

$\widetilde{p}_t$ uses steady-state shares of sectors, ζ_k, in the aggregate production of intermediate inputs as weights,

$$\zeta_k \equiv \sum_{k'=1}^{K} n_{k'} \omega_{k'k}. \tag{37}$$

$\{n_k\}_{k=1}^{\infty}$ are the shares of sectors in aggregate gross output. These shares coincide with the measure of firms in each sector and we interpret them as sectors' size in steady state

$$n_k = \left(1-\psi\right) \omega_{ck} + \psi \zeta_k \text{ for all } k = 1, ..., K. \tag{38}$$

$\psi \equiv \frac{Z}{Y}$ is the fraction of total gross output used as intermediate input in steady state.

Third, the response of total gross output y_t to shocks depends on the response of value added, c_t, and production of intermediate inputs, z_t, according to

$$y_t = \left(1-\psi\right) c_t + \psi z_t, \tag{39}$$

such that z_t solves

$$z_t = \left(1+\Gamma_c\right) c_t + \Gamma_p \left(p_t^c - \widetilde{p}_t\right) - \Gamma_a \sum_{k'=1}^{K} n_{k'} a_{k't} \tag{40}$$

and $\Gamma_c \equiv \frac{(1-\delta)(\sigma+\varphi)}{(1-\psi)+\varphi(\delta-\psi)}, \Gamma_a \equiv \frac{1+\varphi}{(1-\psi)+\varphi(\delta-\psi)}, \Gamma_p \equiv \frac{1-\delta}{(1-\psi)+\varphi(\delta-\psi)}$.

Thus, another channel through which sectoral productivity shocks affect labor demand is through their effect on the aggregate demand for intermediate inputs. This expression implicitly involves upstream effects, because the total demand for intermediate inputs depends on the demand of the shocked sector as well as all other sectors that respond to the shock.

To sum up, equation (23) still gives the solution for c_t, but the vector of multipliers χ is now

$$\chi \equiv (\mathbb{I} - \Lambda) \left[\gamma_1 \mathbb{I} + \gamma_2 \aleph \iota'\right] \left[\mathbb{I} - \varphi \left[\gamma_3 \iota \Omega_c' + \gamma_4 \iota \vartheta' - \gamma_5 \iota'\right] (\mathbb{I} - \Lambda) - \gamma_6 \Omega' (\mathbb{I} - \Lambda)\right]^{-1} \Omega_c, \tag{41}$$

with $\gamma_1 \equiv \frac{1+\varphi}{1+\delta\varphi}$, $\gamma_2 \equiv \frac{\psi(1-\delta)\Gamma_a}{1+\delta\varphi}$, $\gamma_3 \equiv \frac{(1-\delta)[(1-\psi)\eta-1]}{1+\delta\varphi}$, $\gamma_4 \equiv \frac{\psi(1-\delta)(\eta-\Gamma_p)}{1+\delta\varphi}$, $\gamma_5 \equiv \frac{\gamma_2}{\Gamma_a}$, $\gamma_6 \equiv \delta\gamma_1$, $\aleph \equiv (n_1, ..., n_K)'$, and $\vartheta = (\zeta_1, ..., \zeta_K)'$.

Relative to the solution for χ in equation (29), multipliers take a richer functional form, capturing all three channels that elastic labor demand introduces. Although the interaction between the GDP shares and network effects becomes more involved, the distortionary effect of heterogeneous price rigidity works similarly as before: through its interaction with sectoral GDP shares and input-output linkages. As we show in the next section, the additional effects of sectoral shocks through labor demand have minor effect in our quantitative results.

Active Monetary Policy We now briefly discuss how an active monetary policy can offset the scale effect on GDP volatility of any shocks which the average price rigidity introduces without impacting the role heterogeneity in price rigidity plays for the power of idiosyncratic shocks to generate aggregate fluctuations.

Consider the log-linear solution of GDP for an arbitrary monetary policy

$$c_t = \left(1 - \chi'\iota\right) m_t + \chi' a_t. \tag{42}$$

For our baseline case we had $\varphi = 0$ and $\chi \equiv (\mathbb{I} - \Lambda) \left[\mathbb{I} - \delta\Omega' (\mathbb{I} - \Lambda)\right]^{-1} \Omega_c$.

We can directly see from equation (42) monetary policy does not interact with the effect of heterogeneous price rigidity for the aggregate implication of sectoral shocks; it only introduces a level effect regardless of whether shocks are aggregate or sector-specific. This aggregate effect partially offsets the level effect due to the average price rigidity that we established in lemmas 1 and 3.

More directly, consider a common monetary policy rule: price level targeting such that $p_t^c = 0$. Price level targeting represents optimal policy under commitment when sectors have equal degrees of price rigidity, and productivity shocks are either aggregate or sector-specific. Under this monetary policy rule,

$$c_t = \frac{\chi' a_t}{\chi' \iota}. \tag{43}$$

Hence, monetary policy targeting the price levels completely offsets the scale effect in Lemmas 1 and 3.

The Pricing Friction Modeling price rigidities using Calvo does not change our analytical results qualitatively and we study the exact quantitative effects in our calibrations below. Calvo pricing adds serial correlation in the response of prices even when shocks are i.i.d.

$$p_{kt} = (1 + \beta + \xi_k)^{-1} \left[\xi_k mc_{kt} + \beta \mathbb{E}\left[p_{kt+1}\right] + p_{kt-1}\right] \text{ for } k = 1, ..., K, \tag{44}$$

where $\xi_k \equiv (1 - \alpha_k)(1 - \beta\alpha_k)/\alpha_k$.

In our simple model above, monetary policy targeting constant nominal GDP does not offset the serial correlation Calvo pricing introduces. However, two effects leave our results nearly unaffected. First, in our simple model, the response of GDP to sectoral shocks generates quantitatively nearly the same impact response of GDP when the pricing friction follows Calvo. Second, more elaborate monetary policy rules also partially offset the serial correlation in the response of GDP to productivity shocks. For instance, if monetary policy follows price level targeting, so $p_t^c = 0$,

$$c_t = \overline{\xi}^{-1} \left(\Omega_c' \Xi a_t + \Omega_c' \Xi \left[\mathbb{I} - \delta\Omega\right] p_t\right), \tag{45}$$

where Ξ is a diagonal matrix with ξ_k as diagonal elements and with mean $\overline{\xi}$. This expression contains the interaction between price rigidity and the network effect, because c_t depends on the response of sectoral prices p_t. Hence, with monetary policy targeting the price level, serial correlation in the response of GDP to sectoral shocks remains only through sectoral prices. For the special case when $\delta = 0$ and $\xi_k = \overline{\xi}$, monetary policy perfectly offsets the persistence in the response of c_t, because it replicates the response of c_t in a frictionless economy. Similarly, a Taylor rule of the form

$$i_t = \phi_\pi^c \left(p_t^c - p_{t-1}^c\right) + \phi_c c_t \tag{46}$$

also partially offsets the serial correlation that price rigidity introduces.

In general, however, we cannot fully eliminate serial correlation in the response of c_t. It might also be possible sectoral productivity shocks are persistent, though the median persistence Boivin et al. (2009) estimate is 0. Nonetheless, we adjust the definitions for multipliers we used above for our calibrations in the next section to capture possible serial correlation. Using a general representation of the solution for c_t

$$c_t = \sum_{\tau=0}^{\infty} \sum_{k=1}^{K} \rho_{k\tau} a_{kt-\tau} \tag{47}$$

we redefine multipliers to

$$\chi_k \equiv \sqrt{\sum_{\tau=0}^{\infty} \rho_{k\tau}^2}, \tag{48}$$

such that $v_c = \|\chi\|_2 \, v$ still holds. To abstract from monetary policy, we compare the multiplier of sectoral shocks on v_c with the multiplier of an aggregate productivity shock, $\sqrt{\sum_{\tau=0}^{\infty} \left(\sum_{k=1}^{K} \rho_{k\tau} \right)^2}$. For robustness, we also report results for active monetary policy rules.

State-Depending Pricing Endogenizing price adjustment, for example via a menu cost technology, should yield similar results for the aggregate effects of sectoral shocks – up to a first-order approximation. The main reason is quantitative state-dependent pricing models do not create a link between the volatility of sectoral or firm-level shocks and the frequency of price changes.

This follows from two empirical facts that discipline state-dependent models: on the one hand, the frequency of price changes is quite heterogeneous across sectors or firms, as documented for example by Nakamura and Steinsson (2008) and Bhattarai and Schoenle (2014). On the other hand, prices are not synchronized within sectors or firms, as documented by Gorodnichenko and Weber (2016), Bhattarai and Schoenle (2014), and Pasten and Schoenle (2016). To make a menu cost model consistent with these two empirical regularities, sectors with a higher frequency of price changes must face highly volatile good-specific shocks; because a high volatility of sectoral shocks would create a high synchronization of price changes within sectors. However, no systematic relationship between the frequency of price adjustment and sectoral or firm-level volatility should exist, leaving our conclusions unaffected.

In general, higher moments such as kurtosis may also affect the frequency of price changes. If they have heterogeneous effects on the sectoral frequency of price changes, then they should imply similar effects to what we document. Of course, we cannot quantify such effects without implementing a state-dependent pricing model. Because our level of discaggregation makes menu-cost models computationally infeasbile, we take a first-order approximation with our model to gain quantitative tractability.

Other Forms of Heterogeneity Across Sectors A straightforward extension of our analytical model allows for heterogeneity in the volatility of sectoral shocks and heterogeneity in intermediate input shares.

Assume sectoral productivity shocks $\{a_{kt}\}_{k=1}^{K}$ are i.i.d. with volatility $\{\sigma_k\}_{k=1}^{K}$ for all k.

Also assume the production function of firm j in sector k is given by

$$Y_{jkt} = A_{kt} L_{jkt}^{1-\delta_k} Z_{jkt}^{\delta_k} \tag{49}$$

for $k = 1, ..., K$ and leave the definition of the aggregator of intermediate inputs unchanged. The only innovation relative to our baseline model is the intermediate input share is now sector-specific and denoted by $\{\delta_k\}_{k=1}^{K}$. Everything else remains identical to before.

The solution of the steady state of this economy will be more complicated than in our baseline model, and the log-linear solution of GDP volatility is now given by

$$\sigma_c = \sqrt{\chi_k^2 \left(\frac{\sigma_k}{\overline{\sigma}}\right)} \overline{\sigma}, \tag{50}$$

where the vector of sectoral multipliers solves

$$\chi = \Omega_c \left[\mathbb{I} - \overline{\delta}\Delta \left(\mathbb{I} - \Lambda\right) \Omega\right]^{-1} \left(\mathbb{I} - \Lambda\right). \tag{51}$$

Here, $\overline{\sigma}$ denotes the average volatility of sectoral shocks, $\overline{\delta}$ denotes the average intermediate input share and Δ is a diagonal matrix with $\left\{\delta_k / \overline{\delta}\right\}$ as diagonal. Simple inspection of these two equations shows the role of heterogeneity in volatility of sectoral shocks is akin to the effect of price rigidity on the granular effect through heterogeneity in sectoral GDP. Analogously, the role of heterogeneity in the intermediate input share is akin to the effect of price rigidity on the network effect. Heterogeneity in other characteristics of sectors or other frictions may also enter through either of these two channels (or both) in the most general expression for χ for elastic labor demand in Equation (41).

IV Data

This section describes the data we use to construct the input-output linkages, and sectoral GDP, and the micro-pricing data we use to construct measures of price stickiness at the sectoral level.

A. Input-Output Linkages and Sectoral Consumption Shares

The Bureau of Economic Analysis (BEA) produces input-output tables detailing the dollar flows between all producers and purchasers in the United States. Producers include all industrial and service sectors, as well as household production. Purchasers include industrial sectors, households, and government entities. The BEA constructs the input-output tables using Census data that are collected every five years. The BEA has published input-output tables every five years beginning in 1982 and ending with the most recent tables in 2012. The input-output tables are based on NAICS industry codes. Prior to 1997, the input-output tables were based on SIC codes.

The input-output tables consist of two basic national-accounting tables: a “make” table and a “use” table. The make table shows the production of commodities by industry. Rows present industries, and columns present the commodities each industry produces. Looking across columns for a given row, we see all the commodities a given industry produces. The sum of the entries comprises industry output. Looking across rows for a given column, we see all industries producing a given commodity. The sum of the entries is the output of a commodity. The use table contains the uses of commodities by intermediate and final users. The rows in the use table contain the commodities, and the columns show the industries and final users that utilize them. The sum of the entries in a row is the output of that commodity. The columns document the products each industry uses as inputs and the three components of value added: compensation of employees, taxes on production and imports less subsidies, and gross operating surplus. The sum of the entries in a column is industry output.

We utilize the input-output tables for 2002 to create an industry network of trade flows. The BEA defines industries at two levels of aggregation: detailed and summary accounts. We use the detailed levels of aggregation to create industry-by-industry trade flows. The BEA also provides the data to calibrate sectoral GDP shares.

The BEA provides concordance tables between NAICS codes and input-output industry codes. We follow the BEA’s input-output classifications with minor modifications to create our industry classifications. We account for duplicates when NAICS codes are not as detailed as input-output codes. In some cases, an identical set of NAICS codes defines different input-output industry codes. We aggregate industries with overlapping NAICS codes to remove duplicates.

We combine the make and use tables to construct an industry-by-industry matrix that details how much of an industry’s inputs other industries produce. We use the make table ($MAKE$) to determine the share of each commodity each industry k produces. We define the market share ($SHARE$) of industry k’s production of commodities as

$$SHARE = MAKE \odot (\mathbb{I} - MAKE)^{-1}_{k,k'} \,.$$

We multiply the share and use tables (USE) to calculate the dollar amount that industry k' sells to industry k. We label this matrix revenue share ($REVSHARE$), which is a supplier industry-by-consumer industry matrix,

$$REVSHARE = SHARE \times USE.$$

We then use the revenue-share matrix to calculate the percentage of industry k' inputs purchased from industry k, and label the resulting matrix $SUPPSHARE$:

$$SUPPSHARE = REVSHARE \odot \left((\mathbb{I} - MAKE)^{-1}_{k,k'} \right)'. \tag{52}$$

The input-share matrix in this equation is an industry-by-industry matrix and therefore consistently maps into our model.[13]

B. Frequencies of Price Adjustments

We use the confidential microdata underlying the producer price data (PPI) from the BLS to calculate the frequency of price adjustment at the industry level.[14] The PPI measures changes in prices from the perspective of producers, and tracks prices of all goods-producing industries, such as mining, manufacturing, and gas and electricity, as well as the service sector. The BLS started sampling prices for the service sector in 2005. The PPI covers about 75% of the service sector output. Our sample ranges from 2005 to 2011.

The BLS applies a three-stage procedure to determine the sample of goods. First, to construct the universe of all establishments in the United States, the BLS compiles a list of all firms filing with the Unemployment Insurance system. In the second and third stages, the BLS probabilistically selects sample establishments and goods based on either the total value of shipments or the number of employees. The BLS collects prices from about 25,000 establishments for approximately 100,000 individual items on a monthly basis. The BLS defines PPI prices as "net revenue accruing to a specified producing establishment from a specified kind of buyer for a specified product shipped under specified transaction terms on a specified day of the month." Prices are collected via a survey that is emailed or faxed to participating establishments. Individual establishments remain in the sample for an average of seven years until a new sample is selected to account for changes in the industry structure.

We calculate the frequency of price adjustment at the goods level, FPA, as the ratio of the number of price changes to the number of sample months. For example, if an observed price

[13] Ozdagli and Weber (2016) follow a similar approach.

[14] The data have been used before in Nakamura and Steinsson (2008); Goldberg and Hellerstein (2011); Bhattarai and Schoenle (2014); Gorodnichenko and Weber (2016); Gilchrist, Schoenle, Sim, and Zakrajšek (2016); Weber (2015); and D'Acunto, Liu, Pflueger, and Weber (2016), among others.

path is \$10 for two months and then \$15 for another three months, one price change occurs during five months, and the frequency is 1/5. We aggregate goods-based frequencies to the BEA industry level.

The overall mean monthly frequency of price adjustment is 22.15%, which implies an average duration, $-1/\log(1-FPA)$, of 3.99 months. Substantial heterogeneity is present in the frequency across sectors, ranging from as low as 4.01% for the semiconductor manufacturing sector (duration of 24.43 months) to 93.75% for dairy production (duration of 0.36 months).

V Calibration

We calibrate the steady-state input-output linkages of our model, Ω, to the U.S. input-output tables in 2002. The same 2002 BEA data also allow us to directly calibrate sectoral GDP shares, Ω_C. The Calvo parameters match the frequency of price adjustments between 2005 and 2011, using the micro data underlying the PPI from the BLS. After we merge the input-output and the frequency-of-price-adjustment data, we end up with 341 sectors.

The detailed input-output table has 407 unique sectors in 2002. We lose sectors for three reasons. First, some sectors produce almost exclusively final goods, so the data do not contain enough observations of such goods to compute frequencies of price adjustment. Second, the goods some sectors produce do not trade in a formal market, so the BLS has no prices to record. Examples of missing sectors are (with I/O industry codes in parentheses) "military armored vehicle, tank, and tank component manufacturing" (336992), "bowling centers" (713950), and "religious organizations" (813100). Third, the data for some sectors are not available at the six-digit level.

We show results for several calibrations of our model. **MODEL1** has linear disutility of labor, $\varphi = 0$, and monetary policy targeting constant nominal GDP. This model is the closest parametrization of our full-blown New Keynesian model to the simplified model we study in Section III, with the modeling of the pricing friction as the only difference.[15]

MODEL2 is identical to **MODEL1**, but we set the inverse-Frisch elasticity to $\varphi = 2$.

MODEL3 is an intermediate case in which $\varphi = 0$, and a monetary policy that follows the Taylor rule we specified in Section II with parameters $\phi_c = 0.33/12 = 0.0275$ and $\phi_\pi = 1.34$.

In **MODEL4**, monetary policy follows the same Taylor rule, but we set the inverse-Frisch elasticity to $\varphi = 2$.

These calibrations are at a monthly frequency, so the discount factor is $\beta = 0.9975$ (implying an annual risk-free interest rate of about 3%). We set the elasticity of substitution across sectors

[15]We interpret the frequencies of price adjustments as the probability a sector can adjust prices after the shock.

to $\eta = 2$ and within sectors to $\theta = 6$ following Carvalho and Lee (2011). We will also report robustness results for the elasticities, setting $\theta = 11$, which is equivalent to a 10% markup. We also set $\delta = 0.5$ so the intermediate inputs share in steady state is $\delta * (\theta - 1)/\theta = 0.42$, which matches the 2002 BEA data.

VI Quantitative Results

In this section, we first study quantitatively the effect of heterogeneity in price stickiness across sectors on the potency of sectoral shocks to drive aggregate fluctuations. We then analyze the distortionary role price rigidities have on the identity of the most important sectors for aggregate volatility.

A. Multipliers

We provide quantitative evidence on the importance of sectoral shocks for aggregate fluctuations by first studying the multipliers that map sectoral shocks into aggregate GDP volatility.

Table 1 reports the magnitude of multipliers, $\|\chi\|$, which we formally define in equation (48), for different experiments. We report multipliers in levels but also relative to the multiplier that maps aggregate productivity shocks into aggregate GDP volatility (we will sometimes refer to the latter as "aggregate multiplier"). Price rigidity has a mechanical effect on aggregate volatility, dampening volatility originating from idiosyncratic, but also aggregate shocks. The relative multiplier controls for the general dampening effect of price rigidity on aggregate volatility and allows a clean comparison of how the different heterogeneities interact.

A.1 Multipliers: Flexible Prices

We start in Panel A of Table 1 with MODEL1, which corresponds to the simplified model of Section III except for the modeling of the pricing friction; that is, it features Calvo price stickiness, a constant nominal GDP target in the monetary policy rule, and linear disutility of labor. Column (1) assumes flexible prices to isolate the quantitative strength of the pure granular effect due to the empirical distribution of sectoral GDP, the pure network effect due to the empirical input-output structure of the U.S. economy, and their joint effect.

We start with an economy in which all sectors are homogeneous, that is, when they have equal size and uniform input-output linkages. As the model in Section III suggests, the multiplier equals $K^{-1/2}$ for K=341 and it is 5.42% of the aggregate multiplier, which equals 1. The multiplier is 0.2047 when we calibrate sector size Ω_C to U.S. data, but shut down intermediate input use ($\delta = 0$). This calibration isolates the granular effect. GDP volatility increases by a factor of 4 with sectoral heterogeneity in size relative to uniform GDP shares across sectors, showing a strong granular effect from idiosyncratic shocks for aggregate volatility.

Intermediate inputs ($\delta = 0.5$) with homogeneous steady-state input-output linkages, Ω, mute the strength of the granular channel of idiosyncratic shocks. As line (3) shows, the relative multiplier is now 11% rather than 20%.

In line (4), we focus on the fully heterogeneous network channel for aggregate fluctuations; that is, we impose equal GDP shares across sectors but calibrate Ω to the actual, heterogeneous U.S. input-output tables. The multiplier is now 8.01%. The network channel increases the multiplier by 50% relative to the multiplier in an economy with a homogeneous steady-state input-output structure (5.42%), but the network channel in isolation is smaller than the granular channel for aggregate fluctuations originating from final goods production.

The last line studies granular and network channels jointly. The multiplier is now 16.88%, indicating the potential of idiosyncratic shocks to be a major driving force behind aggregate fluctuations. The multiplier in this case is 50% larger than in an economy in which we calibrate GDP shares to U.S. data but impose a symmetric input-output structure across sectors. The overall effect is remarkably close to the one predicted by Gabaix's (2011) measure of total sales.

A.2 Multipliers: Homogeneous Sticky Prices

We now allow for rigid prices in column (2) of Table 1 but impose homogeneous price stickiness across sectors. Specifically, we calibrate the sectoral Calvo parameter to the average frequency of price adjustment in the United States for all sectors.

Comparing columns (1) and (2) across rows, we find price rigidity reduces the level of aggregate volatility sectoral shocks generate by an order of magnitude, just as our model in Section III predicts (the scale effect). However, sticky prices in general also tend to dampen aggregate volatility due to aggregate shocks, which is why we focus our discussion on relative multipliers. We argued in Section III active monetary policy can undo the scale effect and verify it in Table A.2 of the Online Appendix.

Relative multipliers under homogeneously sticky prices are similar to the case with flexible prices in column (1), with two exceptions: (i) introducing homogeneous input-output linkages offsets the granular channel less than under flexible prices (compare rows (2) and (3) across columns (1) and (2)), and (ii) the network effect in row (4) becomes slightly weaker (going from 8.01% to 6.09%). We expect these results based on our analysis in Section III. Pricing frictions mitigate the network effect of second-order outdegrees more than the network effect of first-order outdegrees. Because the distribution of second-order outdegrees is more fat-tailed than the distribution of first-order outdegrees, even homogeneous price stickiness across sectors reduces the quantitative strength of the network effect.

A.3 Multipliers: Heterogeneous Sticky Prices

Column (3) of Table 1 presents the main results of this section. The calibration captures the empirical sector-size distribution, the actual input-output structure of the U.S. economy at the most granular level, as well as detailed, heterogeneous output price stickiness across sectors, and allows us to analyze the relevance of idiosyncratic shocks for aggregate fluctuations.

The calibration empirically confirms our theoretical predictions of Section III. First, across rows, we see heterogeneous price rigidity increases the *level* of aggregate fluctuations originating from idiosyncratic shocks by at least 95% and up to 180% relative to the case of equal price stickiness in column (2).

Second, heterogeneity in price stickiness alone increases the *relative* multiplier of sectoral shocks: the relative multiplier goes from 5.42% to 12.36% in a calibration with equal GDP shares across sectors and homogeneous input-output linkages (see row (1)). Heterogeneous price stickiness thus increases the relative multiplier by more than the network effect, which generates a relative multiplier of 8.01% and 6.09% depending on whether prices are flexible or homogeneously sticky across sectors (see row (4) in columns (1) and (2)). Thus, heterogeneous price rigidity creates a "frictional" channel of aggregate volatility independent of the "granular" or "network" channels in the literature.

Third, a strong interaction between the granular effect of heterogeneous sector sizes and the frictional channel exists. In a calibration without intermediate inputs, $\delta = 0$, we find a relative multiplier of 37.18% when price rigidities follow the empirical distribution instead of 20.47% when price rigidity is equal for all sectors (see rows 2 in columns (2) and (3)). If $\delta = 0.5$ and input-output linkages are equal for all sectors, the relative multiplier is 33.73%, whereas it is only 11% in an economy with flexible prices and 17% in an economy with equal price stickiness across sectors (see row 3).

Fourth, a strong interaction exists between the network channel of aggregate fluctuations and the frictional channel: the relative multiplier is 13.16% with sticky prices calibrated to the U.S. economy, whereas it is only 8.01% in a flexible-price economy and 6.09% in an economy with equal price stickiness (compare row (4) across columns).

Overall, when our model matches the sector-size distribution, the input-output linkages of the U.S. economy, and the distribution of price rigidity across sectors, the relative multiplier that maps sectoral productivity shocks into aggregate volatility equals almost a third of the multiplier of an aggregate productivity shock. This is an almost 90% increase compared to a relative multiplier of 16.88% in a frictionless economy (last row), and almost six times larger than in an economy with homogeneous sectors.

We find across calibrations that (i) heterogeneity in price stickiness alone can generate large aggregate fluctuations from idiosyncratic shocks, (ii) homogeneous input-output linkages mute the granular effect relative to an economy without intermediate input use, and (iii) introducing heterogeneous price stickiness across sectors in an economy with sectors of different sizes but homogeneous input-output linkages increases the size of the relative multipliers. Section III in the online appendix explains the economics behind these findings within our simplified model.

A.4 Multipliers: Alternative Model Specifications

Our results continue to hold for three alternative model specifications. We present them in Panels B to D of Table 1. MODEL2 drops the assumption of a linear disutility of labor. MODEL3 assumes a standard Taylor rule instead of a monetary policy targeting constant nominal GDP, whereas MODEL4 additionally drops the assumption of linear disutility of labor. The level of the multipliers differs from MODEL1 in Panel A, but the relative multipliers are almost identical across different calibrations for flexible and homogeneously sticky prices. Under heterogeneous price stickiness, the levels of the multipliers are similar across calibrations, with some differences in relative multipliers when we drop the assumption of linear disutility of labor.

Our results also continue to hold when we only focus on the impact multipliers. Table 2 reports multipliers in levels and relative to the aggregate multipliers for the same four models, but studies only the impact effect of sectoral shocks on GDP. Multipliers differ only slightly relative to the ones in reported in Table 1, suggesting the Calvo assumption introduces only a small degree of persistence relative to the simple specification of price rigidity we study in the simplified model of Section III.

We follow Carvalho and Lee (2011) in the calibration of deep parameters, but one might be concerned a low elasticity of substitution within sector might partially drive our findings.[16] Table 3 shows our findings across models and calibrations barely change when we increase the within-sectors elasticity of substitution, θ, from a baseline value of 6 to 11, which reduces the markup from 20% to 10%.[17]

In our baseline analysis, we have to drop the construction sectors because the BLS does not provide pricing information at the six-sector NAICS level. Table A.1 in the Online Appendix

[16] We thank Susanto Basu for raising this point.

[17] We also lower δ from 0.5 to 0.46 to match the ratio of C/Y in the data.

reports results for a calibration in which we assign the same price stickiness measure to all six-digit construction sectors. Results are similar to the one we discussed above. In untabulated results, we also find similar results for a model with occasionally-binding ZLB.

B. Distorted Idiosyncratic Origin of Fluctuations

One of the central results of Section III is heterogeneity in price stickiness can change the identity and relative importance of sectors as origin of aggregate fluctuations. Table 4 shows introducing heterogeneity in the frequency of price adjustment across sectors indeed changes the identity and relative contribution of the five most important sectors for the multiplier for different calibrations of MODEL1. Relative contributions sum to 1, and the entries in Table 4 tell us directly the fraction of the multiplier coming from the reported sectors.[18]

In column (1), we calibrate Calvo parameters to the sectoral frequency of price changes in the United States, but impose equal GDP shares across sectors, and input-output linkages are homogeneous. The five most important sectors are the five sectors with most the flexible prices, which are mostly commodities and farming products: "Dairy cattle and milk production" (112120), "Alumina refining and primary aluminum production" (33131A), "Primary smelting and refining of copper" (331411), "Oil and gas extraction" (211000), and "Poultry and egg production" (1121A0). The relative contributions to the overall multiplier range from 7.62% to 5.49%. If all sectors were perfectly identical, all sectors would have a contribution of 0.29% (341^{-1}).

Columns (2) and (3) in Table 4 show how price rigidity affects the granular channel of idiosyncratic shocks. Column (2) assumes flexible prices but steady-state sectoral GDP shares that match the data. Column (3) also matches the sectoral frequency of price changes. The identity and relative contribution changes across calibrations: with flexible prices, the most important sectors and are "Retail trade" (4A0000), "Wholesale trade" (420000), and "Real estate" (531000), with relative contributions of 33.33%, 14.43%, and 10.89%, respectively; once we introduce rigid prices, the most important sectors are "Monetary authorities and depository credit intermediation" (52A000), "Wholesale trade" (420000), and "Oil and gas extraction" (211000) with relative contributions of 25.33%, 18.74%, and 13.50%.

Columns (4) and (5) of Table 4 studies the distortion price rigidity introduces on the network effect of aggregate fluctuations. Column (4) assumes flexible prices and steady-state input-output linkages calibrated to the U.S. input-output tables, whereas column (5) also matches sectoral frequencies of price adjustment. Again, the identity of the five most important sectors

[18]Results are similar for the other models.

changes completely: with flexible prices, the most important sectors are “Wholesale trade” (420000), followed by “Real estate” (531000), “Electric power generation, transmission, and distribution” (221100), “Monetary authorities and depository credit intermediation” (52A000), and “Retail trade” (4A0000), with relative contributions of 24.53%, 7.61%, 3.66%, 3.26%, and 2.90%.

Once we allow for sticky prices, the contributions of the five most important sectors range from 9.85% to 5.76% which in descending order are “Electric power generation, transmission, and distribution” (211000), “ Dairy cattle and milk production” (112120), “Petroleum refineries” (324110), “Primary smelting and refining of copper” (331411), and “Cattle ranching and farming” (1121A0). In short, energy sectors become the most important, followed by farming sectors, once we allow for price stickiness to follow the empirical distribution.

Finally, we compare columns (6) and (7) in Table 4 to see how the introduction of heterogeneous price stickiness across sectors changes the importance and identity of sectors for the multiplier when both the granular and network channels are at work.

The relative contributions of the five most important sectors with flexible prices are: “Retail trade” (4A0000), “Real estate” (531000), “Wholesale trade” (420000), “Monetary authorities and depository credit intermediation” (52A000), and “Telecommunications” (517000). With flexible prices, “Retail trade” and “Real estate” jointly account for 45% of the aggregate fluctuations originating from shocks at the micro level.

When we turn on heterogeneous sticky prices, instead, “Real estate” no longer belongs to the top five sectors and the contribution of “Retail trade” drops to 10%. Interestingly, “Monetary authorities and depository credit intermediation” becomes the most important sector, with a contribution of almost 30% when we allow for heterogeneities along all three dimension in the most realistic calibration.

The discussion so far focused on the identity and contribution of the five most important sectors. The distorting nature of heterogeneous price stickiness, however, is a more general phenomenon. Figure 1 is a scatter plot of the sectoral rank in the contribution to aggregate fluctuations originating from sectoral shocks. The y-axis plots the rank in an economy with heterogeneous price stickiness, and the x-axis plots the rank in an economy with identical price stickiness across sectors, while we allow for heterogeneity in input-output linkages and consumption shares in both cases. We see the introduction of differential price stickiness changes the rank of sectors throughout the whole distribution, and drastically so for some sectors.

Overall, sectoral heterogeneity of price rigidity distorts the identity and the relative contribution of the most important sectors for aggregate fluctuations originating from sectoral productivity shocks. The evidence on the changing identity and relative importance of sectors for aggregate fluctuations originating from sectoral shocks we observe in Table 4 and Figure 1 underlines the importance of studying granular, network, and frictional channels in combination. A central bank that aims to stabilize sectoral prices of "big" or "central" sectors might make systematic policy mistakes if it does not take into account the "frictional" origin of aggregate fluctuations.

VII Concluding Remarks

This paper studies the potential of idiosyncratic shocks to drive aggregate fluctuations when nominal output prices are heterogeneously rigid across sectors. We do so theoretically and quantitatively in a calibrated 341 sector New Keynesian model with intermediate inputs and heterogeneity in sector size, sector input-output linkages, and output price stickiness.

Heterogeneity in price rigidity has first-order effects: it generates a frictional origin of aggregate fluctuations, it amplifies the granular and network channels of idiosyncratic shocks, and it changes the identity and relative importance of sectors for aggregate fluctuations originating from sectoral shocks. Importantly, sector sales are no longer a sufficient statistic for a sector's contribution to aggregate volatility, as in Hulten (1978). Interestingly, we moreover find in our most realistic calibration which allows for heterogeneous price rigidities across sectors matched to U.S. data, "Monetary authorities and depository credit intermediation" to be the most important sector for aggregate fluctuations originating from shocks at the micro level.

To date, the implications of price rigidity, and frictions in general, for the granular and network effects remain largely unexplored. Our analysis suggests price rigidity has direct and important implications for the modeling and understanding of business cycles. The interaction also has important implications for the conduct of monetary policy. A central bank that aims to stabilize sectoral prices of "big" or "central" sectors might make systematic policy mistakes if it does not take into account the "frictional" origin of aggregate fluctuations. Although beyond the scope of this paper, future work may explore the design of optimal monetary policy in our heterogeneous production economy.

To make the points of this paper, we assumed exogenously given price rigidity. We argue in the paper endogenizing price adjustments may amplify our results, because sectors hit by larger shocks typically adjust prices more frequently. However, the exact result may depend on the respective price-adjustment technology. We leave this extension to future research.

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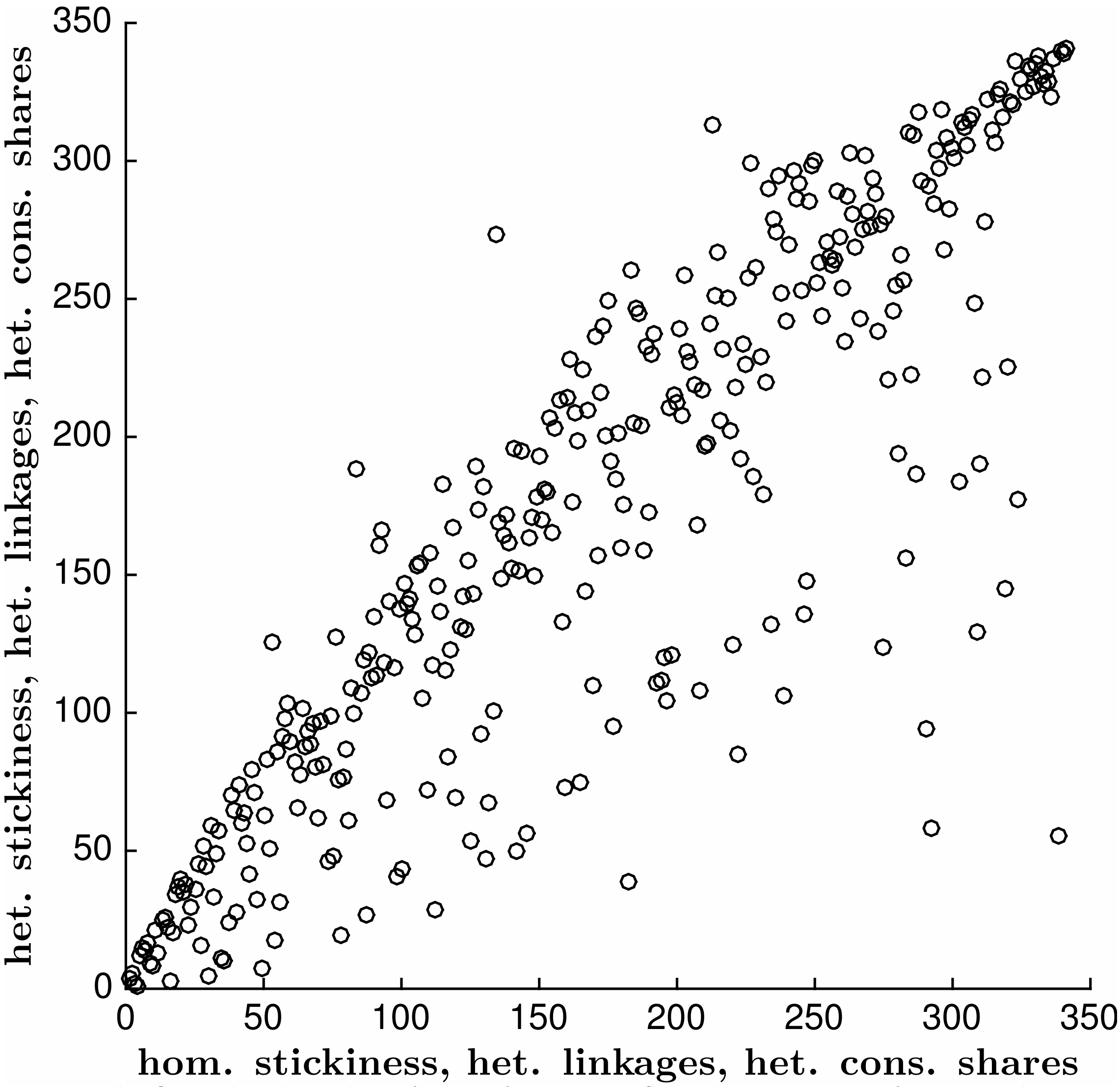
Figure 1: **Ranking of Sectors: heterogeneous versus homogeneous Price Stickiness**



This figure plots the ranking of sectors for aggregate fluctuations originating from sectoral shocks for an economy with heterogeneous price stickiness across sectors (y-axis) and an economy with identical price stickiness for all sectors (x-axis). We assume heterogeneous GDP shares and input-output linkages calibrated to the United States in both cases.

Table 1: **Multipliers of Sectoral Shocks into Aggregate Volatility**

This table reports multipliers of sectoral productivity shocks on GDP volatility , with relative multipliers in parentheses. The former are defined as the Euclidean norm of vector χ with elements $\chi_k = \sqrt{\sum_{\tau=0}^{\infty} \rho_{k\tau}^2}$, The latter are relative to the multiplier of an aggregate productivity shock on GDP volatility, $\sqrt{\sum_{\tau=0}^{\infty} \left(\sum_{k=1}^{K} \rho_{k\tau}\right)^2}$. Ω_c represents the vector of GDP shares and Ω the matrix of input-output linkages. We calibrate a 341-sector version of our model to the input-output tables and sector size from the BEA and the frequencies of price adjustment from the BLS.

			Flexible Prices		Homogeneous Calvo		Heterogeneous Calvo	
			(1)		(2)		(3)	
					Panel A: MODEL1			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0017	(5.42%)	0.0045	(12.36%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.0105	(20.47%)	0.0226	(37.18%)
(3)	het Ω_c	hom Ω	0.1126	(11.26%)	0.0054	(17.00%)	0.0114	(33.73%)
(4)	hom Ω_c	het Ω	0.0801	(8.01%)	0.0019	(6.09%)	0.0054	(13.16%)
(5)	het Ω_c	het Ω	0.1688	(16.88%)	0.0060	(18.96%)	0.0117	(31.78%)
					Panel B: MODEL2			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0031	(5.42%)	0.0049	(8.16%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.0223	(20.47%)	0.0320	(30.28%)
(3)	het Ω_c	hom Ω	0.1162	(11.62%)	0.0088	(15.36%)	0.0137	(22.97%)
(4)	hom Ω_c	het Ω	0.0780	(7.80%)	0.0037	(6.38%)	0.0062	(9.22%)
(5)	het Ω_c	het Ω	0.1700	(17.00%)	0.0105	(18.30%)	0.0154	(24.14%)
					Panel C: MODEL3			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0011	(5.42%)	0.0059	(15.26%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.0081	(20.47%)	0.0265	(46.11%)
(3)	het Ω_c	hom Ω	0.1126	(11.26%)	0.0037	(18.51%)	0.0132	(44.82%)
(4)	hom Ω_c	het Ω	0.0801	(8.01%)	0.0012	(6.00%)	0.0068	(15.87%)
(5)	het Ω_c	het Ω	0.1688	(16.88%)	0.0040	(19.60%)	0.0128	(39.81%)
					Panel D: MODEL4			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0025	(5.42%)	0.0063	(9.40%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.0226	(20.47%)	0.0384	(33.09%)
(3)	het Ω_c	hom Ω	0.1162	(11.62%)	0.0074	(16.10%)	0.0158	(26.80%)
(4)	hom Ω_c	het Ω	0.0780	(7.80%)	0.0029	(6.23%)	0.0076	(10.20%)
(5)	het Ω_c	het Ω	0.1700	(17.00%)	0.0086	(18.58%)	0.0169	(26.59%)

Table 2: **Multipliers of Sectoral Shocks into Aggregate Volatility: Impact Response**

This Table reports the impact multipliers of sectoral productivity shocks on GDP volatility, with relative multipliers, in parentheses. The latter are relative to the multiplier of an aggregate productivity shock on GDP volatility. Ω_c represents the vector of GDP shares and Ω the matrix of input-output linkages. We calibrate a 341-sector version of our model to the input-output tables and sector size from the BEA and the frequencies of price adjustment from the BLS.

			Flexible Prices		Homogeneous Calvo		Heterogeneous Calvo	
			(1)		(2)		(3)	
					Panel A: MODEL1			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0008	(5.42%)	0.0042	(13.92%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.0058	(20.47%)	0.0192	(42.79%)
(3)	het Ω_c	hom Ω	0.1126	(11.26%)	0.0029	(19.47%)	0.0096	(40.89%)
(4)	hom Ω_c	het Ω	0.0801	(8.01%)	0.0008	(5.45%)	0.0049	(14.67%)
(5)	het Ω_c	het Ω	0.1688	(16.88%)	0.0030	(20.01%)	0.0094	(36.68%)
					Panel B: MODEL2			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0018	(5.42%)	0.0045	(8.77%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.0153	(20.47%)	0.0277	(31.63%)
(3)	het Ω_c	hom Ω	0.1162	(11.62%)	0.0055	(16.77%)	0.0116	(25.22%)
(4)	hom Ω_c	het Ω	0.0780	(7.80%)	0.0019	(5.87%)	0.0055	(9.66%)
(5)	het Ω_c	het Ω	0.1700	(17.00%)	0.0062	(18.85%)	0.0125	(25.45%)
					Panel C: MODEL3			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0011	(5.42%)	0.0043	(13.44%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.0081	(20.47%)	0.0211	(40.37%)
(3)	het Ω_c	hom Ω	0.1126	(11.26%)	0.0037	(18.15%)	0.0101	(38.82%)
(4)	hom Ω_c	het Ω	0.0801	(8.01%)	0.0011	(5.60%)	0.0051	(14.15%)
(5)	het Ω_c	het Ω	0.1688	(16.88%)	0.0039	(19.43%)	0.0100	(35.02%)
					Panel D: MODEL4			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0025	(5.42%)	0.0048	(8.49%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.0226	(20.47%)	0.0323	(30.42%)
(3)	het Ω_c	hom Ω	0.1162	(11.62%)	0.0073	(15.95%)	0.0127	(24.18%)
(4)	hom Ω_c	het Ω	0.0780	(7.80%)	0.0028	(6.09%)	0.0060	(9.40%)
(5)	het Ω_c	het Ω	0.1700	(17.00%)	0.0085	(18.52%)	0.0141	(24.69%)

Table 3: **Multipliers of Sectoral Shocks into Aggregate Volatility: High Elasticity of Substitution**

This table reports multipliers of sectoral productivity shocks on GDP volatility , with relative multipliers in parentheses. The former are defined as the Euclidean norm of vector χ with elements $\chi_k = \sqrt{\sum_{\tau=0}^{\infty} \rho_{k\tau}^2}$, The latter are relative to the multiplier of an aggregate productivity shock on GDP volatility, $\sqrt{\sum_{\tau=0}^{\infty}\left(\sum_{k=1}^{K} \rho_{k\tau}\right)^2}$. Ω_c represents the vector of GDP shares and Ω the matrix of input-output linkages. We calibrate a 341-sector version of our model to the input-output tables and sector size from the BEA and the frequencies of price adjustment from the BLS. We increase the elasticity of substitution across sectors, θ, from a baseline value of 6 to 11.

			Flexible Prices		Homogeneous Calvo		Heterogeneous Calvo	
			(1)		(2)		(3)	
					Panel A: MODEL1			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0018	(5.42%)	0.0048	(12.40%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.0105	(20.47%)	0.0226	(37.18%)
(3)	het Ω_c	hom Ω	0.1195	(11.95%)	0.0058	(17.34%)	0.0123	(34.05%)
(4)	hom Ω_c	het Ω	0.0764	(7.64%)	0.0020	(5.96%)	0.0057	(13.11%)
(5)	het Ω_c	het Ω	0.1710	(17.10%)	0.0064	(19.11%)	0.0125	(32.20%)
					Panel B: MODEL2			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0035	(5.42%)	0.0055	(7.81%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.0223	(20.47%)	0.0320	(30.28%)
(3)	het Ω_c	hom Ω	0.1215	(12.15%)	0.0101	(15.39%)	0.0153	(22.12%)
(4)	hom Ω_c	het Ω	0.0754	(7.54%)	0.0042	(6.33%)	0.0068	(8.84%)
(5)	het Ω_c	het Ω	0.1717	(17.17%)	0.0120	(18.31%)	0.0173	(23.58%)
					Panel C: MODEL3			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0012	(5.42%)	0.0064	(15.26%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.0081	(20.47%)	0.0265	(46.11%)
(3)	het Ω_c	hom Ω	0.1195	(11.95%)	0.0041	(18.65%)	0.0142	(44.92%)
(4)	hom Ω_c	het Ω	0.0764	(7.64%)	0.0013	(5.90%)	0.0073	(15.81%)
(5)	het Ω_c	het Ω	0.1710	(17.10%)	0.0043	(19.66%)	0.0138	(40.28%)
					Panel D: MODEL4			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0030	(5.42%)	0.0070	(8.86%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.0226	(20.47%)	0.0384	(33.09%)
(3)	het Ω_c	hom Ω	0.1215	(12.15%)	0.0088	(15.95%)	0.0177	(25.27%)
(4)	hom Ω_c	het Ω	0.0754	(7.54%)	0.0034	(6.21%)	0.0083	(9.67%)
(5)	het Ω_c	het Ω	0.1717	(17.17%)	0.0103	(18.52%)	0.0192	(25.60%)

Table 4: **Contribution of Sectors to Multiplier of Sectoral Shocks on GDP Volatility**

This table reports the contribution of five most important sectors to the multiplier of sectoral shocks on GDP volatility for MODEL1 and the identity of sectors in parentheses. The different columns represent calibrations which match the frequency of price adjustments (λ), the distribution of consumption shares (Ω_c), or the actual input-output matrix (Ω). 1121A0: Cattle ranching and farming; 112120: Dairy cattle and milk production; 211000: Oil and gas extraction; 221100: Electric power generation, transmission, and distribution; 324110: Petroleum refineries; 33131A: Alumina refining and primary aluminum production; 331411: Primary smelting and refining of copper; 336111: Automobile manufacturing; 4A0000: Retail trade; 420000: Wholesale trade; 517000: Telecommunications; 52A000: Monetary authorities and depository credit intermediation; 531000: Real estate; 621A00: Offices of physicians, dentists, and other health practitioners; 622000: Hospitals

λ (1)	Ω_c (2)	λ, Ω_c (3)	Ω (4)	λ, Ω (5)	Ω_c, Ω (6)	λ, Ω_c, Ω (7)
7.62% (112120)	33.33% (4A0000)	25.33% (52A000)	24.53% (420000)	9.85% (211000)	23.22% (4A0000)	28.64% (52A000)
6.33% (33131A)	14.43% (420000)	18.74% (420000)	7.61% (531000)	6.69% (112120)	21.99% (531000)	20.71% (420000)
6.32% (331411)	10.89% (531000)	13.50% (211000)	3.66% (221100)	6.23% (324110)	16.85% (420000)	11.46% (324110)
5.92% (211000)	6.69% (621A00)	11.55% (324110)	3.26% (52A000)	6.15% (331411)	6.25% (52A000)	10.49% (4A0000)
5.49% (1121A0)	5.72% (622000)	10.73% (336111)	2.90% (4A0000)	5.76% (1121A0)	5.58% (517000)	9.24% (336111)

Online Appendix: Price Rigidities and the Granular Origins of Aggregate Fluctuations

Ernesto Pasten, Raphael Schoenle, and Michael Weber

Not for Publication

I Steady-State Solution and Log-linear System

A. Steady-State Solution

Without loss of generality, set $a_k = 0$. We show below conditions for the existence of a symmetric steady state across firms in which

$$W_k = W,\ Y_{jk} = Y,\ L_{jk} = L,\ Z_{jk} = Z,\ P_{jk} = P \text{ for all } j, k.$$

Symmetry in prices across all firms implies

$$P^c = P^k = P_k = P$$

such that, from equations (1), (2), (10), and (13) in the main body of the paper,

$$\begin{aligned} C_k &= \omega_{ck} C, \\ C_{jk} &= \frac{1}{n_k} C_k, \\ Z_{jk}\left(k'\right) &= \omega_{kk'} Z, \\ Z_{jk}\left(j', k'\right) &= \frac{1}{n_{k'}} Z_{jk}\left(k'\right). \end{aligned}$$

The vector $\Omega_c \equiv [\omega_{c1}, ..., \omega_{cK}]'$ represents steady-state sectoral shares in value-added C, $\Omega = \{\omega_{kk'}\}_{k,k'=1}^{K}$ is the matrix of input-output linkages across sectors, and $\aleph \equiv [n_1, ..., n_K]'$ is the vector of steady-state sectoral shares in gross output Y.

It also holds that

$$
\begin{aligned}
C &= \sum_{k=1}^{K} \int_{\Im_k} C_{jk} dj, \\
Z_{jk} &= \sum_{k'=1}^{K} \int_{\Im_{k'}} Z_{jk}\left(j', k'\right) dj' = Z.
\end{aligned}
$$

From Walras' law in equation (19) and symmetry across firms, it follows

$$
Y = C + Z. \tag{A.1}
$$

Walras' law and results also imply for all j, k

$$
\begin{aligned}
Y_{jk} &= C_{jk} + \sum_{k'=1}^{K} \int_{\Im_{k'}} Z_{j'k'}\left(j, k\right) dj', \\
Y &= \frac{\omega_{ck}}{n_k} C + \frac{1}{n_k} \left(\sum_{k'=1}^{K} n_{k'} \omega_{k'k} \right) Z,
\end{aligned}
$$

so $\aleph$ satisfies

$$
\begin{aligned}
n_k &= \left(1 - \psi\right) \omega_{ck} + \psi \sum_{k'=1}^{K} n_{k'} \omega_{k'k}, \\
\aleph &= \left(1 - \psi\right) \left[I - \psi \Omega' \right]^{-1} \Omega_c,
\end{aligned}
$$

for $\psi \equiv \frac{Z}{Y}$. Note by construction $\aleph' \iota = 1$, which must hold given the total measure of firms is 1.

Steady-state labor supply from equation (7) is

$$
\frac{W_k}{P} = g_k L_k^{\varphi} C^{\sigma}.
$$

In a symmetric steady state, $L_k = n_k L$, so this steady state exists if $g_k = n_k^{-\varphi}$ such that $W_k = W$ for all k. Thus, steady-state labor supply is given by

$$
\frac{W}{P} = L^{\varphi} C^{\sigma}. \tag{A.2}
$$

Households' budget constraint, firms' profits, production function, efficiency of production (from equation (15)) and optimal prices in steady state are, respectively,

$$CP = WL + \Pi \tag{A.3}$$

$$\Pi = PY - WL - PZ \tag{A.4}$$

$$Y = L^{1-\delta} Z^{\delta} \tag{A.5}$$

$$\delta WL = (1-\delta) PZ \tag{A.6}$$

$$sP = \frac{\theta}{\theta - 1} \xi W^{1-\delta} P^{\delta} \tag{A.7}$$

for $\xi \equiv \frac{1}{1-\delta}\left(\frac{\delta}{1-\delta}\right)^{-\delta}$.

Equation (A.7) solves

$$\frac{W}{P} = \left(\frac{\theta - 1}{\theta \xi}\right)^{\frac{1}{1-\delta}}. \tag{A.8}$$

This latter result together with equations (A.5), (A.6), and (A.7) solve

$$\frac{\Pi}{P} = \frac{1}{\theta} Y.$$

Plugging the previous result in equation (A.4) and using equation (A.1) yields

$$\begin{aligned} C &= \left[1 - \delta\left(\frac{\theta - 1}{\theta}\right)\right] Y \\ Z &= \delta\left(\frac{\theta - 1}{\theta}\right) Y, \end{aligned} \tag{A.9}$$

such that $\psi \equiv \delta\left(\frac{\theta-1}{\theta}\right)$.

This result and equation (A.7) gives

$$L = \left[\delta\left(\frac{\theta - 1}{\theta}\right)\right]^{-\frac{\delta}{1-\delta}} Y,$$

where Y from before together with equations (A.2), (A.9) and (A.8) solves

$$Y = \left(\frac{\theta - 1}{\theta \xi}\right)^{\frac{1}{(1-\delta)(\sigma+\varphi)}} \left[\delta\left(\frac{\theta - 1}{\theta}\right)\right]^{\frac{\delta\varphi}{(1-\delta)(\sigma+\varphi)}} \left[1 - \delta\left(\frac{\theta - 1}{\theta}\right)\right]^{-\frac{\sigma}{\sigma+\varphi}}.$$

B. Log-linear System

B.1 Aggregation

Aggregate and sectoral consumption which we interpret as value-added, given by equations (1) and (2), are

$$\begin{aligned} c_t &= \sum_{k=1}^{K} \omega_{ck} c_{kt}, \\ c_{kt} &= \frac{1}{n_k} \int_{\Im_k} c_{jkt} dj. \end{aligned} \tag{A.10}$$

Aggregate and sectoral production of intermediate inputs are

$$\begin{aligned} z_t &= \sum_{k=1}^{K} n_k z_{kt}, \\ z_{kt} &= \frac{1}{n_k} \int_{\Im_k} z_{jkt} dj, \end{aligned} \tag{A.11}$$

where equations (10) and (13) imply that $z_{jk} = \sum_{r=1}^{K} \omega_{kr} z_{jk}(r)$ and $z_{jk}(r) = \frac{1}{n_r} \int_{\Im_r} z_{jk}(j', r) dj'$.

Sectoral and aggregate prices are (equations (4), (6), and (12)),

$$\begin{aligned} p_{kt} &= \int_{\Im_k} p_{jk} dj \text{ for } k = 1, ..., K \\ p_t^c &= \sum_{k=1}^{K} \omega_{ck} p_{kt}, \\ p_t^k &= \sum_{k'=1}^{K} \omega_{kk'} p_{k't}. \end{aligned}$$

Aggregation of labor is

$$\begin{aligned} l_t &= \sum_{k=1}^{K} l_{kt}, \\ l_{kt} &= \int_{\Im_k} l_{jkt} dj. \end{aligned} \tag{A.12}$$

B.2 Demand

Households' demands for goods in equations (3) and (5) for all $k = 1, ..., K$ become

$$\begin{aligned} c_{kt} - c_t &= \eta \left(p_t^c - p_{kt} \right), \\ c_{jkt} - c_{kt} &= \theta \left(p_{kt} - p_{jkt} \right). \end{aligned} \tag{A.13}$$

In turn, firm jk's demands for goods in equation (11) and (14) for all $k, r = 1, ..., K$,

$$\begin{aligned} z_{jkt} \left(k' \right) - z_{jkt} &= \eta \left(p_t^k - p_{k't} \right), \\ z_{jkt} \left(j', k' \right) - z_{jkt} \left(k' \right) &= \theta \left(p_{k't} - p_{j'k't} \right). \end{aligned} \tag{A.14}$$

Firms' gross output satisfies Walras' law,

$$y_{jkt} = (1 - \psi) c_{jkt} + \psi \sum_{k'=1}^{K} \int_{\Im_{k'}} z_{j'k't} (j, k) \, dj'. \tag{A.15}$$

Total gross output follows from the aggregation of equations (19),

$$y_t = (1 - \psi) c_t + \psi z_t. \tag{A.16}$$

B.3 IS and Labor Supply

The household Euler equation in equation (8) becomes

$$c_t = \mathbb{E}_t \left[c_{t+1} \right] - \sigma^{-1} \left\{ i_t - \left(\mathbb{E}_t \left[p_{t+1}^c \right] - p_t \right) \right\}.$$

The labor supply condition in equation (7) is

$$w_{kt} - p_t^c = \varphi l_{kt} + \sigma c_t. \tag{A.17}$$

B.4 Firms

Production function:

$$y_{jkt} = a_{kt} + (1 - \delta) l_{jkt} + \delta z_{jkt} \tag{A.18}$$

Efficiency condition:

$$w_{kt} - p_t^k = z_{jkt} - l_{jkt} \tag{A.19}$$

Marginal costs:

$$mc_{kt} = (1 - \delta) w_{kt} + \delta p_t^k - a_{kt} \tag{A.20}$$

Optimal reset price:

$$p_{kt}^* = (1 - \alpha_k \beta) mc_{kt} + \alpha_k \beta \mathbb{E}_t \left[p_{kt+1}^* \right]$$

Sectoral prices:

$$p_{kt} = (1 - \alpha_k) p_{kt}^* + \alpha_k p_{kt-1}$$

B.5 Taylor Rule:

$$i_t = \phi_\pi \left(p_t^c - p_{t-1}^c \right) + \phi_c c_t$$

II Solution of Key Equations in Section III

A. Solution of Equation (29)

Setting $\sigma = 1$ and $\varphi = 0$ in equation (A.17) yields

$$w_{kt} = c_t + p_t^c = 0,$$

where the equality follows from the assumed monetary policy rule, so equation (A.20) becomes

$$mc_{kt} = \delta p_t^k - a_{kt}.$$

Here, sectoral prices for all $k = 1, ..., K$ are governed by

$$\begin{aligned} p_{kt} &= (1 - \lambda_k)\, mc_{kt} \\ &= \delta\,(1 - \lambda_k)\, p_t^k - (1 - \lambda_k)\, a_{kt}, \end{aligned}$$

which in matrix form solves

$$p_t = -\left[\mathbb{I} - \delta\,(\mathbb{I} - \Lambda)\,\Omega\right]^{-1}(\mathbb{I} - \Lambda)\, a_t.$$

$p_t \equiv [p_{1t}, ..., p_{Kt}]'$ is the vector of sectoral prices, Λ is a diagonal matrix with the vector $[\lambda_1, ..., \lambda_K]'$ on its diagonal, Ω is the matrix of input-output linkages, and $a_t \equiv [a_{1t}, ..., a_{Kt}]'$ is the vector of realizations of sectoral technology shocks.

The monetary policy rule implies $c_t = -p_t^c$, so

$$c_t = \left(\mathbb{I} - \Lambda'\right)\left[\mathbb{I} - \delta\left(\mathbb{I} - \Lambda'\right)\Omega'\right]^{-1}\Omega_c' a_t.$$

Solution of Equation (41)

Setting $\sigma = 1$ and $\varphi > 0$ in (A.17) yields

$$w_{kt} = \varphi l_{kt}^s + c_t + p_t^c = \varphi l_{kt}^d,$$

which follows from the assumed monetary policy rule.

Labor demand is obtained from the production function in equation (A.18), the efficiency condition for production in equation (A.19), and the aggregation of labor in equation (A.12)

$$l_{kt}^{d} = y_{kt} - a_{kt} - \delta \left(w_{kt} - p_t^k \right).$$

y_{kt} follows from equations (A.10), (A.11), (A.13), (A.14), and (A.15)

$$y_{kt} = y_t - \eta \left(p_{kt} - \left[(1-\psi)\, p_t^c + \psi \sum_{k=1}^{K} n_k p_t^k \right] \right),$$

where

$$\widetilde{p}_t \equiv \sum_{k=1}^{K} n_k p_t^k = \sum_{k=1}^{K} \zeta_k p_{kt},$$

with $\zeta_k \equiv \sum_{k'=1}^{K} n_{k'} \omega_{k'k}$.

To solve for y_t, we use equations (A.11), (A.12), (A.16) and $y_t = \sum_{k=1}^{K} \int_{\Im_k} y_{jkt} dj$ to get

$$y_t = c_t + \psi \left[\Gamma_c c_t - \Gamma_p \left(\widetilde{p}_t - p_t^c \right) - \Gamma_a \sum_{k=1}^{K} n_k a_{kt} \right],$$

where $\Gamma_c \equiv \frac{(1-\delta)(1+\varphi)}{(1-\psi)+\varphi(\delta-\psi)}$, $\Gamma_p \equiv \frac{1-\delta}{(1-\psi)+\varphi(\delta-\psi)}$, $\Gamma_a \equiv \frac{1+\varphi}{(1-\psi)+\varphi(\delta-\psi)}$.

Putting together all these equations, sectoral wages solve

$$w_{kt} = \frac{\varphi}{1+\delta\varphi} \left[\begin{array}{c} \left(1+\psi\Gamma_c\right) c_t - a_{kt} - \psi \Gamma_a \sum_{k'=1}^{K} n_{k'} a_{k't} \\ \left[(1-\psi)\,\eta + \psi \Gamma_p \right] p_t^c + \psi \left(\eta - \Gamma_p \right) \widetilde{p}_t + \delta p_t^k - \eta p_{kt} \end{array} \right].$$

With this expression, the solution to equation (41) follows the same steps as the solution to equation (29).

III The Network Effect, the Granular Effect, and Price Rigidity

We find in Section VI across calibrations that (i) heterogeneity in price stickiness alone can generate large aggregate fluctuations from idiosyncratic shocks, (ii) homogeneous input-output linkages mute the granular effect relative to an economy without intermediate input use, and (iii) introducing heterogeneous price stickiness across sectors in an economy with sectors of different sizes but homogeneous input-output linkages increases the size of the relative multipliers.

Consider the economy of Section III with sectors of potentially different sizes, input-output linkages, and price rigidities. In this general case, the vector of multipliers up to second-order terms has elements

$$\chi_k \geq (1-\lambda_k)\left[\omega_{ck} + \delta \widehat{d}_k + \delta^2 \widehat{q}_k\right]. \tag{A.21}$$

As before, ω_{ck} denotes the size of sector k, $\widehat{d}_k$ the **generalized outdegree** of sector k, and $\widehat{q}_k$ the **generalized second-order outdegree** of sector k:

$$\begin{aligned} \widehat{d}_k &\equiv \sum_{k'=1}^{K} \omega_{ck'}\left(1-\lambda_{k'}\right)\omega_{k'k}, \qquad (A.22) \\ \widehat{q}_k &= \sum_{k'=1}^{K} \widehat{d}_{k'}\left(1-\lambda_{k'}\right)\omega_{k'k}. \end{aligned}$$

These two terms embody the effects of heterogeneity of GDP shares, input-output linkages, and price rigidity across sectors.

The multiplier of idiosyncratic shocks as in the previous derivations equals $\|\chi\|_2 = \sqrt{\sum_{k=1}^{K}\chi_k^2}$, and $\sum_{k=1}^{K}\chi_k$ represents the multiplier of an aggregate shock.

Lemma 5 *If input-output linkages and sector sizes are homogeneous across sectors, that is,* $\omega_{ck} = \omega_{kk'} = 1/K$ *for all* k, k'*, but price stickiness* λ_k *is heterogeneous, then the multiplier of idiosyncratic shocks is*

$$\|\chi\|_2 = \frac{1}{K\left(1-\delta\left(1-\overline{\lambda}\right)\right)}\sqrt{\sum_{k=1}^{K}\left(1-\lambda_k\right)^2},$$

where $\overline{\lambda} \equiv \frac{1}{K}\sum_{k=1}^{K}\lambda_k$*. The multiplier is increasing in the dispersion of price stickiness across sectors. The aggregate multiplier is invariant to allowing for price dispersion. Thus, the multiplier of sectoral shocks relative to aggregate shocks is increasing in the dispersion of price rigidity.*

Proof. See Online Appendix. ■

The intuition for the previous proposition follows exactly as in Section III *B.* The next proposition considers the case in which only input-output linkages are restricted to be homogeneous.

Lemma 6 *If input-output linkages are homogeneous across sectors, that is, $\omega_{kk'} = 1/K$ for all k, k', but sector size ω_{ck} is unrestricted and prices are frictionless ($\lambda_k = 0$), then given* $\text{var}(\omega_{ck}) \geq var(1/K)$, *the multiplier of sectoral shocks relative to the aggregate shock multiplier,*

$$\frac{\sqrt{\sum_{k=1}^{K}\left(\omega_{ck} + \frac{\delta/K}{1-\delta}\right)^2}}{(1-\delta)^{-1}} \leq \sqrt{\sum_{k=1}^{K}\omega_{ck}^2},$$

is ceteris paribus smaller compared to an economy without input-output linkages, that is, ($\delta = 0$).

Proof. See Online Appendix. ■

Allowing for price stickiness ($\lambda_k > 0$) is an important case in the calibrations. We study this case next. Relative to the previous proposition, we find the introduction of heterogeneous price rigidity leads to an overall increase in the relative multiplier.

Lemma 7 *If input-output linkages are homogeneous across sectors, that is, $\omega_{kk'} = 1/K$ for all k, k', but sector size ω_{ck} is unrestricted, and price rigidity is heterogeneous ($\lambda_k > 0$), then given $\overline{\lambda} \equiv \frac{1}{K}\sum_{k=1}^{K}\lambda_k$, $\overline{\overline{\lambda}} \equiv \frac{1}{K}\sum_{k=1}^{K}\omega_{ck}\lambda_k$ the multiplier of idiosyncratic shocks relative to aggregate shocks,*

$$\frac{\|\chi\|_2}{\sum_{k=1}^{K}\chi_k} = \frac{\sqrt{\sum_{k=1}^{K}(1-\lambda_k)^2\left(\omega_{ck} + \frac{\delta\left(1-\overline{\overline{\lambda}}\right)/K}{1-\delta\left(1-\overline{\lambda}\right)}\right)^2}}{\left(1-\overline{\overline{\lambda}}\right)/\left[1-\delta\left(1-\overline{\lambda}\right)\right]},$$

is (1) increasing in the simple and weighted average of heterogeneous price rigidity across sectors, $1-\overline{\lambda}$, and $1-\overline{\overline{\lambda}}$, (2) increasing in the covariance of price rigidity and sector size, $cov((1-\lambda_k, \omega_{ck})$, and (3) increasing in the dispersion of sectoral price flexibility, λ_k.

Proof. See Online Appendix. ■

The first effect (1) is an effect due to the average degree of price rigidity in the economy. The last two effects (2) and (3) capture the effect of heterogeneity in the interaction with sector size and the dispersion of price flexibility.

IV Proofs

Most proofs below are modifications of the arguments in Gabaix (2011), Proposition 2, which rely heavily on the Levy's Theorem (as in Theorem 3.7.2 in Durrett (2013) on p. 138).

Theorem 8 (Levy's Theorem) *Suppose $X_1, ..., X_K$ are i.i.d. with a distribution that satisfies*

(i) $\lim_{x\to\infty} \Pr\left[X_1 > x\right] / \Pr\left[|X_1| > x\right] = \theta \in (0,1)$

(ii) $\Pr\left[|X_1| > x\right] = x^{-\zeta} L(x)$ *with* $\zeta < 2$ *and* $L(x)$ *satisfies* $\lim_{x\to\infty} L(tx)/L(x) = 1$.

Let $S_K = \sum_{k=1}^{K} X_k$,

$$a_K = \inf\left\{x : \Pr\left[|X_1| > x\right] \le 1/K\right\} \text{ and } b_K = K\mathbb{E}\left[X_1 \mathbf{1}_{|X_1|\le a_K}\right], \tag{A.23}$$

As $K \to \infty$, $(S_K - b_K)/a_K \xrightarrow{d} u$, *where* u *has a nondegenerated distribution.*

A. Proof of Proposition 1

In the following proofs, we go through three cases: first, when both first and second moments exist, second, when only the first moment exists, and third, when neither first nor second moments exist.

Generally, when there are no intermediate inputs ($\delta = 0$) and price rigidity is homogeneous across sectors ($\lambda_k = \lambda$ for all k),

$$\|\chi\|_2 = \frac{1-\lambda}{K^{1/2}\overline{C}_k}\sqrt{\frac{1}{K}\sum_{k=1}^{K} C_k^2}.$$

Given the power-law distribution of C_k, the first and second moments of C_k exist when $\beta_c > 2$, so

$$K^{1/2}\|\chi\|_2 \longrightarrow \frac{\sqrt{\mathbb{E}\left[C_k^2\right]}}{\mathbb{E}\left[C_k\right]}.$$

In contrast, when $\beta_c \in (1,2)$, only the first moment exists. In such cases, by the Levy's theorem,

$$K^{-2/\beta_c}\sum_{k=1}^{K} C_k^2 \xrightarrow{d} u_0^2,$$

where u_0^2 is a random variable following a Levy's distribution with exponent $\beta_c/2$ since $\Pr\left[C_k^2 > x\right] = x_0^{\beta} x^{-\beta_c/2}$.

Thus,

$$K^{1-1/\beta_c}\left\|\chi\right\|_2 \xrightarrow{d} \frac{u_0}{\mathbb{E}\left[C_k\right]}.$$

When $\beta_c = 1$, the first and second moments of C_k do not exist. For the first moment, by Levy's theorem,

$$\left(\overline{C}_k - \log K\right) \xrightarrow{d} g,$$

where g is a random variable following a Levy distribution.

The second moment is equivalent to the result above and hence

$$\left(\log K\right)\left\|\chi\right\|_2 \xrightarrow{d} u'.$$

B. Proof of Proposition 2

Let λ_k and C_k be two independent random variables distributed as specified in the Proposition, the counter-cumulative distribution of $z_k = \left(1-\lambda_k\right)C_k$ is given by

$$f_Z\left(z\right) = \int_z^{z/y_0} f_{C_k}\left(z/y\right) f_{1-\lambda_k}\left(y\right) dy,$$

which follows a Pareto distribution with shape parameter β_c. The proof of the Proposition then follows the proof of Proposition 1 for

$$\left\|\chi\right\|_2 = \frac{1}{K^{1/2}\overline{C}_k}\sqrt{\frac{1}{K}z_k^2}. \tag{A.24}$$

C. Proof of Proposition 3

As specified in the proposition, λ_k and C_k are related through $Z_k = \left(1-\lambda_k\right)C_k = \phi C_k^{1+\mu}$. When $\mu < 0$, Z_k is distributed Pareto with shape parameter $\beta_c/\left(1+\mu\right)$. Proceeding similarly steps as in the proof of Proposition 1, when $\beta_c > \max\left\{1, 2\left(1+\mu\right)\right\}$, both $\mathbb{E}\left[Z_k^2\right]$ and $\mathbb{E}\left[C_k\right]$ exist, so $v_c \sim v/K^{1/2}$. When $\beta_c \in \left(1, \max\left\{1, 2\left(1+\mu\right)\right\}\right)$, $\mathbb{E}\left[C_k\right]$ exist but $\mathbb{E}\left[Z_k^2\right]$ does not.

Applying Levy's theorem,

$$K^{-2(1+\mu)/\beta_c}\sum_{k=1}^{K} Z_k^2 \xrightarrow{d} u^2.$$

Thus, $v_c \sim \frac{u_1}{K^{1-(1+\mu)/\beta}}v$.

When $\beta_c = 1$, the last result also holds. But now $\mathbb{E}\left[C_k\right]$ does not exist. As in Proposition 1,

$\left(\frac{1}{K}\sum_{k=1}^{K} C_k - \log K\right) \xrightarrow{d} g$. Thus, if $\mu \in [-1/2, 0]$, $v_c \sim \frac{u_2}{K^{-\mu}\log K} v$, whereas if $\mu \in (-1, -1/2)$, $v_c \sim \frac{u_2}{K^{1/2}\log K} v$.

The then obtain proposition for $\mu < 0$ by rearranging terms.

When $\mu > 0$, Z_k is distributed piece-wise Pareto such that

$$\Pr\left[Z_k \geq z\right] = \begin{cases} x_0^{\beta_c} z^{-\beta_c} & \text{for } z > \phi^{-2/\mu} \\ z_0^{-\beta_c/(1+\mu)} z^{-\beta_c/(1+\mu)} & \text{for } z \in \left[z_0^2, \phi^{-2/\mu}\right]. \end{cases}$$

We now follow the same steps as in the proof of Proposition 1. When $\beta_c > 2(1+\mu)$, $\mathbb{E}\left[Z_k^2\right]$ and $\mathbb{E}\left[C_k\right]$ exist, so $v_c \sim v/K^{1/2}$. When $\beta_c \in (1, 2(1+\mu))$, $\mathbb{E}\left[C_k\right]$ exists but $\mathbb{E}\left[Z_k^2\right]$ does not. Applying Levy's theorem,

$$\frac{1}{a_K}\sum_{k=1}^{K} Z_k^2 \xrightarrow{d} u^2,$$

where

$$a_K = \begin{cases} x_0^2 K^{2/\beta_c} & \text{for } K > K^* \\ z_0^2 K^{2(1+\mu)/\beta_c} & \text{for } K \leq K^* \end{cases}$$

for $K^* \equiv x_0^{-\beta_c}\phi^{-\beta_c/\mu}$. Thus, $v_c \sim \frac{u_1}{K^{1-\frac{1+1\{K\leq K^*\}\mu}{\beta_c}}} v$ for some random variable u_1.

When $\beta_c = 1$, $\left(\frac{1}{K}\sum_{k=1}^{K} C_k - \log K\right) \xrightarrow{d} g$, so now $v_c \sim \frac{u_2}{K^{-1\{K\leq K^*\}\mu}\log K} v$ for some random variable u_2, completing the proof.

D. Proof of Proposition 4

When $\delta \in (0,1)$, $\lambda_k = \lambda$ for all k, and $\Omega_c = \frac{1}{K}\iota$, we know

$$\begin{aligned} \|\chi\|_2 &\geq \frac{1-\lambda}{K}\sqrt{\sum_{k=1}^{K}\left[1+\delta' d_k + \delta'^2 q_k\right]^2} \\ &\geq (1-\lambda)\sqrt{\frac{1+2\delta'+2\delta'^2}{K} + \frac{\delta'^2}{K^2}\sum_{k=1}^{K}\left[d_k^2 + 2\delta' d_k q_k + \delta'^2 q_k^2\right]}. \end{aligned}$$

Following the same argument as in Proposition 2,

$$K^{-2/\beta_d} \sum_{k=1}^{K} d_k^2 \longrightarrow u_d^2,$$
$$K^{-2/\beta_q} \sum_{k=1}^{K} q_k^2 \longrightarrow u_q^2,$$
$$K^{-1/\beta_z} \sum_{k=1}^{K} d_k q_k \longrightarrow u_z^2,$$

where u_d^2, u_q^2 and u_z^2 are random variables. Thus, if $\beta_z \geq 2\min\{\beta_d, \beta_q\}$,

$$v_c \geq \frac{u_3}{K^{1-1/\min\{\beta_d,\beta_q\}}} v$$

where u_3^2 is a random variable.

E. Proof of Proposition 5

Analogous to the proof of Proposition 4.

F. Proof of Proposition 5

This proposition follows from the dispersion of price stickiness across sectors and hence, the same steps as in the discussion of the granularity effect in Section III *B*.

G. Proof of Proposition 6

The proof of this proposition follows the same steps as the previous ones. Note that the inequality holds if var$(\omega_{ck} \geq 1/K$.

H. Proof of Proposition 7

This follows directly from the expression in the proposition, as well as from Jensen's Inequality.

V Distribution of the Frequency of Price Changes

Here, we report the shape parameters of the power law distribution for the frequencies of price adjustments following Gabaix and Ibragimov (2011). To do so, we compute the OLS estimator of the empirical log-counter cumulative distribution on the log sequence of the variables using the data in the upper 20% tail. The shape parameter of the sectoral distribution of frequency of price changes is 2.5773 (st dev 0.4050); that is, the distribution of the frequency of price adjustment is not fat-tailed.

Table A.1: **Multipliers of Sectoral Shocks into Aggregate Volatility: with construction**

This table reports multipliers of sectoral productivity shocks on GDP volatility , with relative multipliers in parentheses. The former are defined as the Euclidean norm of vector χ *with elements* $\chi_k = \sqrt{\sum_{\tau=0}^{\infty} \rho_{k\tau}^2}$, *The latter are relative to the multiplier of an aggregate productivity shock on GDP volatility,* $\sqrt{\sum_{\tau=0}^{\infty} \left(\sum_{k=1}^{K} \rho_{k\tau} \right)^2}$. Ω_c *represents the vector of GDP shares and* Ω *the matrix of input-output linkages. We calibrate a 341-sector version of our model to the input-output tables and sector size from the BEA and the frequencies of price adjustment from the BLS.*

			Flexible Prices		Homogeneous Calvo		Heterogeneous Calvo	
			(1)		(2)		(3)	
					Panel A: MODEL1			
(1)	hom Ω_c	hom Ω	0.0535	(5.35%)	0.0016	(5.35%)	0.0044	(11.94%)
(2)	het Ω_c	$\delta = 0$	0.1922	(19.22%)	0.0093	(19.22%)	0.0190	(32.57%)
(3)	het Ω_c	hom Ω	0.1067	(10.67%)	0.0047	(16.01%)	0.0096	(29.50%)
(4)	hom Ω_c	het Ω	0.0793	(7.93%)	0.0018	(6.02%)	0.0053	(12.89%)
(5)	het Ω_c	het Ω	0.1604	(16.04%)	0.0053	(17.88%)	0.0096	(27.87%)
					Panel B: MODEL2			
(1)	hom Ω_c	hom Ω	0.0535	(5.35%)	0.0029	(5.35%)	0.0049	(7.93%)
(2)	het Ω_c	$\delta = 0$	0.1922	(19.22%)	0.0197	(19.22%)	0.0263	(25.84%)
(3)	het Ω_c	hom Ω	0.1100	(11.00%)	0.0078	(14.49%)	0.0114	(19.72%)
(4)	hom Ω_c	het Ω	0.0773	(7.73%)	0.0034	(6.31%)	0.0061	(8.95%)
(5)	het Ω_c	het Ω	0.1614	(16.14%)	0.0093	(17.27%)	0.0125	(20.78%)
					Panel C: MODEL3			
(1)	hom Ω_c	hom Ω	0.0535	(5.35%)	0.0010	(5.35%)	0.0058	(14.83%)
(2)	het Ω_c	$\delta = 0$	0.1922	(19.22%)	0.0070	(19.22%)	0.0227	(41.68%)
(3)	het Ω_c	hom Ω	0.1067	(10.67%)	0.0032	(17.44%)	0.0112	(40.56%)
(4)	hom Ω_c	het Ω	0.0793	(7.93%)	0.0011	(5.93%)	0.0067	(15.68%)
(5)	het Ω_c	het Ω	0.1604	(16.04%)	0.0034	(18.47%)	0.0107	(36.12%)
					Panel D: MODEL4			
(1)	hom Ω_c	hom Ω	0.0535	(5.35%)	0.0027	(5.35%)	0.0069	(8.61%)
(2)	het Ω_c	$\delta = 0$	0.1922	(19.22%)	0.0195	(19.22%)	0.0319	(28.39%)
(3)	het Ω_c	hom Ω	0.1149	(11.49%)	0.0076	(15.05%)	0.0148	(22.02%)
(4)	hom Ω_c	het Ω	0.0747	(7.47%)	0.0031	(6.13%)	0.0082	(9.41%)
(5)	het Ω_c	het Ω	0.1628	(16.28%)	0.0089	(17.48%)	0.0157	(22.27%)

Table A.2: **Multipliers of Sectoral Shocks into Aggregate Volatility: Price-level Targeting**

This table reports multipliers of sectoral productivity shocks on GDP volatility, with relative multipliers in parentheses. The former are defined as the Euclidean norm of vector χ with elements $\chi_k = \sqrt{\sum_{\tau=0}^{\infty} \rho_{k\tau}^2}$, The latter are relative to the multiplier of an aggregate productivity shock on GDP volatility, $\sqrt{\sum_{\tau=0}^{\infty} \left(\sum_{k=1}^{K} \rho_{k\tau}\right)^2}$. Ω_c represents the vector of GDP shares and Ω the matrix of input-output linkages. We calibrate a 341-sector version of our model to the input-output tables and sector size from the BEA and the frequencies of price adjustment from the BLS.

			Flexible Prices		Homogeneous Calvo		Heterogeneous Calvo	
			(1)		(2)		(3)	
					Panel A: MODEL1			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0017	(5.42%)	0.0045	(12.36%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.0105	(20.47%)	0.0226	(37.18%)
(3)	het Ω_c	hom Ω	0.1126	(11.26%)	0.0054	(17.00%)	0.0114	(33.73%)
(4)	hom Ω_c	het Ω	0.0801	(8.01%)	0.0019	(6.09%)	0.0054	(13.16%)
(5)	het Ω_c	het Ω	0.1688	(16.88%)	0.0060	(18.96%)	0.0117	(31.78%)
					Panel B: MODEL1 Price-level Targeting			
(1)	hom Ω_c	hom Ω	0.0542	(5.42%)	0.0542	(5.42%)	0.0958	(9.58%)
(2)	het Ω_c	$\delta = 0$	0.2047	(20.47%)	0.2047	(20.47%)	0.3420	(34.20%)
(3)	het Ω_c	hom Ω	0.1162	(11.62%)	0.1733	(17.33%)	0.2841	(28.41%)
(4)	hom Ω_c	het Ω	0.0780	(7.80%)	0.0575	(5.75%)	0.1038	(10.38%)
(5)	het Ω_c	het Ω	0.1700	(17.00%)	0.1908	(19.08%)	0.2772	(27.72%)