MARKET STRUCTURE AND MONETARY NON-NEUTRALITY[*]

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Abstract

I study a general equilibrium menu cost model with a continuum of sectors, each consisting of strategically engaged firms. Compared to an economy with monopolistically competitive sectors parameterized to match the same data on good-level price flexibility, the duopoly economy features a smaller inflation response to monetary shocks and output responses that are more than twice as large. The model (i) requires smaller menu costs and idiosyncratic shocks to match the data, addressing a challenge for mechanisms that generate non-neutrality via *micro*-complementarities, (ii) implies four times larger welfare losses from nominal rigidities, and (iii) rationalizes small, positive, menu-costs: firms prefer a small degree of nominal rigidity. When evaluated under the same parameters, output responses are four times larger in the duopoly economy, and prices adjust half as much. Barcode-level data supports this finding, exhibiting a negative within-good, across-region relationship between wholesale-firm market concentration and price flexibility.

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1 Introduction

Golosov and Lucas (2007) demonstrate that an equilibrium version of the menu cost model of Barro (1972) implies approximate monetary neutrality when confronted with microdata. While a number of papers have since modified the framework to generate a smaller elasticity of inflation to real marginal cost following a monetary shock, these elasticities are still much larger than that implied by the estimated slope of the Phillips curve in New Keynesian models.[1] Further, complementary, mechanisms are therefore required in order to generate realistic monetary non-neutrality. This paper presents one such mechanism that is grounded in a prominent feature of the data: goods markets are concentrated. I show that integrating an oligopolistic market structure *a la* Atkeson and Burstein (2008) into the Golosov and Lucas (2007) model (henceforth GL), implies monetary business cycles that are two and a half times as large.[2]

The motivation for investigating the macroeconomic implications of oligopolistic markets is simple: product markets are highly concentrated. Figure 1 documents this fact for a broad range of narrowly defined markets: a product category (e.g., ketchup) within a state in a particular month.[3] The median effective number of wholesale firms—a measure of market concentration given by the inverse Herfindahl index—is only 3.7, and the median revenue share of the two largest firms is over two-thirds.[4] The number of firms setting prices in each market may be large, but most revenues accrue to a few. If these firms with market power set prices strategically what are the implications for monetary nonneutrality?

To answer this question I study an equilibrium menu cost model of price adjustment that accommodates a duopoly within each sector. Firms face persistent, idiosyncratic shocks, must pay a cost to change their price, and compete strategically under a Markov perfect equilibrium (MPE) concept. Aggregating a continuum of oligopolistic sectors reveals how the strategic behavior of firms affects the equilibrium response of output to monetary shocks.

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[1]Table A1 presents a meta-study of these results, showing that the implied slope of the Phillips curve λ in extensions of the menu cost model are significantly smaller than the baseline model, but still significantly larger than those required to generate monetary business cycles of the magnitude required in estimated New Keynesian models.

[2]The implied response of inflation to an increase in real marginal cost due to a monetary shock—the slope of the New-Keynesian Phillips curve—is one fourth as large (Table A1).

[3]IRI data are used to construct measures of wholesale-firm-level revenue, which are then used to construct measures of concentration. The IRI data are weekly good-level data for the universe of goods in a panel of over 5,000 supermarkets in the US from 2001 to 2011. Wholesale firms, like Kraft in the market for ketchup, are identified from the first six digits of a barcode. For a detailed description of how these measures are constructed see Appendix A.

[4]The inverse Herfindahl index (IHI) admits an interpretation of "effective number of firms" as follows. The IHI of a sector with n equally sized firms is n. Therefore, if a sector has an IHI of 2.4, then it has a Herfindahl index between that of a market with 2 and 3 equally sized firms. For more on this interpretation, see Adelman (1969). For a recent paper that uses this measure of market concentration, see Edmond, Midrigan, and Xu (2015).

I compare the dynamic oligopoly economy to a benchmark economy with a monopolistically competitive market structure in which each sector is populated with a continuum of non-strategic firms. Both models are calibrated to the same microdata on price changes and the same average markup. In these two economies with different competitive structures, but identical idiosyncratic price flexibility, the aggregate price level is less flexible under oligopoly. As a consequence, output fluctuations in response to monetary shocks are around two and half times as large.[5]

Micro- and macro-complementarities   The mechanism in the oligopoly model is based on complementarities in price setting that are unique to a dynamic Bertrand oligopoly model under costly price adjustment. Before detailing how this *dynamic complementarity* arises, it is worth noting that in general, complementarities have long been understood as crucial for monetary nonneutrality. Such complementarities come in two forms, those that introduce variable desired markups through changes to the microeconomic environment facing firms: *micro-complementarities*. Others include nominal wage rigidity, and sticky prices for intermediate inputs that slow the pass-through of monetary shock to nominal marginal costs: *macro-complementarities*. In time-dependent models, both have been successful, but in state-dependent models, only the latter have.[6]   The oligopoly model presents a successful micro-complementarity.

Success is measured obliquely by the fact that the oligopoly model achieves significant non-neutrality with smaller menu costs and idiosyncratic shocks than the monopolistically competitive model. The addition of non-CES preferences (Klenow and Willis, 2016), or decreasing returns to scale (Burstein and Hellwig, 2007) to state-dependent models have been found to moderately flatten the implied Phillips curve (Table A1), but lead firms to over respond to idiosyncratic shocks. Counter-factually large firm-level shocks and menu costs are then required for firm adjustment to be consistent with the data.[7]   On this basis, the consensus has formed that such

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[5]The real effects of monetary shocks are measured as the time series standard deviation of output in an economy with only monetary shocks. For technical reasons, in both models I assume that menu costs are random. Output fluctuations in the duopoly model are five times larger than the monopolistically competitive model with fixed menu costs.

[6]Woodford (2003, chap. 3) compares the effect of many such sources of complementarity in the New-Keynesian literature (time dependent adjustment and no idiosyncratic shocks). These include micro-complementarities such as non-CES preferences in Kimball (1995) and firm-level decreasing returns to scale in Sbordone (2002), and macro-complementarities such as round-a-bout production in Basu (1995).

[7]As well as the papers themselves, Nakamura and Steinsson (2010) and Gopinath and Itskhoki (2011) provide extensive summaries of these issues. Beck and Lein (2015) provide an exhaustive study that extends Klenow and Willis (2016) and find that even under the small departures from CES they estimate in micro-data, monthly shocks of around 22 percent are required to bring the average size of price changes back up to its value in the data. Burstein and Hellwig (2007) find that menu costs equivalent to around three percent of output are required in the decreasing returns model to bring the average frequency of price change back down to its value in the data. Like Burstein and Hellwig (2007),

micro-complementarities between firm and aggregate price cannot be a source of propagation.

The duopoly model resolves the core quantitative issue that lead to over responsiveness in the presence of micro-complementarities. Note that complementarities between the firm and aggregate price operate by small changes in the aggregate price depressing firm adjustment. Aggregate shocks are small, so these aggregate price movements are small. More pressing for the firm is the major determinant of price changes: large idiosyncratic shocks. A large positive idiosyncratic shock to costs will wash out any small aggregate shock, and, as the complementarity works in reverse, pushes the firm to adjust. But because idiosyncratic shocks are large, in the duopoly model, a firm's competitor's price movements are also large. A large positive idiosyncratic shock to costs no longer necessarily implies that the firm's adjustment probability increases. Its competitor may receive a large shock that reduces this incentive. The link between complementarity and over-responsiveness is broken, and no larger menu costs are required to get firm-level price dynamics correct. I go through this in detail in Section 5.3.

That smaller menu costs and shocks are required under oligopoly, but amplification still occurs through a form of *micro-complementarity* is, therefore, significant. Just as importantly, my mechanism neither relies on nor excludes macro-complementarities. To make this point most cleanly the macroeconomic structure of both economies are the same, and the pass-through of monetary shocks to nominal marginal costs is complete. Sticky intermediate prices and round-a-bout production as in Nakamura and Steinsson (2010), or nominal wage rigidity (also studied by Burstein and Hellwig (2007) and Klenow and Willis (2016)) could therefore be added to the model. The meta-study in Table A1 shows that such macro-complementarities get us part of the way to realistic monetary business cycles in state-dependent models, but that complementary mechanisms that are also consistent with microdata are needed. The duopoly model is one such mechanism.

Dynamic complementarity   Before describing other results, I briefly describe the particular way complementarity in prices arises in the model, and how this dampens the inflation response to a monetary shock. Crucially, I distinguish between *static complementarity*, and *dynamic complementarity*, which I explain in turn.[8]

Static complementarity arises from the fact that oligopolists understand how their price affects

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the model of Gertler and Leahy (2008) also features complementarity through increasing marginal costs, but modelled through an increasing sectoral labor supply curve.

[8]Throughout I drop the term *strategic* when discussing *strategic complementarity*, and reserve the term to distinguish between the two models: under oligopoly firms behave strategically, and under monopolistic competition firms behave competitively, or non-strategically.

household demand across sectors. In terms of the profit function of the firm, this is embodied in the fact that a firm's optimal price is increasing in the price of its direct competitor. Absent adjustment frictions, however, the Nash equilibrium price, p^*, would obtain, which is a constant markup over nominal cost. In equilibrium, absent macro-complementarities, a monetary expansion increases nominal costs one for one, causing all prices to increase one for one.

Dynamic complementarity, arises from the interaction of static complementarity with menu costs in the dynamic model, breaks the neutrality of money.[9] This is seen in the following example. Suppose two competitors—Firm A and Firm B—begin the period with prices $p_A \gg p_B > p^*$. Consider these actions: Firm A keeps its price fixed, Firm B pays the menu cost and increases its price but undercuts firm A: $p'_B \in (p_B, p_A)$. Given Firm A's inertia, static complementarity means that a price just undercutting p_A is Firm B's best response, and profitable net of the menu cost. Given Firm B's price change, the menu costs ensures that inaction is Firm A's best response. Prices are dynamic (or intertemporal) complements in that a higher (lower) p_A yields a higher (lower) p'_B and a higher (lower) value of a price increase on the equilibrium path.

How does this dynamic complementarity dampen the response of inflation to a positive monetary shock? Since households use nominal wage payments to buy goods, the complementarity will be in prices relative to the wage: $\hat{p}_A = p_A/W$ and $\hat{p}_B = p_B/W$. In equilibrium, a monetary expansion increases nominal wages W, reducing $\hat{p}_A$ and $\hat{p}_B$. This selects more firms like Firm B, with an initially low price, to increase their price, and increase it by more to compensate for the increase in cost. These *extensive* and *intensive* margin responses are large when—as they are in the data—the average size and frequency of price adjustment are large.[10] Under monopolistic competition, Firm B contributes substantially to both margins, driving the response of inflation.

Dynamic complementarity dampens the response of Firm B on both margins. The increase in the wage brings Firm A's high price into line with its costs, reducing its probability of a price cut. From Firm B's perspective, the falling relative price of its competitor $\hat{p}_A$, dampens Firm B's impulse toward a price increase. Its optimal price increase is dampened, weakening intensive margin adjustment. Its value of a price change is dampened, weakening extensive margin adjustment. A statistical decomposition of movements in inflation into intensive and extensive margin

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[9]I take the terminology of static and dynamic complementarity from Jun and Vives (2004), who study a dynamic Bertrand game with two firms and convex costs of price adjustment.

[10]This decomposition into extensive and intensive margin components in the spirit of Caballero and Engel (2007) has provided an accounting tool for this class of models and has been used by Midrigan (2011), Alvarez and Lippi (2014), and others. In Figure A1 I replicate the canonical diagrammatic representation of these margins in a monopolistically competitive fixed menu cost model.

components reveals that—relative to the competitive model—both are weakened equally in the duopoly model.

The presence of menu costs is crucial for this mechanism. Firm *B*'s desired price, and its decrease following the monetary shock, takes into account the cost Firm *A* would incur in order to later cut its price. For a given degree of *static complementarity*, the pricing setting technology determines the degree of *dynamic complementarity*, and the latter determines output fluctuations. If instead firms reprice at random, then the incentive of a firm to reprice near its competitor is weaker. This delivers the novel result that in a Calvo model the size of output fluctuations are approximately the same in both economies. This implies that (i) standard fixes to monetary neutrality that include adding Calvo-like elements to a menu-cost model may not be successful when firms behave strategically, (ii) we might not expect integrating oligopolistic markets into a standard New Keynesian model to generate larger output effects.

Other results   First, as in the baseline New Keynesian model, sticky prices distort output relative to a frictionless benchmark economy. In the oligopoly economy, these distortions are four times larger than the monopolistically competitive economy. Moreover, the distortion due to the dispersion in prices—the elimination of which is the focus of optimal monetary policy in the New Keynesian model—are the same. Nominal rigidity enables strategic firms to achieve higher markups in equilibrium, creating first order output losses that are three times larger than those due to price dispersion. Market structure therefore has implications both for the dynamics of output and its level, and the dynamic complementarity which drives these distortions markups is potentially responsive to policy.

Second, and related, the model rationalizes non-zero menu costs: the value of the firm is non-monotonic in the menu cost. Small menu costs increase dynamic complementarity, thereby increasing markups and increasing value. Large menu costs render firms unresponsive to the large idiosyncratic shocks they face, reducing value. From the firms' perspective, a value-maximizing, positive menu cost exists. The model therefore provides a novel rationale for actions that increase the cost of price adjustment, such as prices widely advertised as fixed for some period.[11]

Third, the strategic behavior of firms in the presence of menu costs generates endogenous stickiness in prices. Low-priced firms sell more, face a lower elasticity of demand, and understand this demand elasticity will increase if they raise their price. High-priced firms are reluctant to cut

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[11]For example on September 24, 2017, the price of Apple's iPhone X ($999)—a product in a clearly oligopolistic market—was available on its website. The product was not available for purchase until November 3, 2017.

prices, since a high price softens competition within the sector, and encourages their competitor to choose a high price. The oligopoly model therefore requires 25 percent smaller menu costs as a fraction of revenue, and slightly smaller idiosyncratic shocks, in order to match the same data on price adjustment. When comparing market structures under the *same* parameters, I find that prices are twice as sticky under duopoly.

Finally, I provide some empirical support for this prediction using variation across markets that plausibly have similar primitives. I exploit variation in market concentration and price flexibility that exists across US states, within narrow product-categories, controlling for market revenue. Using barcode level revenue from the IRI data, I compute wholesale firm market concentration and price flexibility in each product-state-quarter (see footnote to Figure 1).[12] The within-product-quarter, across-region correlation between price flexibility and wholesale firm concentration is consistent with the causal implications of the model. In relative terms, prices are less flexible in markets with a lower concentration.[13]

Further related literature   The model is situated in two distinct literatures: (i) papers following Golosov and Lucas (2007) that have studied whether menu cost models of price adjustment can explain monetary non-neutrality, and (ii) dynamic games of price setting with adjustment frictions.

I have already discussed the existing literature that introduces complementarity into the GL framework. A prominent alternative is presented by Midrigan (2011) and Alvarez and Lippi (2014), who show that once the model accounts for small price changes, output responses similar to a Calvo model of price adjustment can be obtained.[14] I show that the oligopoly model cannot be operating through this channel, by simply observing that the distribution of desired and realized price changes under both market structures are nearly identical.[15] Section 5.4 carefully

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[12]Goldberg and Hellerstein (2013), Eichenbaum, Jaimovich, and Rebelo (2011) and Nakamura and Zerom (2010) study retail and wholesale prices, and find that pass-through is almost complete from wholesale to retail. This implies that price flexibility computed using retail data should reflect price flexibility in the unobserved wholesale prices. It also implies that the correct measure of market concentration is among wholesalers (e.g. Kraft vs Hellmans in Mayonnaise in Ohio) instead retailers (e.g. WholeFoods vs Wegmans).

[13]This is consistent with Barro and Tenreyo (2006), who find that within manufacturing, relative output prices, a measure of markups, are more counter-cyclical in more concentrated sectors.

[14]Midrigan (2011) and Alvarez and Lippi (2014) achieve this through multiproduct firms with economies of scope in price changes. However Midrigan (2011) shows that the precise mechanism used to account for small price changes is inconsequential: a single-product model with random menu costs that matches the same distribution of price changes as the multi-product model can also deliver large output responses.

[15]Both models therefore share the same sufficient statistics for an output response to a monetary shock as derived by Alvarez, LeBehin, and Lippi (2016). That they in fact generate very different output responses reinforces that models with complementarity, with variable desired markups, are not a subject of these sufficient statistics.

differentiates the model from those cited here and above.

The industrial organization literature established that nominal rigidities induce dynamic complementarity in prices when markets are oligopolistic. Maskin and Tirole (1988b) first make this point. They show that in an environment with exogenous short-run commitment to prices, MPE strategies can accommodate prices above the frictionless equilibrium. Lapham and Ware (1994) extend this result to a quadratic game and Jun and Vives (2004) to a differential game with general convex costs of adjustment. These papers establish the difference between *static complementarity*—due to the static profit function—and *dynamic complementarity* due to the combination of static complementarity and pricing frictions.[16] Future menu costs commit a firm to a high price once they increase it, and a higher price softens conditions for its competitor, eliciting a similarly high price.

These papers provide a theoretical foundation for dynamic complementarity, but abstract from the elements common to quantitative general equilibrium macroeconomic models of price setting. In particular, firms face large idiosyncratic costs and small fixed costs of adjustment, such that—as opposed to convex costs—large price cuts are not more costly. In such an uncertain environment is there room for dynamic complementarity to play a significant role in pricing decisions, and in a way that impacts macroeconomic outcomes? The answer provided by this paper is, yes.

The most closely related papers at the microeconomic level are Nakamura and Zerom (2010) and Neiman (2011). Both study single sector, partial equilibrium, oligopolistic models of price setting under menu costs. The former studies three firms subject to a sectoral shock to the cost of inputs, but no idiosyncratic cost shocks. I show that idiosyncratic shocks are important for creating the types of sectors—with initially dispersed markups—that most depress the response of the aggregate price level.[17] The latter studies two firms subject only to idiosyncratic shocks, and focuses on how one firm responds to a shock to its competitor, instead of how both firms respond to a common shock, like a monetary shock.

This paper complements and significantly expands on the applicability of these papers. First, by integrating the standard elements of a macroeconomic equilibrium menu cost model: a continuum of sectors, large idiosyncratic shocks, aggregate uncertainty. Second, by providing an exhaustive comparison of the model to the monopolistically competitive benchmark, and study-

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[16]Note that dynamic complementarity is sometimes referred to as intertemporal strategic complementarity.

[17]Additionally, sectors with initially very similar markups either over-respond (when their markups are low) or do not respond at all (when their markups are high). Adding only these sectors together would result in a response similar to the monopolistically competitive model.

ing the model under alternative price-setting technologies. Third, by assessing the consequences of the interaction of strategic firms and pricing frictions for output and firm value.

More generally, this paper demonstrates that the strategic interaction of firms can be quantitatively important for the cyclicality of macroeconomic aggregates. This should be of broad interest given increasing concentration in many sectors of the US economy, which recent empirical work has associated with numerous trends.[18]

Outline Section 2 presents the model. Section 3 describes the main mechanism using simulations of the model. Section 4 presents the calibration. Section 5 presents the main results, decomposition exercise, robustness, and distinguishes the results from the papers discussed above. Section 6 shows how nominal rigidities distort output. Section 7 presents the empirical results. Section 8 concludes. An Appendix contains—among other details—further discussion of model assumptions, and theoretical results for a simple one-period duopoly price-setting game under menu costs.

2   Model

Time is discrete. There are two types of agents: households and firms. Households are identical, consume goods, supply labor, and buy shares in a portfolio of all firms in the economy. Firms are organized in a continuum of sectors indexed $j \in [0, 1]$. Each sector contains two firms indexed $i \in \{1, 2\}$. Goods are differentiated first across, then within sectors. Good ij is produced by a single firm operating a technology with constant returns to scale in labor. Aggregate uncertainty arises from shocks to the growth rate g_t of the money supply M_t, and idiosyncratic uncertainty arises from shocks to preferences for each good z_{ijt}. Each period every firm draws a menu cost $\xi_{ijt} \sim H(\xi)$ and may change their price p_{ijt} conditional on paying ξ_{ijt}.

I write agents' problems recursively, such that the time subscript t is redundant. The aggregate state is denoted $\mathbf{S} \in \mathcal{S}$. The sectoral state is denoted $s \in S$. The measure of sectors with state s is given by $\lambda(s, \mathbf{S})$. When integrating over sectors, I integrate s over $\lambda(s, \mathbf{S})$ rather than j over $U[0, 1]$.

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[18] Autor, Dorn, Katz, Patterson, and Reenen (2017) show that across sectors, declines in the labor share are correlated with increases in concentration. Gutierrez and Philippon (2016) show that the decline in the predictive power of Tobin's Q for aggregate investment is due to sectors that have experienced large increases in concentration. de Loecker and Eeckhout (2017) provide evidence for increasing average markups, which may also be linked to increasing concentration.

2.1 Household

Given prices for all goods in all sectors $p_i(s, \mathbf{S})$, wage $W(\mathbf{S})$, price of shares $\Omega(\mathbf{S})$, aggregate dividends $\Pi(\mathbf{S})$, the distribution of sectors $\lambda(s, \mathbf{S})$, and law of motion for the aggregate state $\mathbf{S}' \sim \Gamma(\mathbf{S}'|\mathbf{S})$, households' policies for consumption demand for each good in each sector $c_i(s, \mathbf{S})$, labor supply $N(\mathbf{S})$, and share demand $X'(\mathbf{S})$, solve

$$\mathbf{W}(\mathbf{S}, X) = \max_{c_i(s), N, X'} \log C - N + \beta \mathbb{E}\Big[\mathbf{W}(\mathbf{S}', X')\Big],$$

$$\text{where} \quad C = \left[\int_S \mathbf{c}(s)^{\frac{\theta-1}{\theta}} d\lambda(s, \mathbf{S})\right]^{\frac{\theta}{\theta-1}},$$

$$\mathbf{c}(s) = \left[\Big(z_1(s)c_1(s)\Big)^{\frac{\eta-1}{\eta}} + \Big(z_2(s)c_2(s)\Big)^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta-1}{\eta}},$$

subject to the nominal budget constraint

$$\int_S \Big[p_1(s, \mathbf{S})c_1(s) + p_2(s, \mathbf{S})c_2(s)\Big] d\lambda(s, \mathbf{S}) + \Omega(\mathbf{S})X' \leq W(\mathbf{S})N + \Big(\Omega(\mathbf{S}) + \Pi(\mathbf{S})\Big)X.$$

Households discount the future at rate β, have time-separable utility, and derive period utility from consumption adjusted for the disutility of work, which is linear in labor.[19] Utility from consumption is logarithmic in a CES aggregator of consumption utility from the continuum of sectors. The cross-sector elasticity of demand is denoted $\theta > 1$. As in Atkeson and Burstein (2008), utility from sector j goods is given by a CES utility function over the two firms' goods. The within-sector elasticity of demand is denoted $\eta > 1$. These elasticities are ranked $\eta > \theta$. The household is more willing to substitute goods within a sector (Pepsi vs. Coke) than across sectors (soda vs. laundry detergent). Finally, household preference for each good is subject to a shifter $z_i(s)$ that evolves according to a random walk,

$$\log z_i'(s') = \log z_i(s) + \sigma_z \varepsilon_i', \quad \varepsilon_i \sim \mathcal{N}(0, 1). \tag{1}$$

The shock ε_i' is independent over firms, sectors, and time.

The solution to the household problem consists of demand functions for each firm's output $c_i(s, \mathbf{S})$, a labor supply function $N(\mathbf{S})$, and an equilibrium share price $\Omega(\mathbf{S})$ which will be used to price nominal firm payoffs. Demand functions are given by

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[19] A parameter controlling the utility cost of labor can be normalized to one, so is not included.

$$c_i(s, \mathbf{S}) = z_i(s)^{\eta-1} \left(\frac{p_i(s, \mathbf{S})}{\mathbf{p}(s, \mathbf{S})} \right)^{-\eta} \left(\frac{\mathbf{p}(s, \mathbf{S})}{P(\mathbf{S})} \right)^{-\theta} C(\mathbf{S}), \tag{2}$$

$$\text{where} \quad \mathbf{p}(s, \mathbf{S}) = \left[\left(\frac{p_1(s, \mathbf{S})}{z_1(s)} \right)^{1-\eta} + \left(\frac{p_2(s, \mathbf{S})}{z_2(s)} \right)^{1-\eta} \right]^{\frac{1}{1-\eta}},$$

$$P(\mathbf{S}) = \left[\int_S \mathbf{p}(s, \mathbf{S})^{1-\theta} d\lambda(s, \mathbf{S}) \right]^{\frac{1}{1-\theta}}.$$

Aggregate real consumption is $C(\mathbf{S})$. The allocation of $C(\mathbf{S})$ to sector s depends on the level of the sectoral price $\mathbf{p}(s, \mathbf{S})$ relative to the aggregate price $P(\mathbf{S})$. The allocation of expenditure to firm i is then determined by $z_i(s)$ and the level of firm i's price relative to $\mathbf{p}(s, \mathbf{S})$.

The aggregate price index satisfies $P(\mathbf{S})C(\mathbf{S}) = \int_S [p_1(s, \mathbf{S})c_1(s, \mathbf{S}) + p_2(s, \mathbf{S})c_2(s, \mathbf{S})] \, d\lambda(s, \mathbf{S})$, such that $P(\mathbf{S})C(\mathbf{S})$ is equal to aggregate nominal consumption. I assume that aggregate nominal consumption must be paid for using money $M(\mathbf{S})$ such that $M(\mathbf{S}) = P(\mathbf{S})C(\mathbf{S})$ in equilibrium.[20] Nominal money supply is exogenous. Its growth rate $g' = M'/M$ evolves as follows:

$$\log g'(\mathbf{S}') = (1 - \rho_g) \log \bar{g} + \rho_g \log g(\mathbf{S}') + \sigma_g \varepsilon_g', \quad \varepsilon_g' \sim \mathcal{N}(0, 1). \tag{3}$$

Hence, the nominal economy is trend stationary around $\bar{g}$. An intratemporal condition determines labor supply and Euler equation prices shares under the nominal discount factor $Q(\mathbf{S}, \mathbf{S}')$:

$$W(\mathbf{S}) = P(\mathbf{S})C(\mathbf{S}), \tag{4}$$

$$\Omega(\mathbf{S}) = \mathbb{E}\left[Q(\mathbf{S}, \mathbf{S}') \left(\Omega(\mathbf{S}') + \Pi(\mathbf{S}') \right) | \mathbf{S} \right], \quad Q(\mathbf{S}, \mathbf{S}') = \beta \frac{P(\mathbf{S})C(\mathbf{S})}{P(\mathbf{S}')C(\mathbf{S}')}. \tag{5}$$

2.2 Firms

I consider the problem for firm i, denoting its direct competitor $-i$. The sectoral state vector s consists of previous prices p_i, p_{-i} and current preferences z_i, z_{-i}. Within a period, information and timing are as follows. After these states are revealed, both firms, independently, draw a menu cost for the period ξ_{ij} from the known distribution $H(\xi)$. I make the additional assumption, discussed below, that these draws are private information. At the same time as its competitor, firm i then chooses whether to adjust its price, $\phi_i \in \{0, 1\}$, and if changing its price, changes it to p_i^*. Prices are then revealed, firms produce the quantity demanded by households, and preference shocks evolve (z_i, z_{-i}) to (z_i', z_{-i}'). Within a period, all moves are simultaneous, and firms do not respond to each other's new price: $p_i' = \phi_i p_i^* + (1 - \phi_i) p_i$.

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[20] An alternative assumption is that money enters the utility function as in Golosov and Lucas (2007). As noted in that paper, if utility is separable, the disutility of labor is linear, and the utility of money is logarithmic, one obtains the same equilibrium conditions studied here.

When determining its actions, firm i takes as given the policies of its direct competitor: $\phi_{-i}(s, \mathbf{S}, \xi_{-i})$, and $p^*_{-i}(s, \mathbf{S})$. Since menu costs are sunk, $p^*_{-i}(s, \mathbf{S})$ is independent of ξ_{-i}. This description of the environment explicitly restricts firm policies to depend only on payoff relevant information $(s, \mathbf{S})$, that is, they are *Markov strategies*. A richer dependency of policies on the history of firm behavior is beyond the scope of this paper.[21]

Let $V_i(s, \mathbf{S}, \xi_i)$ denote the present discounted expected value of nominal profits of firm i after the realization of the sectoral and aggregate states $(s, \mathbf{S})$ and its menu cost ξ_i. Then $V_i(s, \mathbf{S}, \xi_i)$ satisfies the following recursion:

$$
V_i(s, \mathbf{S}, \xi_i) = \max_{\phi_i \in \{0,1\}} \phi_i \left[V_i^{adj}(s, \mathbf{S}) - W(\mathbf{S})\xi_i \right] + (1 - \phi_i)V_i^{stay}(s, \mathbf{S}), \tag{6}
$$

$$
V_i^{adj}(s, \mathbf{S}) = \max_{p_i^*} \int \left[\phi_{-i}(s, \mathbf{S}, \xi_{-i}) \left\{ \pi_i\left(p_i^*, p^*_{-i}(s, \mathbf{S}), s, \mathbf{S}\right) + \mathbb{E}\left[Q(\mathbf{S}, \mathbf{S}')V_i\left(s'_{adj}, \mathbf{S}', \xi_i'\right)\right] \right\} \right.
$$

$$
\left. + \left(1 - \phi_{-i}(s, \mathbf{S}, \xi_{-i})\right) \left\{ \pi_i\left(p_i^*, p_{-i}, s, \mathbf{S}\right) + \mathbb{E}\left[Q(\mathbf{S}, \mathbf{S}')V_i\left(s'_{adj}, \mathbf{S}', \xi_i'\right)\right] \right\} \right] dH(\xi_{-i}),
$$

$$
\pi_i\left(p_i, p_{-i}, s, \mathbf{S}\right) = d_i\left(p_i, p_{-i}, s, \mathbf{S}\right)\left(p_i - z_i(s)W(\mathbf{S})\right),
$$

$$
s'_{adj} = \phi_{-i}(s, \mathbf{S}, \xi_{-i}) \times (p_i^*, p^*_{-i}(s, \mathbf{S}), z_i', z_{-i}') + \left(1 - \phi_{-i}(s, \mathbf{S}, \xi_{-i})\right) \times (p_i^*, p_{-i}, z_i', z_{-i}')
$$

$$
\mathbf{S}' \sim \Gamma\left(\mathbf{S}'|\mathbf{S}\right).
$$

The first line states the extensive margin problem, where adjustment requires a payment of menu cost ξ_i in units of labor. The value of adjustment is independent of the menu cost and requires choosing a new price p_i^*. The firm integrates out the unobserved state of its competitor—the menu cost ξ_{-i}—and takes as given the effect of its competitor's pricing decisions on current payoffs and future states. The term in braces on the second (third) line gives the flow nominal profits plus continuation value of the firm if its competitor does (does not) adjust its price. Non-adjustment value $V_i^{stay}(s, \mathbf{S})$ and state s'_{stay} are identical, up to $p_i^* = p_i$.

The above flow payoff introduces a role for $z_i(s)$ in costs. As in Midrigan (2011) and Alvarez and Lippi (2014), I assume that $z_i(s)$— which increases demand for the good with an elasticity of $(\eta - 1)$ — also increases total costs with a unit elasticity. This technical assumption, discussed below, will enable me to reduce the state space of the firm's problem, a crucial step to maintain

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[21]In the words off Maskin and Tirole (1988a), "Markov strategies...depend on as little as possible, while still being consistent with rationality." Rotemberg and Woodford (1992) study an oligopoly with arbitrary history dependence of policies but no nominal rigidity or idiosyncratic shocks. Implicit collusion leads to countercyclical markups: the value of deviating from collusion increases when demand is high, reducing the level of the markup that the trigger strategies can sustain.

computational tractability of the model.[22]

The household's nominal discount factor $Q(\mathbf{S}, \mathbf{S}')$ is used to discount future nominal profits, and expectations are taken with respect to both the equilibrium transition density $\Gamma(\mathbf{S}'|\mathbf{S})$ and firm-level shocks. Through the household's demand functions $d_i(p_i, p_{-i}, s, \mathbf{S})$, nominal profit depends on aggregate consumption $C(\mathbf{S})$ and the aggregate price index $P(\mathbf{S})$, which the firm takes as given.

That menu costs are sunk and *iid* allows for a number of simplifications. Since p^*_{-i} is independent of ξ_{-i}, firm i need only know the probability that its competitor changes its price: $\gamma_{-i}(s, \mathbf{S}) = \int \phi_{-i}(s, \mathbf{S}, \xi_{-i}) dH(\xi_{-i})$. Since ξ_i is *iid*, it can be integrated out of firm i's Bellman equation. These observations imply that ξ_i is not a state:

$$V_i(s, \mathbf{S}) = \int \max \left\{ V_i^{adj}(s, \mathbf{S}) - W(\mathbf{S})\xi_i, V_i^{stay}(s, \mathbf{S}) \right\} dH(\xi_i), \tag{7}$$

$$V_i^{adj}(s, \mathbf{S}) = \max_{p^*_i} \ \gamma_{-i}(s, \mathbf{S}) \left\{ \pi_i\left(p^*_i, p^*_{-i}(s, \mathbf{S}), s, \mathbf{S}\right) + \mathbb{E}\left[Q(\mathbf{S}, \mathbf{S}')V_i(s', \mathbf{S}')\right] \right\}$$
$$+ \left(1 - \gamma_{-i}(s, \mathbf{S})\right) \left\{ \pi_i\left(p^*_i, p_{-i}, s, \mathbf{S}\right) + \mathbb{E}\left[Q(\mathbf{S}, \mathbf{S}')V_i(s', \mathbf{S}')\right] \right\}.$$

Given $p^*_{-i}(s, \mathbf{S})$ and $\gamma_{-i}(s, \mathbf{S})$, the solution to this problem delivers firm i's optimal price adjustment $p^*_i(s, \mathbf{S})$ and probability of price adjustment $\gamma_i(s, \mathbf{S}) = H[(V^i_{adj}(s, \mathbf{S}) - V^i_{stay}(s, \mathbf{S}))/W(\mathbf{S})]$.

2.3 Equilibrium

Given the above, the aggregate state vector $\mathbf{S}$ must contain the level of nominal demand M, its growth rate g, and distribution of sectors over sectoral state variables λ. A *recursive equilibrium* is

  (i) Household demand functions $d_i(p_i, p_{-i}, s, \mathbf{S})$

 (ii) Functions of the aggregate state: $W(\mathbf{S})$, $N(\mathbf{S})$, $P(\mathbf{S})$, $C(\mathbf{S})$, $Q(\mathbf{S}, \mathbf{S}')$

(iii) Law of motion $\Gamma(\mathbf{S}, \mathbf{S}')$ for the aggregate state $\mathbf{S} = (g, M, \lambda)$

(iv) Firm value functions $V_i(s, \mathbf{S})$ and policies $p^*_i(s, \mathbf{S})$, $\gamma_i(s, \mathbf{S})$

such that

 (a) Demand functions in (i) are consistent with household optimality conditions (2).

 (b) The functions in (ii) are consistent with household optimality conditions (4).

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[22]This assumption does not change the underlying economics of the problem. In reality, idiosyncratic demand or productivity shocks may lead firms to change prices. In the model, under constant returns to scale and homothetic preferences, the two enter symmetrically. The fundamental idea that a firm increases (decreases) its price when its price is too low (high) relative to some benchmark, holds under either demand or productivity shocks. Importantly, the aggregate shock is only to nominal demand.

(c) Given functions (i), (ii), (iv), and competitor policies; p_i^*, γ_i, and V_i are consistent with firm i optimization and Bellman equation (7).

(d) Aggregate price $P(\mathbf{S})$ equals the household price index under $\lambda(s, \mathbf{S})$, $p_i^*(s, \mathbf{S})$ and $\gamma_i(s, \mathbf{S})$.

(e) Nominal aggregate demand satisfies $P(\mathbf{S})C(\mathbf{S}) = M(\mathbf{S})$.

(f) The household holds all shares ($X(\mathbf{S}) = 1$) and the price of shares is consistent with (4).

(g) The law of motion for g and path for M are determined by (3).

(h) The law of motion for λ is consistent with firm policies and (1). Let $X = P_1 \times P_2 \times Z \times Z \in \mathbb{R}_+^4$, and the corresponding set of Borel sigma algebras on X be given by $\mathcal{X} = \mathcal{P}_1 \times \mathcal{P}_2 \times \mathcal{Z}_1 \times \mathcal{Z}_2$. Then $\lambda : \mathcal{X} \to [0,1]$ and obeys the following law of motion for all subsets of $\mathcal{X}$:[23]

$$\lambda'(\mathcal{X}) = \int_X \mathbb{E}_{\gamma_1(s,\mathbf{S}),\gamma_2(s,\mathbf{S})} \mathbf{1}\left\{(p_1^*(s,\mathbf{S}), p_2^*(s,\mathbf{S})) \in \mathcal{P}_1 \times \mathcal{P}_2\right\} \mathbb{P}\left[z_1' \in \mathcal{Z}_1 | z_1\right] \mathbb{P}\left[z_2' \in \mathcal{Z}_2 | z_2\right] d\lambda(s,\mathbf{S}).$$

This contributes an extension of the standard definition of a recursive competitive equilibrium: firms are competitive with respect to firms in other sectors of the economy, but strategic with respect to firms in their own sector. Condition (c) requires that these strategies constitute an MPE.

2.4 Monopolistic competition and monopoly

The monopolistically competitive model is identical to the above, but where firm i belongs to a continuum of firms $i \in [0,1]$ in sector j. The demand system is identical to (2), but where $\mathbf{p}_j(\mathbf{S}) = [\int (p(s,\mathbf{S})/z(s))^{1-\eta} d\lambda_j(s,\mathbf{S})]^{1/(1-\eta)}$. Since firms are competitive, they take $\mathbf{p}_j(\mathbf{S})$ as given. The idiosyncratic state of the firm is therefore its own z_i and past price p_i. Moreover, since sectors are homogeneous in parameters, and the law of large numbers applies for each sector, then the distribution of firms λ_j is the same in all sectors. Therefore $\mathbf{p}_j(\mathbf{S}) = \mathbf{p}_k(\mathbf{S})$ for all j and k, and $P(\mathbf{S}) = \mathbf{p}_j(\mathbf{S})$. The cross-sector elasticity of demand θ is therefore absent from the firm problem and all equilibrium conditions.

Note the connection between monopolistic competition and another market structure: sectoral monopoly. Under monopoly, the sectoral price index is the monopolist's price, and the within-sector elasticity of demand η is redundant. Sectoral monopolistic competition under $(\theta, \eta) = (\theta_{mc}, x)$ will therefore be identical in firm and aggregate dynamics to sectoral monopoly with $(\theta, \eta) = (x, \eta_m)$ for any values of θ_{mc} and η_m.

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[23]In this definition, $\mathbb{E}_{\gamma_1(s,\mathbf{S}),\gamma_2(s,\mathbf{S})}[f(s,\mathbf{S})]$ is the expectation of f under the sector s probabilities of price adjustment.

2.5 Markups

A sectoral MPE, nested in a macroeconomic equilibrium, is computationally infeasible with four continuous state variables. However, under my assumptions regarding idiosyncratic shocks, it may be restated in terms of markups, which are the ratio of nominal price to nominal marginal cost: $\mu_{ij} = p_{ij}/(z_{ij}W)$. Similarly, I define the sectoral markup $\mu_j = \mathbf{p}_j/W$ and aggregate markup $\mu = P/W$. Along with (2), these definitions imply $\mu_j = [\mu_{1j}^{1-\eta} + \mu_{2j}^{1-\eta}]^{1/(1-\eta)}$, and $\mu = [\int_0^1 \mu_j^{1-\theta} dj]^{1/(1-\theta)}$.

Expressed in markups and normalized by the wage, the profit of the firm is

$$\pi_i\left(\mu_i, \mu_{-i}, \mathbf{S}\right)/W(\mathbf{S}) = \tilde{\pi}_i\left(\mu_i, \mu_{-i}\right)\mu(\mathbf{S})^{\theta-1}, \quad \tilde{\pi}_i\left(\mu_i, \mu_{-i}\right) = \mu_i^{-\eta}\mu_j\left(\mu_i, \mu_{-i}\right)^{\eta-\theta}\left(\mu_i - 1\right), \quad (8)$$

which implies that complementarity in prices carries over to complementarity in markups.[24] Value functions can also be normalized. Let $v(s, \mathbf{S}) = V(s, \mathbf{S})/W(\mathbf{S})$, then

$$v_i\left(\mu_i, \mu_{-i}, \mathbf{S}\right) = \int \max\left\{v_i^{adj}\left(\mu_i, \mu_{-i}, \mathbf{S}\right) - \xi_i, v_i^{stay}\left(s, \mathbf{S}\right)\right\}dH(\xi_i), \quad (9)$$

$$v_i^{adj}\left(\mu_i, \mu_{-i}, \mathbf{S}\right) = \max_{\mu_i^*} \gamma_{-i}(\mu_i, \mu_{-i}, \mathbf{S})\left\{\tilde{\pi}_i\left(\mu_i^*, \mu_{-i}^*(\mu_i, \mu_{-i}, \mathbf{S})\right)\mu(\mathbf{S})^{\theta-1} + \beta\mathbb{E}\left[v_i\left(\frac{\mu_i^*}{g'e^{\varepsilon_i'}}, \frac{\mu_{-i}^*(\mu_i, \mu_{-i}, \mathbf{S})}{g'e^{\varepsilon_{-i}'}}, \mathbf{S}'\right)\right]\right\}$$

$$+ \left(1 - \gamma_{-i}(\mu_i, \mu_{-i}, \mathbf{S})\right)\left\{\tilde{\pi}_i\left(\mu_i^*, \mu_{-i}\right)\mu(\mathbf{S})^{\theta-1} + \beta\mathbb{E}\left[v_i\left(\frac{\mu_i^*}{g'e^{\varepsilon_i'}}, \frac{\mu_{-i}}{g'e^{\varepsilon_{-i}'}}, \mathbf{S}'\right)\right]\right\}.$$

This renders the firm problem stationary and clarifies the mechanics of the shocks. A random walk idiosyncratic shock ε_i' is a permanent *iid* shock to the markup of firm i should the firm not adjust its price. A single positive innovation to money growth causes equilibrium nominal marginal cost to increase, which reduces both firms' markups. As money growth returns to $\bar{g}$ at rate ρ_g, the markup continues to decline. Firm i pays a real cost ξ_i to adjust its markup.

In this way, all equilibrium conditions can be stated in markups. Note that aggregate consumption is $C(\mathbf{S}) = 1/\mu(\mathbf{S})$. An increase in the money supply causes an equilibrium increase in wages, reducing all firms' markups. If all prices do not increase one for one with wages, the real wage increases, labor supply increases, and output increases.

A solution for the equilibrium involves the function $\mu(\mathbf{S})$, requiring the infinite dimensional distribution $\lambda\left(\mu_i, \mu_{-i}\right)$ as a state variable. To make the problem tractable, I follow the lead of Krusell and Smith (1998). Since I already need to specify a price function for μ, a convenient choice of moment to characterize λ is last period's aggregate markup, μ_{-1}. The following then serves as both pricing function and law of motion for the approximate aggregate state:

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[24]When μ_{-i} is large, the effect of a change in μ_i on $\mu_j(\mu_i, \mu_{-i})$ is larger: $\partial\mu_j/\partial\mu_i = (\mu_j/\mu_i)^\eta$. Since $\eta > \theta$, then $\tilde{\pi}_i$ is increasing in μ_j. Combined, these imply that the cross-partial derivative of $\tilde{\pi}_i$ is positive.

$$\mu\left(\mu_{-1}, g\right) = \exp\left(\bar{\mu} + \beta_1(\log \mu_{-1} - \log \bar{\mu}) + \beta_2(\log g - \log \bar{g})\right).$$

Applying this to (9) verifies that the approximate aggregate state consists of $\mathbf{S} = (\mu_{-1}, g)$. Appendix B provides more details on the solution of the firm problem and equilibrium.

Appendix D discusses a number of modeling assumptions: CES preferences, structure of idiosyncratic shocks, and random menu costs and their information structure. Following the insight of Doraszelski and Satterthwaite (2010), this last assumption is made to accommodate a solution in pure strategies. A model with fixed costs would yield mixed strategy equilibria, becoming computationally infeasible. In Appendix C, I prove a number of results for a one-period game of price adjustment with a fixed menu cost, equal initial prices, and a general profit function with complementarity. For any menu cost, even in this simple setting, there is always a range of initial prices for which multiple equilibria exist (see Figure A2).

3   Illustrating the mechanism

To understand the dynamics of markups in the two models of market structure, I consider an exercise that corresponds to the central experiment in Golosov and Lucas (2007). Idiosyncratic shocks are present, but inflation and aggregate shocks are zero, and I study the response to a one-time unforeseen increase in money in period τ ($g_\tau > 0$, $\rho_g = 0$). Firms assume that the aggregate markup remains at its steady-state level.

Both models are solved under full idiosyncratic risk, and then simulated under particular paths of shocks chosen for illustrative purposes. The parameters of each model are those estimated in Section 4, Table 1.

3.1   Monopolistic competition

Figure 2 describes the behavior of firms in the monopolistically competitive model. Black (grey) lines describe a firm that, from period five onward, has received a string of positive (negative) idiosyncratic shocks. For $t < 5$, firms draw zero menu costs, and for $t \geq 5$, both firms draw large menu costs such that their prices do not adjust.[25] Thin solid lines in panel A plot the evolution

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[25]Specifically, I set $\mu_{i0} = \mu_{-i0}$ to some arbitrary initial markup. I then set $\xi_{it} = \xi_{-it} = 0$ and $\varepsilon_{it} = \varepsilon_{-it} = 0$ for $t \leq 5$ and use the firms' policies to evolve (μ_{it}, μ_{-it}), this means firms quickly adjust to $\bar{\mu}$ that satisfies $\bar{\mu} = \mu_i^*(\bar{\mu}, \bar{\mu})$. From $t = 6$ onwards I choose the realizations of the menu cost $\xi_{it} = \xi_{-it} = \bar{\bar{\xi}}$ such that prices do not adjust. I choose the realizations of the idiosyncratic shocks $\varepsilon_{it} = \bar{\varepsilon}$ and $\varepsilon_{-it} = -\bar{\varepsilon}$, such that one firms markup steadily increases, and the other decreases. I then plot $\mu_i^*(\mu_{it}, \mu_{-it})$ and $\gamma_i(\mu_{it}, \mu_{-it})$. This should make clear that the firms policies are solved under full idiosyncratic uncertainty, and—for illustrative purposes—I am only choosing the realized path for

of each firm's markup absent the increase in money supply. Dashed lines in panel A describe the optimal reset markup of each firm μ_{it}^*. Since μ_{it} is payoff irrelevant once the firm decides to change its price, the reset markup is constant and the same for both firms. Thin lines in panel B plot the firm's probability of adjustment $\gamma_{it} = \gamma(\mu_{it})$.

The thick lines in Figure 2 describe the response to a permanent increase in the money supply in period 40 which, absent adjustment, reduces both firms' markups. The low-markup firm's probability of adjustment increases as its markup moves away from its reset value. The size of its optimal adjustment increases by ΔM, accommodating the entire increase in aggregate nominal cost. The high-markup firm moves closer to its reset value, its probability of adjustment falls, and its size of adjustment falls by ΔM. The firms' optimal markups are unaffected by the shock.[26]

As detailed by Golosov and Lucas (2007), this behavior sharply curtails the real effects of the monetary expansion. The distribution of adjusting firms shifts toward those with already low prices. These are firms that are increasing their prices and now by larger amounts. Monetary neutrality owes to the behavior of these firms with low markups and a high probability of adjustment that are *marginal* with respect to the shock.

3.2   Duopoly

I now repeat this exercise in the duopoly model for two firms in the same sector. The firms differ both in their policies absent the shock and in their response to the shock. These differences are due to the interaction of menu costs and complementarity in prices that arise in the duopoly model.

Static complementarity   Prices are *static complements* when the cross-partial derivative of a firm's profit function ($\tilde{\pi}_{12} > 0$) is positive. Economically, this is the case for two reasons: (i) firms are strategic, so they understand how their price affects the sectoral price, and (ii) the household has a lower ability to substitute across sectors than within sectors. As μ_2 increases, firm 1 sells to more of the market. Because of (i), firm 1 understands that this changes its demand elasticity. Because of (ii), the elasticity it faces falls, encouraging a higher markup. A high μ_2 encourages a high μ_1 and vica-versa, yet if both firms had identical high markups, then absent a cost of downward adjustment, both undercut each other such that only the frictionless Nash equilibrium $\mu_1 = \mu_2 =$

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the simulation.

[26]Since the shock to money growth is not persistent, the optimal markup of the firm does not change. If $\rho_g > 0$, then the optimal markup would itself increase, as the firm understands that knowing that future positive money growth will wear down its markup in consecutive periods.

μ^* would be attainable. Figure 3A plots the static best response function of firm 1: $\mu_1^*(\mu_2)$.[27]

Dynamic complementarity   In an MPE with zero menu costs, static complementarity does not imply monetary non-neutrality. The best-response function may be upward sloping but $\mu_1^*(\mu_1, \mu_2) = \mu^*$, is independent of μ_1 and μ_2. An increase in money supply which reduces $\mu_i' < \mu_i$ for both firms at the start of the period, will be complete offset as both firms jump back to μ^*.

In the presence of menu costs, however, properties of the static upward sloping best-response function surface in the MPE policies of the firm. In particular, μ_1^* is not independent of (μ_1, μ_2). As we will see in Figure 4, a high μ_2 at the start of the period—due to either past actions or the accumulation of current and past idiosyncratic and aggregate shocks—elicits a high equilibrium response of firm 1 within the period. Just like the static best response, a low-priced firm adjusts to a price that is below but close to its high-priced competitor. Prices are *dynamic complements* in that, in equilibrium, increases in the pre-determined state-variable of one firm elicits an increasing response from its competitor.[28]

Menu costs, are small though—in my model they will represent around 0.1 percent of revenue— Figure 3 uses static profit functions to provide an intuition for why even small menu costs may sustain such strategies. While the static best response $\mu_1^*(\mu_2)$ is to undercut μ_2 (Panel A), it does not substantially increase firm 1's profit above what is obtained if it could only commit to $\mu_1 = \mu_2$ (Panel B). Small values of menu costs punish downward deviations from high prices, and since both firms want high prices conditional on their competitor having a high price ($\pi_{12} > 0$), this is enough to sustain markups and profits that are higher than those that occur at the frictionless Nash equilibrium μ^*. Figure 4 uses a simulation to draw out the policy functions in the dynamic model that achieve this.

Appendix C provides a number of theoretical results for a one-period game with a fixed menu cost where (μ_1, μ_2) are given. For any menu cost and general profit function with $\pi_{12} > 0$, I show that (i) there exists a set of initial markups $\mu_1 = \mu_2 > \mu^*$, such that the Nash equilibrium involves no adjustment, and (ii) for initial markups that are very high, the only equilibrium involves both firms paying the menu cost and choosing μ^*. Thus positive menu costs can only sustain limited

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[27] In Appendix C I show that the best response function in a static, frictionless model under CES preferences with $\eta > \theta$ is upward sloping with a slope less than one. This implies that if μ_{-i} is greater than the frictionless Nash equilibrium markup μ^*, then the static best response of firm i is to undercut: $\mu_i^*(\mu_{-i}) \in (\mu^*, \mu_j)$. Figure A6 provides— around the calibrated values of θ and η—comparative statics of the best response function with respect to η, and other features of the profit function.

[28] I take this language from Jun and Vives (2004), who differentiate between static and dynamic complementarity in the MPE of dynamic oligopoly models of Cournot and Bertrand competition with convex costs of adjustment.

deviations from the equilibrium under no menu costs. This will also be a feature of the dynamic model.

Steady-state policies   Returning to the simulation exercise, Figure 4 confirms that the reset markups $\mu_i^*(\mu_i, \mu_j)$ are no longer equal, and the low-markup (grey) firm sets μ_{it}^* to below, but near, that of its competitor. Choosing a high reset markup and high probability of adjustment discourages undercutting by the high markup (black) firm. This maintain's the grey firm's market share in the short run while supporting a high sectoral price in the long run. The menu costs faced by the black firm rationalizes its low probability of a price cut as a best response to the grey firm's policy.

In this way, the firms' policies in the non-cooperative MPE sustain markups substantially above the frictionless Bertrand-Nash equilibrium, even in the presence of large idiosyncratic shocks. Note, however, that the size of this wedge is limited. Figure 3B shows that in terms of flow profits, higher initial markups increasingly invite undercutting: $\tilde{\pi}_1(\mu_1^*(\mu_2), \mu_2)) - \tilde{\pi}_1(\mu_2, \mu_2)$ increases as μ_2 exceeds μ^*. In Figure 4A, this is reflected in the flattening out of the grey firm's reset markup. If the grey firm adjusted to an even higher markup, the menu cost would be insufficient to dissuade the black firm from cutting its price.

The fact that firms know the distribution of costs of price change faced by their competitor, is key to these policies. In a Calvo model, firm adjusts at random. As I show below, the MPE of a Calvo model features less dynamic complementarity: when the price adjustment of its competitor is random the grey firm's optimal markup is less dependent on the black firm's. This will lead the duopoly model to generate similar output responses under menu costs and Calvo.

Response to monetary shock   Dynamic complementarity leads the duopoly model to respond differently to the monopolistically competitive model following a monetary shock. The desired price increase at the low-markup firm still jumps to cover the increase in aggregate nominal cost, but this is tempered by the decline in its competitor's markup. The equilibrium best response of the marginal firm is increasing in the initial markup of the inframarginal firm, so with a lower markup at the inframarginal firm, the optimal markup of the marginal firm falls. With a lower markup at its competitor, the increase in the value of a price change is also dampened since any price increase will be met with lower, more elastic demand.[29] In the example of Figure 4, the

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[29]For completeness, consider the symmetric case of a negative money supply shock. The nominal wage falls and—conditional on non-adjustment—markups increase. The marginal firm now has the high markup and considers decreasing its markup, while the shock has increased the markup of its competitor. The increasing markup at its competitor shifts the marginal firm's demand curve out and lowers its elasticity, reducing the value of a price decrease and its

probability and size of price adjustment at the marginal firm increase by half as much as they do in Figure 2.[30]

Monetary non-neutrality occurs because price adjustment at marginal firms is weakened by the falling relative price at inframarginal firms. Figure 4 provides a stark example, considering firms with markups below and above their reset markups. In Section 5.2 I show that these are exactly the types of sectors that drive the slow response of inflation. Figures A3 and A4 repeat the above experiment for sectors with two initially low markups. Here duopolists over respond relative to two monopolistically competitive firms with low prices. With both firms' probability of adjustment increasing, the firms increase their prices by more than ΔM in order to encourage a high price from their competitor. A full understanding of the real effects of monetary shocks in a model with oligopolistic sectors therefore requires two key features of my model: (i) many sectors and (ii) idiosyncratic shocks (which generate within sector markup dispersion).

4 Calibration

Both models are calibrated at a monthly frequency with $\beta = 0.95^{1/12}$. I follow the same procedure as Midrigan (2011) for calibrating the persistence and size of shocks to the growth rate of money: $\rho_g = 0.61$, $\sigma_g = 0.0019$.[31] I set $\log \bar{g} = 0.0021$ to replicate 2.5 percent average inflation in the US from 1985 to 2016. The final parameter set externally is the cross-sector elasticity θ which I set to 1.5, consistent with Nechio and Hobijn (2017), one of the few studies to provide empirical estimates of upper-level demand elasticities.[32]

The same set of parameters remain in both models: (i) within-sector elasticity of substitution η, (ii) size of idiosyncratic shocks σ_z, (iii) distribution of menu costs. I assume menu costs are uniformly distributed $\xi_{ijt} \sim U\left[0, \bar{\xi}\right]$ and refer to $\bar{\xi}$ as the menu cost. These parameters are chosen to match the average absolute size and frequency of price change in the IRI data, as well as a

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optimal size.

[30]Note the small increase in μ_{it}^* at the high markup firm. Increasing μ_{it}^* encourages its competitor to choose a high markup conditional on adjustment, which is now a more likely event.

[31]Specifically, I take monthly time series for M1 and regress $\Delta \log M1_t$ on current and 24 lagged values of the monetary shock series constructed by Romer and Romer (2004). I then estimate an AR(1) process on the predicted values. The coefficient on lagged money growth is $\rho_g = 0.608$, with standard error 0.045. The standard deviation of residuals gives σ_g.

[32] Edmond, Midrigan, and Xu (2015) estimate $\theta = 1.24$ and $\eta = 10.5$ in a static oligopoly model with trade. In their quantitative application Atkeson and Burstein (2008) choose θ "close to one" and $\eta = 10$. When estimating within-sector elasticities of substitution, it is common practice in industrial organization to assume that $\theta = 1$ such that preferences are Cobb-Douglas across sectors (for an example, see Hottman, Redding, and Weinstein (2014)). Meanwhile Cobb-Douglas preferences across sectors ($\theta = 1$) are commonly used in trade models, for example Gaubert and Itskhoki (2016) and references therein.

measure of the average markup.[33]

As shown by Golosov and Lucas (2007), matching these first two moments severely constrains the ability of the monopolistically competitive menu cost model to generate sizeable output fluctuations. A large average size of price change implies that the additional low-markup firms adjusting after a monetary shock will have large positive price changes. If prices change frequently, then the increase in nominal cost is quickly incorporated into the aggregate price index. The average absolute log size of price change (conditional on price change) is 0.10, and the average frequency of price change is 0.13.[34] Below, in Table 4, I show that second, third, and fourth moments of the distributions of price changes in both models are also similar.

The third moment, the average markup, is motivated two ways. First, note that the duopolist faces an overall elasticity of demand between θ and η, since it does not take the sectoral markup as given. Therefore, if η and θ were the same in both models, then the lower demand elasticity facing the duopolist would be a force toward less frequent price adjustment, requiring a significantly lower menu cost to match the data. Calibrating to the same average markup means the elasticity of demand faced by firms in both models is approximately the same. Below in Figure 8, I show that the shape of the profit functions in both models are essentially the same when fixing other prices.

Second, equating average markups equates average profits. A ranking of calibrated menu costs is therefore preserved when transformed into the ratio of menu costs to profits, which is an economically more meaningful measure. I can therefore make statements regarding the price stickiness endogenously generated by each model by simply comparing the calibrated menu costs. Note that by calibrating both models to match the same frequency of price change, there is no role for any such endogenous price stickiness in the comparison of aggregate dynamics. The spirit of the experiment is to control for price flexibility with respect to idiosyncratic shocks and examine the differential response to aggregate shocks.

I target an average markup of $\mathbb{E}[\mu_{it}] = 1.30$, which forms the consensus of a range of stud-

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[33]The parameter η has an overwhelming effect on the average markup. Given a value of η, one can match the size and frequency of price change by changing $\bar{\xi}$ and σ_z. Conditional on η, the argument for identification of σ_z and $\bar{\xi}$ is the same as Vavra (2014), Berger and Vavra (2013), and others. Let $x_{it} = \left| \log \left(\mu_{it}^* / \mu_{it} \right) \right|$. Increasing $\bar{\xi}$ lowers adjustment probabilities for any x_{it}, lowering frequency of price change. The average size of price change increases since x_{it} will on average be larger by the time the firm adjusts. Increasing σ_z increases frequency of price change, since any large value of x_{it} now occurs more often. The average size of price change increases since more frequent adjustment is costly, leading the firm to wait until x_{it} is larger before adjusting. As shown by Barro (1972), this argument leads to exact identification in a continuous time, fixed menu cost model.

[34]Appendix A details the construction of these measures from IRI data, noting here that I exclude sales and small price changes that may be deemed measurement error.

ies using various techniques. In their estimation of markups across 50 sectors, Christopoulou and Vermeulen (2008) find an average markup in the US of 1.32. For the US auto industry, Berry, Levinsohn, and Pakes (1995) estimate an average markup of 1.31. For retail goods, Hottman (2016) estimates an average markup between 1.29 and 1.33. For Compustat firms, de Loecker and Eeckhout (2017) estimate an average markup between 1.20 and 1.30 for the pre-1990 period.

The choices of θ and $\mathbb{E}[\mu_{it}]$ are designed to be conservative with respect to the degree of complementarity in the model. Macroeconomic models with monopolistic competition are commonly calibrated to a lower average markup around 1.20. Since θ is already above the value used in most multi-sector models, this would require a higher η, implying stronger complementarities and larger output fluctuations.[35] Lowering θ toward values commonly used $\theta \approx 1$ in multi-sector models would increase the average markup, requiring a further increase in η, increasing $\eta - \theta$, and again implying stronger complementarities.

The first two columns of Table 1 provide baseline calibrations Duo_I and MC_I. The calibration exercise successfully delivers two models that have the same good-level price dynamics. The remaining columns provide alternative calibrations of the monopolistically competitive model, which are referred to below.

Menu costs are lower in the duopoly model. The upper bound $\bar{\xi}$ is lower, and given that average markups are the same and $H(\xi_i)$ is uniform, the average menu cost draw is also lower as a fraction of profits which is the economically meaningful measure when thinking about firm pricing decisions. As a further benchmark, total menu costs paid are 0.105 (0.076) percent of total revenue in MC_I (Duo_I), which are a little more than the 0.04 percent average *Physical cost* as a fraction of revenue reported in Zbracki et. al. (2004).[36]

Before moving on to comparing aggregate-price dynamics, I first compare the MC_I and MC_{II} parameterizations of the monopolistically competitive model to demonstrate the importance of ensuring that Duo_I and MC_I match the same microdata on price adjustment. In MC_{II} the monopolistically competitive model is evaluated at the Duo_I parameters. MC_{II}, with a higher η, lower $\bar{\xi}$ and smaller σ_z, features more frequent and smaller price adjustments than MC_I. With more flexible firm-level prices, output fluctuations—as measured by the standard deviation of log aggregate

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[35]See references in previous footnote 32.

[36]See their Table 5. When including *Managerial costs* and *Physical costs*, total costs amount to 1.22 percent of revenue. This latter statistic is widely used to benchmark menu cost models. Total menu costs paid are 0.522 (0.455) percent of total profits in MC_I (Duo_I), which are a little less than the *Physical cost* as a percentage of *Net margin* in Zbracki et. al. (2004) Table 5.

consumption $\sigma(\log C_t)$—are half as large (0.06 vs. 0.13).[37] The calibration strategy therefore works toward comparatively less, rather than more, amplification in the duopoly model. This predicts that when comparing markets with similar parameters but different market concentration, prices should be far more flexible when there are many similarly sized firms. In Section 7 I verify this prediction using across-region variation in price-flexibility within the same wholesale goods category.

5 Aggregate dynamics

Table 1 delivers the main result of the paper, which is that fluctuations in output are around 2.4 times larger in the duopoly model (0.31 vs. 0.13).[38] Figure 5A plots the impulse response of aggregate consumption to a one standard deviation shock to money growth, computed via local projection.[39] Panel B shows that the cumulative response is also more than twice as large in the duopoly model (0.83 vs. 0.36).

These results can be compared with other papers that study the neutrality of money in extensions of the Golosov and Lucas (2007) model. Output fluctuations are slightly larger than in the multiproduct model of Midrigan (2011) ($\sigma(\log C_t) = 0.29$). The ratio of $\sigma(\log C_t)$ under duopoly to monopolistic competition is also larger than what Nakamura and Steinsson (2010) find when comparing single and multisector menu cost models (a ratio of 1.82 compared to 2.38 here).[40] I

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[37]The standard deviation of log consumption is a common summary statistic for the output effects of monetary shocks in the menu cost models cited in Section 1. Specifically, $\sigma(\log C_t)$ is equal to the standard deviation of HP-filtered deviations of log of consumption from its value in an economy in which $g_t = \bar{g}$.

[38]The monopolistically competitive model under random menu costs generates larger output fluctuations than under a fixed menu cost. Calibrated to the same data, a fixed menu cost model delivers $\sigma(\log C_t) = 0.06$ This difference is for the reason discussed extensively in Midrigan (2011): random menu costs generate some small price changes, dampening the extensive margin response of inflation—or selection effect—following a monetary shock.

[39]Impulse response functions in this section are computed as follows, an approach that is econometrically equivalent to the approach used by Jorda (2005). The economy is simulated for 5,000 periods with aggregate and idiosyncratic shocks. Given the known time series of aggregate shocks to money growth ε_t^g, the horizon τ IRF is $IRF_\tau = \sum_{s=0}^{\tau} \hat{\beta}_\tau$, where $\hat{\beta}_\tau$ is estimated from OLS on $\Delta \log C_t = \alpha + \beta_\tau \varepsilon_{t-\tau}^g + \eta_t$. The benefits of computing the IRF in this manner are (i) it is exactly what one would compute in the data if the realized path of monetary shocks was known, which is consistent with the approach that uses identified monetary shocks from either a narrative or high-frequency approach (Gertler and Karadi, 2015); (ii) it avoids the time-consuming approach of simulating the model many times, as is usually done in heterogeneous agents models with aggregate shocks; and (iii) it averages out any state dependence which might bias the results from computing an IRF from a specific state, as well as any non-linearity in the size of the response following positive / negative and small / large shocks; (iv) Berger, Caballero, and Engel (2017) extensively assess the benefits of this approach in accurately capturing the persistence of aggregate dynamics in lumpy adjustment models. To the best of my knowledge this is the first paper to consider this as the baseline computational approach for the impulse response.

[40]See their Table VI (first row, first two columns). On the lower end, this ratio is 1.63 when comparing single and multisector versions of the Calvo+ model (a menu cost model where $\xi > 0$ with probability α and $\xi = 0$ with probability $(1 - \alpha)$. On the high end, this ratio is 2.00 when comparing single and multisector versions of the standard menu cost model. In general, the Calvo+ framework increases output responses but does not further amplify the effect of the

therefore add a new and realistic feature to the class of models with menu costs and idiosyncratic shocks—markets are concentrated—and move the model toward the large real effects of monetary shocks found in the data, and does so without deviating away from estimates of the empirical size of menu costs or idiosyncratic shocks.

Importantly, the duopoly mechanism does not exclude existing approaches. So while no existing approach alone generates the real effects of monetary shocks observed in the data, they may be combined in ways that could. For example, the *macro-complementarity*—that slows the pass-through of monetary shocks to aggregate marginal cost—studied in Nakamura and Steinsson (2010) would operate independently of the *micro-complementarity* studied here. See Table A1 for further comparisons and the model's implied slope of the Phillips curve.

5.1 Verifying the mechanism I: Impulse responses

To check whether the intuition from Section 3 holds in the full model, I study the response of the average absolute size and frequency of price change for low- and high-markup firms following a positive monetary shock. Figure 6 shows that the broad dynamics of both models are the same. Low-markup firms adjust more (panel A), and the size of their price change increases (panel B). High-markup firms adjust less, and the size of their price change falls. However, both the frequency and size of price change of low-markup firms respond by less in the duopoly model. Idiosyncratic shocks may increase or decrease their competitor's markup but the aggregate shock implies that *on average* their competitor's markup falls, reducing the value of a price increase and the optimal price conditional on adjustment.

Observe that the average size of price changes at high-markup firms falls by less in the duopoly model. The increase in probability of upward adjustment by their low-markup competitor, reduces the incentive for high-markup firms to decrease their price. This would be a force toward a larger increase in inflation response in the duopoly model. However, the falling probability of adjustment for high markup firms implies that this reduction in the size of optimal downward adjustment is rarely incorporated into the aggregate price index.

5.2 Verifying the mechanism II: Decomposing inflation

The response of inflation can be more formally decomposed into an extensive and intensive margin response, and these margins compared across sectors of the economy. I follow the spirit of the

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macro-complementarity.

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theoretical decomposition in Caballero and Engel (2007), which can be applied to a wide class of lumpy adjustment models.[41]

Consider two simulations of the model, where the model has been *solved* in the presence of aggregate shocks. In one simulation, aggregate shocks are set to zero leaving only trend inflation. A second simulation features identical draws of idiosyncratic shocks, but includes a single shock to the money growth at date t. Denote by $\Delta \bar{p}_t$ the log change in the aggregate price index in the first simulation and by $\Delta \hat{p}_t$ the same statistic in the simulation with the shock. Inflation due to the shock is $\pi_t = \Delta \hat{p}_t - \Delta \bar{p}_t$. Let $x_{it} = \log p_{it}^* - \log p_{it-1}$ denote the desired log price change of firm i, and γ_{it} denote the probability of price change. Then $\Delta p_t \approx N^{-1} \sum_{i=1}^{N} \gamma_{it} x_{it}$. This implies the following decomposition of inflation:

$$\pi_t \approx N^{-1} \sum_{i=1}^{N} \underbrace{\bar{\gamma}_{it} \left(\hat{x}_{it} - \bar{x}_{it} \right)}_{\text{1. Intensive}} + \underbrace{\bar{x}_{it} \left(\hat{\gamma}_{it} - \bar{\gamma}_{it} \right)}_{\text{2. Extensive}} + \underbrace{\left(\hat{\gamma}_{it} - \bar{\gamma}_{it} \right) \left(\hat{x}_{it} - \bar{x}_{it} \right)}_{\text{3. Covariance}}. \tag{10}$$

Panel A of Table 2 provides this decomposition for each of the two models. The first two lines show that in both models, inflation is generated roughly equally by adjustment on the intensive and extensive margins. The main result from the previous section was that inflation responds by more in the monopolistically competitive model, producing smaller output effects. Panel B shows that the difference in inflation is roughly equally accounted for by decreases in all margins of adjustment.

Panel C accounts for these differences across the distribution of sectors. For example, the bottom left entry states that 9 percent of the difference in the intensive margin of adjustment can be accounted for by sectors in which both firms have markups above the median markup.[42]

Panel C quantifies the earlier claim that sectors with dispersed markups due to accumulated large idiosyncratic shocks account for the difference between the two models (this ex-post fact motivated the simulations studied in Section 3). By extension, this implies that the presence of independent idiosyncratic shocks—a key feature of the menu-cost literature in monetary economics—is important. Beyond the study of general equilibrium, comparison of oligopoly and monopolistic

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[41]See Figure A1 for a diagrammatic representation of this decomposition in a monopolistically competitive model with fixed menu costs.

[42]In these experiments, the realizations of random numbers used to generate the simulations are the same across models. Two firms in one sector in the duopoly model therefore have two corresponding, but unrelated, firms in the monopolistically competitive model. The different parameters of each model map random numbers into different idiosyncratic shocks and menu costs, but the underlying random numbers are the same for each of these pairs. In each model, these pairs of firms are then assigned to quadrants of the distribution of markups according to their markups relative to the median markup.

competition, and welfare results, idiosyncratic shocks differentiate the sectoral model from Naka-mura and Zerom (2010).

Since this is central to the results, Appendix D provides some support for the importance of these shocks. For large firms (e.g. Kraft in the Mayonnaise market in Ohio), changes in revenue are mostly due to changes in their revenue share within their sector, as opposed to changes in the revenue share of the sector within the region—as would be the case with sectoral shocks—or total regional spending—as would be the case with regional shocks.

Panel C also shows that sectors with low markups contribute substantially toward greater aggregate price flexibility (recall Figure A4). In the oligopoly model with menu costs the presence of static complementarity does not uniformly imply more aggregate price stickiness, and leads some sectors to over adjust. Quantitatively, however, the dispersed markup sectors shape the aggregate inflation response for two reasons. First, there are simply twice as many sectors with low-and-high markups than low-and-low markups. Second, there is little difference in the behavior of sectors with two initially high markups.

5.3 Robustness

State-dependent price setting The central result of Golosov and Lucas (2007) is that a monopo-listically competitive menu cost model exhibits far greater neutrality under menu costs than Calvo. Table 3 verifies this remains the case under random menu costs. Under a Calvo price setting technology where the exogenous frequency of price adjustment α and σ_z are calibrated to match the size and frequency of adjustment, output fluctuations in the monopolistically competitive model are nearly three times larger under Calvo (0.38 vs 0.13). However, this is not the case for the duopoly model: output fluctuations are only 30 percent larger under Calvo (0.41 vs. 0.31).[43]

This has two significant implications. First, adding Calvo-like elements to amplify the real effects of monetary shocks is not a solution to monetary non-neutrality when firms behave strategically. Second, changing market structures *within* the Calvo model will have negligible effects (0.41 vs. 0.38).

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[43]Table 3 also reveals that the duopoly model accounts for around three-quarters of the difference between monopo-listically competitive Calvo and menu cost models. This comparison may seem unwarranted. However, a feature of the literature has been to ask whether state-dependent models can deliver output fluctuations as large as time-dependent models. For example, in Midrigan (2011), a Golosov-Lucas model delivers $\sigma(C_t) = 0.07$, a Calvo model $\sigma(C_t) = 0.35$, and the author's benchmark multiproduct model $\sigma(C_t) = 0.29$. The main result is that the multiproduct model generates real effects of monetary shocks that are 78 percent as large as a Calvo model. In my case this number is around 75 percent.

What drives this result? Monetary non-neutrality in the menu-cost duopoly model is due to the amount of dynamic complementarity that the pricing friction generates. When a firms know—even imperfectly—the cost their competitor must pay to change their price, in equilibrium it reprices close to its competitor (recall Figure 4). When a firm knows that its competitor will change their price at random—as under Calvo—, the incentive of a low-priced firm to reprice close to its competitor is weakened. The attenuation of the intensive margin response to a monetary shock is therefore no longer as powerful as under time-dependent pricing.

This raises a general point that should broaden the interest in this class of pricing complementarity. As opposed to other popular forms of micro-complementarity, which I describe next, the amount of dynamic complementarity depends not on one parameter but on the whole environment. In particular, it is not invariant to changes in policy or technologies. Table 3 provides one relevant example, and leaves open how changes in trend inflation, size of monetary shocks, and other features may weaken or strengthen the amount of complementarity.

Demand elasticity An alternative strategy for calibrating the elasticity of demand would have been to choose η such that markups in a frictionless economy coincided exactly.[44] In Appendix C I derive the familiar frictionless markups in each model under Bertrand competition:

$$\mu^*_{Duo} = \frac{\frac{1}{2}\left(\eta_{Duo} + \theta\right)}{\frac{1}{2}\left(\eta_{Duo} + \theta\right) - 1}, \quad \mu^*_{MC} = \frac{\eta_{MC}}{\eta_{MC} - 1}.$$

Under the baseline calibration $\eta_{Duo_I} = 10.5$, which implies $\mu^*_{Duo_I} = 1.20$ (Table 1, Duo_I). This is substantially less than the observed average markup, a point I return to below. Setting $\mu^*_{MC} = \mu^*_{Duo_I}$, therefore requires $\eta_{MC} = 6$. Calibration MC_{III} in Table 1 uses $\eta_{MC_{III}} = 6$ and a higher value of the menu cost in order to match the same moments. The real effects of monetary shocks are the same as in the baseline MC_I. Calibration MC_{IV} considers the extreme case of $\eta_{MC_{IV}} = \eta_{Duo_I} = 10.5$, but even then, after recalibrating parameters, $\sigma(\log C_t)$ is unaffected.

Figure 7 shows that this holds across $\eta_{MC} \in [2, 10]$, or equivalently, $\mu^*_{MC} \in [1.11, 2.00]$. Solid lines describe the monopolistically competitive model under different values of η_{MC}, each time recalibrating the menu cost (panel A) to best match the data (panel B).[45] Dashed lines describe the

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[44]Such an approach is appealing. Benchmarking models in the absence of nominal rigidity is better situated to ask *"How do the affects of nominal rigidity depend on market structure?"* This is closer to the spirit of Maskin and Tirole (1988b), Jun and Vives (2004) and Lapham and Ware (1994), who—in models without shocks—ask how *introducing* exogenous price stickiness may affect the pricing of oligopolists.

[45]This is imperfect, but very close, since for Figure 7 I leave σ_z fixed at its value under MC_I.

same economies but with the menu cost fixed at $\eta_{MC_{III}} = 0.29$. In all cases, $\sigma(\log C_t) \approx 0.13$. It does not matter which monopolistically competitive economy—indexed by η_{mc}—I compare the duopoly model to, so long as it is calibrated to match the same moments. Put differently, larger output fluctuations can not obtained by simply giving *more market power to monopolistically competitive firms*.[46]

5.4   Alternative extensions of Golosov and Lucas (2007)

Previous extensions of Golosov and Lucas (2007) aim to reduce monetary neutrality by (i) changing the *macroeconomic* environment to introduce complementarities between aggregate nominal cost and the aggregate price level, (ii) changing the *microeconomic* environment to introduce complementarities between the firm's price and the aggregate price level, a category this paper fits into, (iii) increasing the kurtosis in the distribution of desired price changes. Significantly, (i) and (iii) are complements, not substitutes to the duopoly mechanism, while, as I discuss, efforts so far toward (ii) have been unsuccessful. Below I verify that the difference between the monopolistically competitive model and the duopoly model is not some form of existing extension.

(i) Macro-complementarity   First, and most simply, the macroeconomic environment of the duopoly and monopolistically competitive model are the same: pass-through of M_t to aggregate nominal cost W_t is immediate in both cases. Since this is the case, I do not compare the model to those that reduce aggregate price flexibility by altering the *macroeconomics* of the model in order to slow the pass-through of M_t to nominal marginal costs. Features such as nominal wage rigidity (Klenow and Willis, 2016) or round-a-bout production—in which nominal cost depends on prices in other sectors which themselves are sticky (Nakamura and Steinsson, 2010)—would slow this pass-through and lead to larger output responses in both the monopolistically competitive and duopoly models. Quantitatively, such *macroeconomic complementarities* have been shown to significantly reduce monetary neutrality, but for reasonable calibrations still imply a steep Phillips Curve.[47]   The finding of significant monetary non-neutrality from the duopoly model therefore

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[46]Alvarez, LeBehin, and Lippi (2016) prove that to a second order approximation, the real effects of small monetary shocks in monopolistically competitive menu cost models will be equal provided they match the same frequency, average absolute size, and kurtosis of price changes. Changing the elasticity of demand while recalibrating the model ensures that these statistics are the same. One can therefore interpret Figure 7 as demonstrating that their theorems hold in a model without any such approximations, and under the empirical size of monetary shocks.

[47]For example, Nakamura and Steinsson (2010) find that the integration of the Basu (1995) round-a-bout production model into a Golosov and Lucas (2007) framework yields a 1.8 times large standard deviation of $\log C_t$. Burstein and Hellwig (2007) find that reduced form wage rigidity of the form $W_t = Y_t^{\gamma} M_t$, with $\gamma = 0.8$, can double the

complements, rather than substitutes, these studies. Importantly my results give pause to the prior conclusion of Nakamura and Steinsson (2010), Klenow and Willis (2016) and Burstein and Hellwig (2007) that *macro-complementarities* are the only type of complementarity able to both (i) generate significant monetary non-neutrality in a menu cost model, (ii) be consistent with micro-data on price adjustment for reasonable parameter values. I turn to this next.

(ii) Micro-complementarity   As noted by Nakamura and Steinsson (2010), *"monetary economists have long relied heavily on complementarity in price setting to amplify monetary non-neutrality generated by nominal rigidities."* Indeed this is the conclusion of Woodford (2003, chap. 3). In a monopolistically competitive menu cost model, such complementarity may be introduced between the firm's price and the aggregate price level through alternative preferences or technology.[48] Yet as they summarize, these approaches *"render the [menu-cost] model unable to match the average size of micro-level price changes for plausible parameter values"*, and *"cast doubt on [micro-]complementarity as a source of amplification."*[49] The duopoly model is an alteration of the micro-economic environment so fits under this categorization of micro-complementarity. It amplifies output responses to the same order as the macro-complementarities mentioned above. It does so at smaller menu costs and smaller idiosyncratic shocks. To understand the simple way that the model avoids these issues, I first discuss these existing approaches, how they slow inflation, why they require large menu costs and shocks, and then how my model differs.

   Features   What are these features that deliver complementarity? First, Kimball (1995) preferences, as studied by Klenow and Willis (2016) and Beck and Lein (2015), imply variable marginal revenue. When the quantity a firm sells decreases, its elasticity of demand increases, as one could understand from the following reduced form demand function:

$$\frac{y_i}{Y} = \left(\frac{\mu_i}{\mu}\right)^{-\eta \exp\left(\chi \log\left(\frac{\mu_i}{\mu}\right)\right)}, \quad \chi \geq 0. \tag{11}$$

Second, a decreasing returns to scale technology (DRS), as studied by Burstein and Hellwig (2007), implies variable marginal cost. When the quantity a firm sells decreases, its marginal cost de-

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size of the output response to a monetary shock. These and others, including Gertler and Leahy (2008) who study complementarity in a model without idiosyncratic shocks, are included in Table A1.

   [48]The sufficient statistics of ABL, which I discuss next, do not apply to these models, since, due to complementarity, the aggregate price has a first order effect on firm profits.

   [49]For a similar discussion and summary see Gopinath and Itskhoki (2011) p.270, who refer to these complementarities as *real rigdities*: *"[These studies] conclude that the levels of real rigidity sufficient to generate significant monetary nonneutrality have implausible implications for the required size of menu costs and idiosyncratic productivity shocks"*.

creases:[50]

$$mc_i = \Omega \frac{y_i^{\chi}}{z_i W}, \quad \chi \geq 0. \tag{12}$$

In both cases, χ controls the degree of complementarity, and a decrease in y_{it} decreases desired price through either a higher demand elasticity, or lower marginal cost.

Amplification These models of variable markups amplify a positive monetary shock as follows. Consider a firm with a relatively low markup of μ_{it} and an optimal markup of $\mu_{it}^* > \mu_{it}$. Since prices are sticky, an increase in the money supply leads to a decline in the aggregate markup: μ_t falls to $\mu_t' < \mu_t$. Is μ_{it}^* still the firm's optimal markup? With $(\mu_{it}^*/\mu_t') > (\mu_{it}^*/\mu_t)$, the firm would sell a lower quantity at μ_{it}^* under μ_t'. In the Kimball (DRS) model, this increases the elasticity of demand (decreases marginal cost) at μ_{it}^*, implying a lower optimal markup $\mu_{it}^{*\prime} < \mu_{it}^*$. So as χ is increased, low-priced firms reduce their desired markup following a monetary expansion, slowing inflation. Large departures from monetary neutrality can be achieved by increasing χ.

Issue But increasing χ also affects firm responsiveness to idiosyncratic shocks. Consider the same firm's response to a decrease in z_{it} to $z_{it}' < z_{it}$, decreasing (μ_{it}/μ_t), which increases output. In the Kimball (DRS) model, this decreases the elasticity of demand (increases marginal cost) at μ_{it}, increasing the value of a price increase. As χ is increased, low-priced firms become more responsive to negative idiosyncratic shocks.

Quantitatively, most price changes are due to idiosyncratic shocks, which are large, not aggregate shocks, which are small, which makes this over-responsiveness to idiosyncratic shocks a serious issue for the calibration of the model. Specifically, Klenow and Willis (2016) and Burstein and Hellwig (2007) find that values of χ that reduce monetary neutrality, require large menu costs and idiosyncratic shocks in order to match the same data on good-level price adjustment.[51] This leads to the previously quoted conclusion of Nakamura and Steinsson (2010).

Solution In the duopoly model amplification occurs due to complementarity, but at even lower $\bar{\xi}$ and σ_z than the monopolistically competitive model. Why does the model avoid the issues in the existing literature? Under DRS or Kimball and monopolistic competition, a large negative shock to μ_{it} will almost always cause (μ_{it}/μ_t) to fall sharply, since shocks to μ_t are small. In my model, a large negative shock to μ_{it} may cause (μ_{it}/μ_{-it}) to rise or fall, depending on the shock to

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[50]If $y_i = z_i^{\alpha} n_i^{\alpha}$, then $\chi = (1 - \alpha)/\alpha$, and $\Omega = 1/\alpha$.

[51]Klenow and Willis (2016) find that the standard deviation of shocks at a monthly frequency would need to be 28 percent to accommodate $\chi = 10$, which delivers amplification similar to my main result. In an exhaustive study of the menu-cost model under Kimball preferences, Beck and Lein (2015) reach the same conclusion. Burstein and Hellwig (2007) conclude that with DRS, matching the observed magnitude of price changes *"requires menu costs that are much higher than existing estimates"*, in their case around three percent of revenue.

μ_{-it}. The shock to μ_{-it} is independent and potentially large. The complementarity therefore does not hamper the ability of the model to generate large idiosyncratic price changes for small menu costs and shocks. Meanwhile, the fact that *on average μ_{-it}* falls at high-markup firms in response to an increase in the money supply is enough to make their low-markup competitors *on average* less likely to adjust.

Figure 8 makes this clear. As is well known, the Kimball profit function under $\chi = 10$ as in Klenow and Willis (2016) is sharply concave; the undesirable by-product of having small declines in μ_t strongly depress the desired adjustment from low μ_{it} firms. With no complementarities with the aggregate markup, the duopoly profit function is not so concave, and—for a fixed μ_{-it}—is only very slightly more concave that under monopolistic competition.[52] Its curvature, and level, however, are constantly fluctuating, due to large changes in μ_{-it}, whereas under Kimball or DRS it remains tightly concave as μ_t moves in a tiny interval. Hence similar parameters achieve the same observed price flexibility.[53]

Summary Existing forms of *micro-complementarity* by definition couple the responses of firms to idiosyncratic and aggregate shocks. Since aggregate shocks are small, the complementarity that is needed makes firms over respond to idiosyncratic shocks. The duopoly model succeeds in decoupling these responses while still presenting a mechanism based on complementarity in price setting.

Finally, note that the *amount* of complementarity in the duopoly model is not governed by an additional parameter like χ, and is instead an endogenous feature of the environment, so unlike χ responds to shocks and policy.[54] This should be of interest given recent evidence that the responsiveness of firms to shocks is counter-cyclical (Berger and Vavra, 2013) and decreased over time (Decker, Haltiwanger, Jarmin, and Miranda, 2017).

(iii) Kurtosis Holding the average size of price changes fixed, the size of the extensive margin response in the Golosov-Lucas model is determined by the new mass of firms increasing their

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[52]This additional curvature is small and roughly equivalent to that which occurs under Kimball with $\chi \approx 0.7$. Beck and Lein (2015) estimate $\chi \approx 1$ using European retail goods, and Gopinath and Itskhoki (2011) estimate $\chi \approx 1.5$ using evidence on pass-through of exchange rate shocks. Hence, the variation in the demand elasticity that occurs naturally under oligopoly with nested CES preferences and reasonable (θ, η) is consistent with empirical evidence on the curvature of demand functions.

[53]The fact $\bar{\xi}$ and σ_z are even slightly lower in the duopoly model owes to the additional rigidity in prices in the oligopoly model due to strategic interactions. This is not related to the main point here, which is that the duopoly places complementarity in the 'right' place: between prices that change a lot, rather than between a price that changes a lot and one that changes a little.

[54]For example, Section 5.3 showed that there was less complementarity in the Calvo model than in the menu-cost model.

prices following a positive monetary shock (see Figure A1). This is determined by the gradient of the distribution of firms near the adjustment thresholds. In a model with Gaussian shocks, this gradient is steep. More kurtosis in this distribution reduces the gradient, leading to less monetary neutrality.

In Midrigan (2011) and further work by Alvarez and Lippi (2014), additional kurtosis stems from multiproduct firms with economy of scope in price changes. When the markup of one good hits an adjustment threshold, a firm reprices all of its goods, despite having some goods with prices close to their optimum. In Gertler and Leahy (2008), infrequent fat-tailed shocks throw the firm's markup conditional on non-adjustment far beyond the adjustment threshold, forcing the firm to adjust while its previous markup has not moved far from its reset value. Alvarez, LeBehin, and Lippi (2016) (hereafter, ABL) formalize these types of results by showing that—within a class of models—the frequency and kurtosis of price changes are sufficient statistics for the real effects of small monetary shocks.

Figure 9A and Table 4 shows that the distribution of price changes are almost identical in both models, and kurtosis of the distribution is in fact slightly less under duopoly.[55] Some additional right skewness and a larger fraction of price increases arises under monopolistic competition due to the asymmetry of the CES profit function (see Figure 8). Under duopoly, low priced firms produce more and so face a lower elasticity of demand, reducing the incentive to increase prices, leading to a more symmetric profit function. Table 4 also shows that the tails of the distribution of price changes are also similar.

In summary, the duopoly model has the same frequency, standard deviation and kurtosis of price changes as the mononpolistically competitive model, and no thicker tails to the price change distribution. That the duopoly model generates larger output effects only confirms that it does not belong to the class of models for which the sufficient statistics of ABL apply.[56]

Finally, note that the random menu cost model generates a bimodal distribution of price changes. This explains the low kurtosis, and is consistent with recent data on price changes compiled by Cavallo (2018) using online prices.[57] Cavallo and Rigobon (2012) test for bimodality in

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[55]Recall that the calibration target was the mean size of absolute price change. Therefore the fact that the standard deviation of price changes is the same is not surprising.

[56]The reason the duopoly model—and those discussed in the last section—are outside the class of models studied by ABL is due to complementarity. The derivations of ABL require that—to a first order—a firm's profit function is independent of all other prices. In the duopoly model (Kimball, DRS) a competitor's price (aggregate price) enters the first order conditions of the firm, breaking the application of these sufficient statistics.

[57]The empirical distribution of price changes in Figure 9 is computed using data available from the companion website for Cavallo (2018): http://www.mit.edu/ afc/data/data-page-scraped.html. The exact data used in Figure 9B

31

the distribution of price changes at 30 retailers across more than 15 countries and reject the null of a unimodel distribution in over 80 percent of the retailers (see their Table 2). Therefore the random menu cost model—although primarily employed for computational tractability in the solution of the MPE problem—produces a price change distribution that is not inconsistent with recent evidence.

6 Welfare implications of nominal rigidity

The oligopoly model has new implications for the welfare costs of nominal rigidity. Studying these are important, especially when we recall that optimal policy in the benchmark New-Keynesian model seeks to close the gap between a corresponding flexible price economy—an RBC model under which output fluctuations due to aggregate shocks are efficient—and the economy with nominal rigidity. As summarized in Gali (2008, chap. 4), the distortions due to sticky prices in that model neatly separate into those due to (a) the presence of market power in goods markets, which effect the average markup, and (b) markup distortion. In that model, as well as the menu cost model, the distortion due to market power under monopolistic competition is unrelated to the presence of sticky prices.[58] In the oligopoly model this is not the case. The distortion due to market power is amplified by the presence of nominal rigidity.

Table 1 revealed that in the presence of menu costs, strategic firms are able to sustain markups that are higher than the frictionless markup: $\mathbb{E}[\mu_{it}] = 1.30 > 1.20 = \mu^*_{Duo_I}$. Similar to the stylized model of Maskin and Tirole (1988b), or models with convex adjustment costs like Jun and Vives (2004), price frictions bestow commitment to high prices, which may be leveraged when prices are static complements. My contribution is to quantify this wedge, and its output consequences, in a model that matches the salient features of firm level data: large, frequent adjustment.

Quantitatively, what are the consequences of this wedge for welfare? Recall that under no nominal rigidity, $\mu_{it} = \mu^*$, which we can compute directly from η and θ in Table 1. Output absent nominal rigidity is then simply $Y^* = 1/\mu^*$. To compute the effect of the level of markups on output (distortion (a)), while controlling for markup dispersion (distortion (b)) set $\mu_{it} = \mathbb{E}[\mu_{it}]$ in both models. Output losses due to the *level* of the markup are then $(\mathbb{E}[\mu_{it}] - \mu^*)/\mu^*$. Given $\mathbb{E}[\mu_{it}] = 1.30$ from Table 1, under monopolistic competition (duopoly) these output losses are 1.1

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excludes price changes due to sales and comes from an unspecified US retailer. He studies five retailers, this is data from *USA5*.

[58]The distortion of $\mathbb{E}[\mu_{it}] > \mu^*_{MC}$ in this paper is only due to the third order properties of the CES profit function, and small.

(8.3) percent. Computing actual output from the model, we can calculate the additional output loss due to markup dispersion. Table 5 summarizes these results, showing that (i) total output losses due to nominal rigidity are four times larger under duopoly, (ii) in contrast to the monopolistic competition economy, this is driven by the level rather than dispersion of markups. Sticky prices make distortion (a) worse, while in the monopolistically competitive model the effect of sticky prices on the level of the markup are minimal and the independence summarized in Gali (2008, chap. 4) holds.

Figure 10 quantifies a related result: the value of the firm is non-monotonic in the size of the adjustment friction. On the one hand, greater frictions lead to greater dynamic complementarity, accommodating higher markups and increasing firm value. On the other hand, greater frictions reduce price flexibility, reducing firm value. The resulting non-monotonic relationship is clear in both the menu cost and Calvo models. While monopolistically competitive firms always prefer smaller frictions and more adjustment, for duopolists, there is value is maximized with $\bar{\bar{\zeta}} > 0$. Compared to the baseline menu cost model ($\bar{\bar{\zeta}}_{Duo_I} = 0.17$), at $\bar{\bar{\zeta}}^*_{Duo_I} = 0.29$, prices change 3ppt less often, but the real value of the firm is 9 percent larger. In the Calvo model, where dynamic complementarity is weaker, smaller frictions would be preferred.

Four potentially interesting paths for future research arise. First, the fact that firms desire some, but not too much, nominal rigidity may rationalize why firms engage in investments that increase the cost of price changes.[59] Second, policies such as higher trend inflation will force firms to adjust prices more frequently, which may reduce the degree of dynamic complementarity. If so, then such policies would have first order output effects.[60] Third, these results imply a systematic downward bias in markups that are estimated from static models of oligopoly. Given unbiased estimates of preference parameters, from a static model one would infer μ^*_{Duo}, which may be substantially less than $\mathbb{E}[\mu_{it}]$. Finally, these results distort the usual welfare implications of frictions in macroeconomics. The standard intuition holds in the monopolistically competitive model: firms and households both dislike frictions. In an oligopoly, there is a range over which higher frictions are redistributive, causing profits to increase but real wages to fall.[61]

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[59]For example, firms print brochures with prices fixed for some period of time.

[60]This is certainly true in the limit. High trend inflation would cause firms to reset their prices every period, yielding the frictionless Nash equilibrium. This would eliminate the first order welfare losses of nominal rigidity but also eliminate any stimulative role for monetary policy, presenting a trade-off for policy.

[61]For example, one could ask whether regulations that create fixed costs of investment may be valuable to oligopolists that would prefer to to under-invest relative to a frictionless benchmark.

7 Endogenous price stickiness and market concentration

In duopoly, prices are endogenously stickier than under monopolistic competition. Price decreases are less valuable as high prices provide an incentive for a firm's competitor to also choose a high price. Price increases are less valuable since they increase a firm's elasticity of demand. Nominal prices therefore change less often, and by smaller amounts, for any $\bar{\bar{\xi}}$, and so a lower $\bar{\bar{\xi}}$ is required to match the data.

An alternative way to see this is to compare models Duo_I and MC_{II} in Table 1. When evaluated at the same parameters, price changes in the monopolistically competitive model occur with a much higher frequency (0.19 vs. 0.13) and small average magnitude (0.05 vs. 0.10). This has the empirical prediction that among markets with plausibly similar parameters, less concentrated markets should have more flexible prices.

Using the IRI data I am able to measure the moments required to assess this prediction.[62] It is straight-forward to use bar-code level data to compute average frequency and magnitude of price changes within a given region-period. As the data contain product revenue and the universe of goods within stores, I can also allow construct measures of revenue based market concentration across the retail stores in the data. The first six-digits of a product bar-code identify the wholesale firm (for example, Kraft or Hellman's in the mayonnaise market), which I use to aggregate revenues for a firm within a region. The literature has determined that most markup adjustment occurs at the wholesale level and pass-through is essentially complete at the retail level, hence measuring market concentration among wholesale firms, rather than retail firms is appropriate.[63]

To capture the notion of parameters being plausibly the same across markets, I use only within product-time, across region variation in market concentration. It turns out that this variation is substantial. Let p denote a product category, s a state, and t a quarter, and the intersection of these denote a market. I then compute the inverse Herfindahl index $iherf_{pst}$ for all markets in the IRI data (31 product categories, 46 states, 44 quarters from 2001 to 2011). Figure 11 provides examples of the variation that I exploit. For both Mayonnaise and Coffee, market concentration is persistent within regions, and heterogeneous across regions.[64] Moreover, concentration is not region spe-

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[62]For more details on the data see Appendix A. In terms of content, the data are comparable to the *Kilts-Nielsen Retail Scanner Data*. In terms of scope, the IRI data is limited to grocery and drug stores, and so lacks categories such as cookware and electronics. Expanding this study to the *Kilts-Nielsen Retail Scanner Data* will be possible for those with better data access.

[63]See Goldberg and Hellerstein (2013), Eichenbaum, Jaimovich, and Rebelo (2011) and Nakamura and Zerom (2010).

[64]This variation in market concentration has been studied using the same data by Bronnenberg, Dhar, and Dubé (2009) and Bronnenberg, Dube, and Gentzkow (2012). The latter points to the migration of individuals—who carry

cific. In relative terms Mayonnaise is less concentrated in MD than NJ, while the opposite is true for Coffee. Cases like this should allay concerns that using within-good, across-region variation merely captures across-region differences that are common to all products.

There is also significant variation in price flexibility across regions, even within these narrow goods categories. In fact, within the IRI data—which is admittedly narrow itself—only a small component of the dispersion in price flexibility is driven by differences across goods. Removing quarter-t fixed effect in a revenue-weighted regression, the standard deviation of residual dispersion in log frequency (size) of price change across products and states is 0.65 (0.41). Adding product-quarter-pt fixed effects causes these to decrease only slightly 0.54 (0.33). Hence around three-quarters as much variation exists within-product-quarters, across-regions as does within-quarters across-product-regions.

I use this variation in the data to assess whether there is a correlation between market concentration and price flexibility. The core data are 61,884 measures of concentration $iherf_{prt}$, average frequency of price change $freq_{prt}$, and average size of price change $size_{prt}$. I first remove product-time fixed effects as well as controls for market revenue and the number of firms operating in the market:

$$y_{prt} = \gamma_{pt} + \beta_0 Firms_{prt} + \beta_1 Revenue_{prt} + \varepsilon_{prt}.$$

The residual $\tilde{y}_{prt}$ is then scaled by its *within* product-quarter-pt standard deviation. I compute averages of $\widetilde{iherf}_{prt}$, $\widetilde{freq}_{prt}$, and $\widetilde{size}_{prt}$ within percentile bins of $\widetilde{iherf}_{prt}$, and plot these in Figure 12.[65] For state markets that are relatively more competitive (a higher $\widetilde{iherf}_{prt}$) than other states, within the same goods category and quarter, the average flexibility of prices is greater.

This brief exercise shows that a large component of good level price flexibility is not good, but good-region specific, and a component of this is associated with good-region market concentration. The latter is qualitatively consistent with the results from the model in Table 1. It is beyond the scope of this paper to isolate a causal claim.

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with them brand preferences—as a major determinant of market shares. Exploiting this variation innovates on Bils and Klenow (2004), who also study the relationship between concentration and price flexibility. However, since they use CPI microdata—which takes small samples of goods from stores—they cannot compute concentration measures locally. They instead project national price flexibility for a good, on national market concentration, and find no significant relationship. The latter can be a misleading measure of product market *competition* if, for example, there are 50 different monopolists operating in 50 states.

[65]A regression of $freq_{prt}$ ($size_{prt}$) on product-quarter dummies with all interactions of $iherf_{prt}$, $Revenuev_{prt}$, $Firms_{prt}$, yields statistically significant positive (negative) coefficients on $iherf_{prt}$.

8 Conclusion

This paper establishes that the competitive structure of markets can be quantitatively important for the transmission of macroeconomic shocks. In particular, in a menu cost model of firm-level price setting—which aggregates to a monetary business cycle model—a monopolistically competitive market structure and a duopoly market structure generate different levels of monetary non-neutrality. Even when calibrated to match the same salient features of price flexibility in the data, the duopoly model generates larger output responses. Following a monetary expansion, the incentive for low-priced firms to respond to the shock increases less sharply as a lower sectoral price reduces the incentive to adjust. Idiosyncratic shocks—which create within-sector markup dispersion—and state-dependent frictions—which make repricing predictable—are key for this mechanism.

The duopoly model does not exclude other mechanisms that have been found to be successful in generating monetary nonneutrality in a menu cost model, while also being consistent with the microdata. Future research that tries to understand how combining these may generate empirically plausible monetary business cycles is a topic for future research.

More broadly, this paper expands the set of general equilibrium macroeconomic models that may be used to interpret microdata. A pervasive feature of many microdata sets on investment, employment, and so on, are fat-tailed size distributions, even within narrow industries. Having quantitative models that might accommodate strategic interaction between these large agents is therefore important.

This Appendix is organized as follows. Section A describes the IRI data and their treatment in the paper. Section B describes the computational methods used to solve the model in Section 2. Section C proves the results for a static game with menu costs and exogenously specified initial markups. I also derive properties of the firm's frictionless best response function and profit functions under general complementarity in pricing and for CES preferences. Section D discusses some of the assumptions of the model.

A Data description

The data used throughout this paper come from the IRI Symphony data. Details can be found in the summary paper by Bronnenberg, Kruger, and Mela (2008).[66] The data are at a weekly frequency from 2001 to 2011 and contain revenue and quantity data at the good level, where a good is defined by a unique bar code number (Universal Product Code—UPC). Data are collected in over 5,000 stores covering 50 metropolitan areas.[67] For each store, data are recorded for all UPCs within each of 31 different product categories. Product categories—for example toothpaste—are determined by IRI and were designed such that the vendor could sell data, by product category, to interested firms.[68] This therefore provides an economically meaningful way to separate goods categories, since firms presumedly would be interested in purchasing data relevant to their product market. The measures that I construct from these data and use in the paper relate to (i) market concentration, and (ii) price changes. In both cases I define a market by product category p, state s and month t.

Constructing measures of market concentration requires market-level sales for each firm. To identify a firm, I use the first five digits of a good's UPC. This uniquely identifies a company. For example, the five digits 00012 in the bar code 00012100064595 identify Kraft within a market for mayonnaise; 48001 would identify Hellman's. As my measures are constructed within a market

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[66]Other recent papers to use these data include Stroebel and Vavra (2014) and Coibion, Gorodnichenko, and Hong (2015). See http://www.iriworldwide.com/en-US/solutions/Academic-Data-Set.

[67]Details on the identification of stores are removed from the data and replaced with a unique identifying number. Walmart is not included in the data.

[68]For completeness, the categories are: beer, razor blades, carbonated beverages, cigarettes, coffee, cold foods, deodorant, diapers, facial tissues, frozen dinner entrees, frozen pizza, household cleaning goods, hot dogs, laundry detergent, margarine and butter, mayonnaise, milk, mustard and ketchup, paper towels, peanut butter, photo products, razors, salted snacks, shampoo, soup, pasta sauces, sugar and substitutes, toilet tissue, toothbrushes, toothpaste, and yogurt.

pst, I consider Kraft within the mayonnaise market in Ohio as a different firm from Kraft within the margarine market in Ohio. Revenue r_{fpst} for each firm f in market *pst* is the sum of weekly revenue from all UPCs at all stores within *pst*. The preferred concentration measure in the paper is the effective number of firms, as measured by the inverse Herfindahl index, which is $h_{pst} = \sum_{f \in pst}(r_{fpst}/r_{pst})^2$.

Computing measures of price changes first requires a measure of price. To obtain weekly prices for each good, I simply divide revenue by quantity. I compute price change statistics monthly and measure prices in the third week of each month. I focus only on regular price changes and deem a price to have been changed between month $t - 1$ and t if it (i) changes by more than 0.1 percent, considering price changes smaller than this to be due to rounding error from the construction of the price, and (ii) was on promotion neither in month $t - 1$, nor in month t. The IRI data include indicators for whether a good is on promotion, and so I use this information directly rather than using a sales filter. This second requirement means that I exclude both goods that go on promotion and come off promotion. The frequency of price change in market *pst* is the fraction of goods that change price in market *pst* between $t - 1$ and t. The size of price change in market *pst* is the average absolute log change in prices for all price changes in market *pst* between $t - 1$ and t.

When computing moments for use in the calibration of the model, I first take a simple average over s and t for each product p. I then take a revenue-weighted average across products, where revenue weights are computed using average national revenue for product p: $r_p = T^{-1} \sum_{t=1}^{T} \left(\sum_{s=1}^{S} r_{pst} \right)$.

B Computation

First I show that Bellman equation (7) corresponds to the Bellman equation in markups under the equilibrium conditions of the model (9), as the latter is used in computation. Second, I describe the numerical methods used in computing the equilibrium of the model.

Price indices Denote the first firm's markup $\mu_{ij} = p_{ij}/z_{ij}W$. Using this, the sectoral price index $\mathbf{p}_j$ can be written

$$\mathbf{p}_j = \left[\left(\frac{p_{1j}}{z_{1j}} \right)^{1-\eta} + \left(\frac{p_{2j}}{z_{2j}} \right)^{1-\eta} \right]^{\frac{1}{1-\eta}} . = W \left[\mu_{1j}^{1-\eta} + \mu_{2j}^{1-\eta} \right]^{\frac{1}{1-\eta}}$$

Define the sectoral markup $\mu_j = \mathbf{p}_j/W$, which implies that $\mu_j = \left[\mu_{1j}^{1-\eta} + \mu_{2j}^{1-\eta}\right]^{1/(1-\eta)}$. Using the sectoral markup, the aggregate price index P can be written

$$P = \left[\int_0^1 \mathbf{p}_j^{1-\theta}dj\right]^{\frac{1}{1-\theta}} = \left[\int_0^1 \mu_j^{1-\theta}dj\right]^{\frac{1}{1-\theta}}W.$$

Define the aggregate markup $\mu = P/W$, which implies that $\mu = \left[\int_0^1 \mu_j^{1-\theta}dj\right]^{1/(1-\theta)}$.

Profits   The expressions for markups can be used to rewrite the firm's profit function. Start with the baseline case

$$\pi_{ij} = z_{ij}^{\eta-1}\left(\frac{p_{ij}}{\mathbf{p}_j}\right)^{-\eta}\left(\frac{\mathbf{p}_j}{P}\right)^{-\theta}\left(p_{ij} - z_{ij}W\right)C.$$

The equilibrium household labor supply condition requires $PC = W$. The the definition of the aggregate markup, therefore implies that $C = 1/\mu$. This, along with $p_{ij} = \mu_{ij}z_{ij}W$, $p_j = \mu_jW$, and $P = \mu W$, gives

$$\pi_{ij} = \left(\frac{\mu_{ij}}{\mu_j}\right)^{-\eta}\left(\frac{\mu_j}{\mu}\right)^{-\theta}\left(\mu_{ij} - 1\right)\frac{W}{\mu} = \tilde{\pi}\left(\mu_{ij}, \mu_{-ij}\right)\mu^{\theta-1}W.$$

The function $\tilde{\pi}$ depends on the aggregate state only indirectly through the policies of each firm within the sector. This makes clear the use of the technical assumption that the demand shifter z_{ij} also increases average cost, allowing profits to be expressed only in markups.

Markup dynamics   Suppose that a firm sells at a markup of μ_{ij} this month. The relevant state next month is the markup that it will sell at if it does not change its price $\mu'_{ij} = p_{ij}/z'_{ij}W'$. Replacing p_{ij} with μ_{ij}, we can write μ'_{ij} in terms of this month's markup, the equilibrium growth of the nominal wage, and the growth rate of idiosyncratic demand:

$$\mu'_{ij} = \mu_{ij}\frac{z_{ij}}{z'_{ij}}\frac{W}{W'} = \mu_{ij}\frac{1}{g'e^{\varepsilon'_{ij}}}.$$

The random walk assumption for z_{ij} implies that $z'_{ij}/z_{ij} = \exp(\varepsilon'_{ij})$. The equilibrium condition on nominal expenditure $PC = M$, combined with the equilibrium household labor supply condition $PC = W$, implies that in equilibrium $W = M$. The stochastic process for money growth then implies that $W'/W = g'$.

Bellman equation Using these results in the firm's Bellman equation reduces the value of adjustment from (7) to the following (here for clarity I assume that the competitor's markup μ_{-i} is fixed):

$$V_i^{adj}\left(\mu_i,\mu_{-i},\mathbf{S}\right) = \max_{\mu_i^*} \tilde{\pi}\left(\mu_i^*,\mu_{-i}\right)\mu(\mathbf{S})^{\theta-1}W(\mathbf{S}) + \mathbb{E}\left[Q(\mathbf{S},\mathbf{S}')V_i\left(\frac{\mu_i^*}{g'e^{\varepsilon_i'}},\frac{\mu_{-i}}{g'e^{\varepsilon_{-i}'}},\mathbf{S}'\right)\right].$$

The equilibrium discount factor is $Q(\mathbf{S},\mathbf{S}') = \beta W(\mathbf{S})/W(\mathbf{S}')$. This implies that all values can be normalized by the wage, where $v_i = V_i/W$:

$$v_i^{adj}\left(\mu_i,\mu_{-i},\mathbf{S}\right) = \max_{\mu_i^*} \tilde{\pi}\left(\mu_i^*,\mu_{-i}\right)\mu(\mathbf{S})^{\theta-1} + \beta\mathbb{E}\left[v_i\left(\frac{\mu_i^*}{g'e^{\varepsilon_i'}},\frac{\mu_{-i}}{g'e^{\varepsilon_{-i}'}},\mathbf{S}'\right)\right].$$

Replacing the aggregate state $\mathbf{S} = (g,\lambda)$ with that used in the approximation $\mathbf{S} = (g,\mu_{-1})$, we have the following:

$$v_i^{adj}\left(\mu_i,\mu_{-i},g,\mu_{-1}\right) = \max_{\mu_i^*} \tilde{\pi}\left(\mu_i^*,\mu_{-i}\right)\hat{\mu}\left(g,\mu_{-1}\right)^{\theta-1} + \beta\mathbb{E}\left[v_i\left(\frac{\mu_i^*}{g'e^{\varepsilon_i'}},\frac{\mu_{-i}}{g'e^{\varepsilon_{-i}'}},g',\hat{\mu}\left(g,\mu_{-1}\right)\right)\right],$$

where $\hat{\mu}$ is given by the assumed log-linear function: $\log\hat{\mu} = \alpha_0 + \alpha_1 g + \alpha_2 \log\mu_{-1}$.

The equilibrium condition requiring the price index be consistent with firm prices has also been restated in terms of markups, which implies the entire equilibrium is now restated in terms of markups. To simulate changes in prices, it is sufficient to know a path for markups μ_{ijt}, innovations ε_{ijt}, and money growth g_t. To determine quantities I need to also simulate paths for M_t and z_{ijt}.

B.1 Price changes

In the footnote of Figure 9 I note that *mark-up gaps* are equal to *price changes* for firms changing their prices. The markup gap is the gap between the firm's markup that would occur should the firm not change its price, which is its state-variable and depends on p_{ijt-1}, and its desired markup, which depends on p_{ijt}^*:

$$\bar{\mu}_{ijt} = \frac{p_{ijt-1}}{z_{ijt}W_t}, \quad \mu_{ijt}^* = \frac{p_{ijt}^*}{z_{ijt}W_t}$$

.

Therefore the firm's desired price change and its markup gap are equivalent:

$$\log \frac{p^*_{ijt}}{p_{ijt-1}} = \log \frac{\mu^*_{ijt}}{\bar{\mu}_{ijt}}.$$

B.2 Solving the MPE

First, for simplicity, suppose that $\theta = 1$ such that no function of the aggregate state enters the firm's problem. Suppose also that shocks to the growth rate of money supply are entirely transitory $(\rho_g = 0)$. In this case, the state variables of the firm's problem are only μ_i and μ_{-i}. Since the parameters associated with each firm in each sector are symmetric, I only consider solutions in symmetric policies $\mu(\mu_i, \mu_{-i})$ and $\gamma(\mu_i, \mu_{-i})$. Suppose that these functions are known; then solving the firm's problem amounts to solving a simple Bellman equation. Define the firm's expected value function $v^e_i(\mu'_i, \mu'_j) = \mathbb{E}\left[v_i\left(\frac{\mu'_i}{g'e^{\varepsilon'_i}}, \frac{\mu'_{-i}}{g'e^{\varepsilon'_{-i}}}\right)\right]$. I can approximate v^e_i with a cubic spline and, given a starting guess, use standard collocation tools to solve the firm's Bellman equation. This requires specifying a grid of collocation nodes for μ_i and μ_{-i}, and then solving for splines with as many coefficients as collocation nodes. Given an approximation of v^e_i, the choices of a firm on these nodes can be solved for, and the values on these nodes used to update the approximation using Newton's method (see Miranda and Fackler (2002)). An alternative approach is to iterate on the Bellman equation.

When solving the MPE, the competitor policies are not initially known. In solving the model, I take a number of approaches, each of which yields the same equilibrium policies. In all cases, I approximate the optimal markup and probability of adjustment policies using cubic splines. The first approach is to consider some large T and assume that from this period onward, prices are perfectly flexible such that the unique frictionless Nash equilibrium is obtained. This determines a starting guess for the policies and value function. Random menu costs imply that each stage game has a unique equilibrium for each point in the state space, which implies that this long subgame perfect Nash equilibrium is unique. One can then iterate backward to $t = 0$, or truncate iterations once the policy functions and values of the firm converge. The second approach is to fix a competitor's policies, solve a firm's Bellman equation, use this to compute new policies, and then continue to iterate in this manner until all objects converge. In practice, both approaches were found to lead to the same policy and value functions. The second approach is faster, since collocation methods can be used to quickly solve the Bellman equation, keeping the competitor policies fixed.

41

Under $\theta > 1$ and persistent shocks to money growth, then the approximate aggregate state (g, μ_{-1}) also enters the firm's state vector. The solution algorithms for the MPE, however, do not change. I approximate the firm's policies using linear splines in each of these additional dimensions. Policy and value functions are approximated using 25 evenly spaced nodes, and the aggregate states are approximated using 7 evenly spaced nodes.[69] Approximating the expected value function implies that expectations are only taken once in each iterative step while solving the value function, rather than on every step of the solver for the optimal μ_i^*. This, along with the use of a continuous approximation to the value function, allows for a high degree of precision in updating the expected value function. Given an expected value function, an optimal policy can be computed, delivering a new value function, which is then integrated over 100 points in both ε_i' and ε_{-i}' in order to compute a new expected value function.[70]

Issues for high and low menu costs   For a fixed set of collocation nodes, issues arise when trying to solve the model for very low or very high menu costs. For very low menu costs, the adjustment probabilities of the firm take on a steep *V*-shape, and small deviations in markups lead to a sharp increase in the probability of adjustment. Approximating such functions is difficult with a conservative number of nodes for the approximant of $\gamma(\mu_i, \mu_{-i})$. When menu costs are very large, the adjustment probabilities take on a very shallow *U*-shape, and markups deviate more widely. This also is hard to approximate with a conservative number of nodes for the approximants.

Figure 10 is symptomatic of this issue. Note that in the Calvo model of adjustment these issues do not arise, since I no longer have to approximate the probability of adjustment function. Therefore the Calvo model can be solved at a very high frequency of adjustment. Figure 10 verifies that as α tends towards one, the value of the firm in the duopoly model smoothly approaches the value of the firm in the monopolistically competitive model, since both models are calibrated to the same frictionless markup.

Krusell-Smith algorithm   I first solve the economy under $\mu_t = \mu^*$, where μ^* is the frictionless Nash equilibrium markup. I then proceed with the Krusell-Smith algorithm, refining the firm's forecast. Solving the model under the initial forecasting rule, I can then simulate the economy.

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[69]Note that when solving the problem for a firm, a competitor's policy is never evaluated off the collocation nodes. The only computations that involve the splines are evaluating the expected value function for proposed μ_i^* values in the maximization step, and the simulation of sectors.

[70]"Quadrature" methods, by contrast, only use a small handful of points in the approximation of the integral. Working with continuous splines and iterating on the expected value function allow a much more precise computation of the integral.

Since firm-level shocks are large, then even for large numbers of simulated sectors, there will be small fluctuations in aggregates. In implementing the Krusell-Smith algorithm I therefore proceed as follows. Let $\{E_t\}_{t=0}^T$ be a sequence of matrices of idiosyncratic shocks—to both productivity and menu costs—to all firms in all sectors, and consider some simulated path of money growth $\{\varepsilon_t^g\}_{t=0}^T$. I simulate two economies, both under $\{E_t\}_{t=0}^T$ and with the same initial distribution of markups, but one under $\{\varepsilon_t^g\}_{t=0}^T$ and the other under $g_t = \bar{g}$ for all t. From the second simulation, I then compute the sequence of aggregate markups and call this $\bar{\mu}_t$, with corresponding μ_t from the first simulation. I then run the following regression on simulated data from $\underline{T}$ to T:

$$(\log \mu_t - \log \bar{\mu}_t) = \alpha_1 (\log g_t - \log \bar{g}) + \alpha_2 (\log \mu_{t-1} - \log \bar{\mu}_{t-1}) + \eta_t.$$

I also compute the average aggregate markup $\bar{\mu} = 1/(T - \underline{T}) \sum_{t=\underline{T}}^{T} \mu_t$. When solving the model on the next iteration, I renormalize the aggregate state space to $S = (\log g - \log \bar{g}, \log \mu_{-1} - \log \bar{\mu})$ and provide firms with the forecasting rule

$$\log \mu(S) = \log \bar{\mu} + \hat{\alpha}_1 S_1 + \hat{\alpha}_2 S_2.$$

In practice, I simulate $10,000$ sectors, set $T = 2,000$, and $\underline{T} = 500$, and iterate to convergence on $\{\bar{\mu}, \alpha_1, \alpha_2\}$. In the monopolistically competitive model, I simulate a single sector with 20,000 firms. This approach controls for simulation error, and allows me to keep the nodes of the state space for S_2 the same across solutions of the model, while incorporating changes in the forecast of the average markup.

The algorithm converges quickly and the rule provides a high R^2 in simulation. This works especially well in the context of this model for a number of reasons, which all relate to the role of μ_t in the firm's problem. First, μ_t simply shifts the level of the firm's profit function, which implies that in a static model, it only affects the value of a price change, not the firm's optimal markup. Second, if θ is close to one, then this movement in the profit function is small for any given fluctuations in μ_t. Third, these fluctuations in μ_t are in fact small, given the empirical magnitude of money growth shocks. From a robustness perspective, this is reassuring: if the rule used by firms was incorrect, then this misspecification would have little impact on the policies of the firm. In practice, this means that the coefficients for $\{\bar{\mu}, \alpha_1, \alpha_2\}$ from the first solution of the model under the rule $\mu_t = \mu^*$, are very close to the final coefficients.

Computing aggregate fluctuations I also correct the computation of other moments for simulation error which might otherwise bias one toward finding larger time-series fluctuations. For example, the key statistic of $\sigma(C_t)$ is computed using $std\,[\log C_t - \log \bar{C}_t]$, where $\bar{C}_t$ is aggregate consumption computed under the simulation with aggregate money growth equal to $\bar{g}$ in all periods. In this "steady-state" economy, there are still fluctuations in aggregate consumption, but these are due only to large shocks to firms not washing out in a simulation of finitely many firms. The same approach is taken when computing impulse response functions for moments such as the frequency of price adjustment of low-markup firms in Figure 6.

C Static game

In this appendix, I study a two-player price-setting game in which the profit function of the firm displays complementarities in prices, firms face a fixed cost of changing prices, and initial prices are above the frictionless Nash equilibrium price. I establish that (i) the frictionless best response function of the firm has a positive gradient bounded between zero and one, (ii) menu costs can sustain higher prices than obtain in a frictionless setting, (iii) the only pure strategy equilibria that exist are ones in which both firms change their price or both keep them fixed, (iv) for any given menu cost, there is always a range of initial prices for which both equilibria exist. I then show that the profit functions—derived from nested CES preferences—in the body of the paper satisfy the necessary assumptions for these results.

Environment Consider two firms with symmetric profit functions $\pi^1(p_1, p_2) = \pi^2(p_2, p_1)$. In what follows, I drop the superscripts on the profit function and prices, with the second argument always referring to the competitor's price. Assume that π is twice continuously differentiable and that the derivatives of π have the following properties: $\pi_{11} < 0$, $\pi_{12} > 0$. The second assumption is the definition of complementarity in prices.

There is one period. Firms begin the period with initial price $\bar{p}$, which is larger than the frictionless Nash equilibrium price p^*. To deviate from this price, a firm must pay a cost ξ. The objective function of firm i is therefore $v(p_i, p_j) = \pi(p_i, p_j) - \mathbf{1}\,[p_i \neq \bar{p}]\,\xi$.

Static best response function The *frictionless best response function $p^*(p)$* is the best response of a firm to its competitor's price p when $\xi = 0$. The key property of the static best response which is discussed in the text is that it has a positive gradient between zero and one. To prove this, take

44

the firm's first order condition: $\pi_1(p^*(p), p) = 0$. By the implicit function theorem, the derivative of $p^*(p)$ can be obtained by rearranging the total derivative of the first order condition:

$$\frac{\partial p^*(p)}{\partial p} = -\frac{\pi_{12}(p^*(p), p)}{\pi_{11}(p^*(p), p)}.$$

The frictionless Nash equilibrium price $p^* = p^*(p^*)$ solves both firms' first order conditions simultaneously. The second order conditions must hold at (p^*, p^*), requiring that the principal minors of the Hessian—evaluated at $p^* = p^*(p^*)$—alternate in sign:

$$\pi_{11}(p^*, p^*) < 0, \quad \text{and} \quad \pi_{12}(p^*, p^*)^2 < \pi_{11}(p^*, p^*)^2.$$

The first condition holds by assumption. The second condition, jointly with the assumption of complementarity $(\pi_{12} > 0)$, gives the result that any Nash equilibrium

$$\frac{\partial p^*(p)}{\partial p}\bigg|_{p=p^*} = -\frac{\pi_{12}(p^*, p^*)}{\pi_{11}(p^*, p^*)} \in (0, 1).$$

Multiple equilibria would require $p^{*\prime}(p^*)$ have a slope greater than one at some other equilibria, so clearly the equilibrium is also unique. Note that $p^*(p) \in (p^*, p)$ for $p > p^*$, that is, the best response function exhibits "undercutting."

Equilibria of the menu cost game Categorize possible pure strategy equilibria into three types: (I) neither firm changes its price, (II) both firms change their price, (III) one firm changes its price.

A necessary and sufficient condition for a Type-I equilibrium is

$$\pi(\bar{p}, \bar{p}) \geq \max_p \pi(p, \bar{p}) - \xi, \tag{C1}$$

or equivalently

$$\xi \geq \Delta_I(\bar{p}) = \pi\left(p^*(\bar{p}), \bar{p}\right) - \pi\left(\bar{p}, \bar{p}\right). \tag{C2}$$

This condition for a Type-I equilibrium holds when (i) ξ is very large or (ii) $\bar{p}$ is small. To show that $\Delta_I(\bar{p})$ is increasing in $\bar{p}$, it is useful to represent $\Delta_I(\bar{p})$ as an integral. The derivative is then

$$\frac{\partial \Delta_I(\bar{p})}{\partial \bar{p}} = \frac{\partial}{\partial \bar{p}}\left[-\int_{p^*(\bar{p})}^{\bar{p}} \pi_1(u, \bar{p}) du\right] = \int_{p^*(\bar{p})}^{\bar{p}} \pi_{12}(u, \bar{p}) du + \pi_1(p^*(\bar{p}), \bar{p}) - \pi_1(\bar{p}, \bar{p}) > 0. \tag{C3}$$

This is positive due to complementarity $(\pi_{12} > 0)$, the definition of $p^*(\bar{p})$ implies the second term is zero, and $\pi_1(\bar{p}, \bar{p}) < 0$ since $\bar{p} > p^*(\bar{p})$. The change in value that accompanies the opti-

mal deviation from $p^*(\bar{p})$ increases in $\bar{p}$. Sustaining initial deviations from the frictionless Nash equilibrium requires the initial deviation to be not too large or menu costs to be not too small.

In a Type-II equilibrium, in which both firms change their price, it must be that the prices chosen are (p^*, p^*). Given that both firms are changing their prices, then the price chosen by each firm must be a best response to its competitor. We then need to check that it is not optimal for a firm to leave its price at $\bar{p}$, which requires

$$\xi \leq \pi\left(p^*, p^*\right) - \pi\left(\bar{p}, p^*\right) \quad \left(= \Delta_{II}(\bar{p})\right). \tag{C4}$$

This condition for a Type-II equilibrium holds when (i) ξ is small or (ii) $\bar{p}$ is large. To see that $\Delta_{II}(\bar{p})$ is increasing in $\bar{p}$, note that $\pi(\bar{p}, p^*)$ is decreasing in $\bar{p}$ for all $\bar{p} > p^*$. The frictionless equilibrium will still obtain when $\bar{p}$ is large relative to the menu cost.

Type-III equilibria do not exist. Observe that a Type-III equilibrium requires that the firm that changes its price, changes it to $p^*(\bar{p})$. There are therefore two necessary conditions for a Type-III equilibrium. First, firm 2 must find it profitable to change its price given that firm 1's price remains at $\bar{p}$:

$$\pi\left(p^*(\bar{p}), \bar{p}\right) - \xi \geq \pi\left(\bar{p}, \bar{p}\right). \tag{C5}$$

This holds when (i) ξ is small or (ii) $\bar{p}$ is large. Second, the frictionless best response of firm 1 to firm 2's price must not be a best response under a positive menu cost. Letting $p^{**}(\bar{p})$ denote the frictionless best response to $p^*(\bar{p})$, we then require

$$\pi\left(p^{**}(\bar{p}), p^*(\bar{p})\right) - \xi \leq \pi\left(\bar{p}, p^*(\bar{p})\right). \tag{C6}$$

This holds when (i) ξ is large or (ii) $\bar{p}$ is small. Intuitively, it seems that these conditions should not simultaneously hold. If one firm finds it valuable to undercut its competitor, then its competitor should find it valuable to respond. Indeed, this can be proven, with the proof found at the end of this appendix.

Having asserted that the only pure strategy equilbria are of Type-I and Type-II, we can also show that for any value of ξ, there exist an interval of $\bar{p}$ for which both Type-I equilibria and Type-II equilibria may exist. First note that $\Delta_I(p^*) = \Delta_{II}(p^*) = 0$. That is, both equilibria trivially exist for zero menu costs at $\bar{p} = p^*$. A sufficient condition for both equilibria to exist for any value of ξ is to show that $\Delta_{II}(\bar{p}) > \Delta_I(\bar{p})$:

$$\pi(p^*, p^*) - \pi(\bar{p}, p^*) > \pi(p^*(\bar{p}), \bar{p}) - \pi(\bar{p}, \bar{p}). \tag{C7}$$

Since p^* is the best response to p^* then $\pi(p^*, p^*) > \pi(p^*(\bar{p}), p^*)$, so showing the following is

sufficient:

$$\pi(p^*(\bar{p}), p^*) - \pi(\bar{p}, p^*) > \pi(p^*(\bar{p}), \bar{p}) - \pi(\bar{p}, \bar{p}). \tag{C8}$$

If π displays complementarity, then this holds.[71]

These results characterize equilibria in $(\bar{p}, \zeta)$-space as follows. Consider fixing $\bar{p}$ and starting at a high value of ζ. In this region, only the Type-I equilibrium exists. Menu costs are sufficiently high that the best response of each firm to the initially high price of its competitor is to keep a high price. As ζ decreases, we reach a point at which Type-II equilibria are also feasible. In this region, if firm 2 changes its price, then the best response of firm 1 is to also change its price (Type-II), but if firm 2 leaves its price fixed, then the best response of firm 1 is to also leave its price fixed (Type-I). As ζ decreases further, the Type-I equilibrium can no longer be sustained as the menu cost is insufficient to commit firms not to respond to a price decrease at their competitor. Alternatively, fixing ζ and increasing $\bar{p}$, first only the Type-I equilibrium exists, then both, then as the value of a price decrease becomes large, only the Type-II equilibrium exists. Figure A2 plots these regions for a profit function discussed below.

In the case of the existence of multiple equilibria, the equilibria are ranked as we would expect: the fixed price Type-I equilibrium is preferred. This requires that $\pi(\bar{p}, \bar{p}) > \pi(p^*, p^*) - \zeta$. Since the Type-I equilibrium exists, then $\zeta \geq \pi(p^*(\bar{p}), \bar{p}) - \pi(\bar{p}, \bar{p})$, and therefore this ranking holds if $\pi(p^*(\bar{p}), \bar{p}) > \pi(p^*, p^*)$. Since prices are complements, this is true: the best response to a high price yields a larger profit than the best response to a low price.

From this static game we learn that for a given menu cost ζ, high prices $\bar{p}$ can be sustained so long as they are not too far from the frictionless Nash equilibrium. If the initial price is too high, one firm has a profitable deviation even it pays the menu cost. If the value of one firm's deviation exceeds the menu cost, then the value of an iterative undercutting strategy from its competitor must also exceed the menu cost. Both firms change their prices, and only the frictionless Nash equilibrium price is attainable. If initial prices are not too high, then the menu cost is enough to negate the small value of the optimal frictionless downward deviation in price, making the high-priced strategy credible. We also learn that the equilibrium is not unique for certain combinations of ζ and $\bar{p}$, while these equilibria are clearly Pareto ranked: if firms could coordinate on

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[71] To see this, rearrange the condition and then express both sides as integrals:

$$\pi(\bar{p}, p^*) - \pi(p^*(\bar{p}), p^*) \quad < \quad \pi(\bar{p}, \bar{p}) - \pi(p^*(\bar{p}), \bar{p}),$$

$$\int_{p^*(\bar{p})}^{\bar{p}} \pi_1(u, p^*) du \quad < \quad \int_{p^*(\bar{p})}^{\bar{p}} \pi_1(u, \bar{p}) du.$$

Due to complementarity, $\bar{p} > p^*$ implies $\pi_1(u, \bar{p}) > \pi_1(u, p^*)$. Since both integrals are over the same support, then the inequality must always hold.

an equilibrium, they would choose not to change their prices.

Getting to $\bar{p}$ Consider the game when the firms prices are initially at p^*. Regardless of the size of ξ, the only equilibrium that can exist is (p^*, p^*). One firm increasing its price is not an equilibrium, since p^* is already the best response to p^*. Both firms raising prices to the same price $\bar{p}$ is not an equilibrium since conditional on changing price $\bar{p}(p^*) \in (p^*, \bar{p})$ is the best response. In a dynamic game, firm 2 may "take the high road" by posting $\bar{p}_2$ today. Its competitor may choose $p'_1 \in (p^*(\bar{p}_2), \bar{p}_2)$ next period, knowing that at $(p'_1, \bar{p}_2)$, the menu cost faced by firm 2 will make a downward response unprofitable. In this way, firms can constructively distribute gains and losses from policies across periods and achieve prices above p^*.

Numerical example In the main text, the profit function of the firm is

$$\pi_1(p_1, p_2) = \left(\frac{p_1}{p(p_1, p_2)} \right)^{-\eta} \left(\frac{p(p_1, p_2)}{P} \right)^{-\theta} (p_1 - 1)C,$$

$$p(p_1, p_2) = \left[p_1^{1-\eta} + p_2^{1-\eta} \right]^{1/1-\eta}.$$

To be consistent with notation in this appendix, I have replaced markups with prices and a unit marginal cost. From this profit function we can solve in closed form for the Nash equilibrium price as follows.

The first order condition of the firm's problem is

$$\left[p_1^{-\eta} - \eta p_1^{-\eta-1}(p_1 - 1) \right] p^{\eta-\theta} + (\eta - \theta) p_1^{-\eta} p^{\eta-\theta-1}(p_1 - 1) \frac{\partial p}{\partial p_1} = 0,$$

where the term in square brackets gives the first order condition of a monopolistically competitive firm facing elasticity of demand η. The second term gives the marginal profit due to the firm increasing the sectoral price. Since $\eta > \theta$, this second term is positive, implying that the term in brackets is negative, and so the equilibrium price must be larger than the monopolistically competitive price under η.

Two additional results for a CES demand system allow us to solve the first order condition in closed form. First,

$$\frac{\partial p}{\partial p_1} = \left[p_1^{1-\eta} + p_2^{1-\eta} \right]^{\frac{1}{1-\eta}-1} p_1^{-\eta} = \left(\frac{p_1}{p} \right)^{-\eta}.$$

Second, the revenue of the firm is $r_1 = p_1(p_1/p)^{-\eta}(p/P)^{-\theta}C$, which gives the following revenue share:

$$s_1 = \frac{r_1}{r_1 + r_2} = \frac{p_1^{1-\eta}}{p_1^{1-\eta} + p_2^{1-\eta}} = \left(\frac{p_1}{p} \right)^{-\eta} \frac{p_1}{p} = \frac{\partial p}{\partial p_1} \frac{p_1}{p}.$$

Using these results in the first order condition we obtain

$$p_1 - \eta(p_1 - 1) + (\eta - \theta)(p_1 - 1)s_1 = 0.$$

Since firms are symmetric, the equilibrium will yield equal revenue shares $s_1 = 0.5$, and $p^* = \varepsilon/(\varepsilon - 1)$, where ε is an average of the within- and across-sector demand elasticities $\varepsilon = 0.5 \times (\eta + \theta)$. The form of the solution implies that markups are consistent with those chosen by a monopolistically competitive firm facing an elasticity of demand equal to ε. Note that since P and C are first order terms in the firm's profit function, they do not affect the Nash equilibrium markup.

Calibration The calibration of the dynamic duopoly model yielded $\theta = 1.5$ and $\eta = 10.5$ (see Table 1). For these values, $\varepsilon = 6$ and $p^* = 1.2$.[72] I apply these values to the equilibrium profit function from the text (8), in which $P^{\theta-1}$ would multiply the profit function instead of $PC^{-\theta}$. Setting P to the average markup 1.30, Figure A2 shows how $(\xi, \bar{p})$-space separates across different equilibria. It is entirely consistent with the theoretical results. Recall that the model was calibrated to the average size and frequency of price change, so the menu cost was not chosen with a particular equilibrium in mind. Note that the average markup in the model is $\bar{p} = 1.3$, and the upper bound on the menu cost is $\bar{\xi} = 0.17$ (marked with an x in the figure). Zbaracki, Ritson, Levy, Dutta, and Bergen (2004) find that price adjustment costs make up 1.2 percent of firm revenue. As a benchmark, $\Delta_{II}(\bar{p})/rev(\bar{p}, \bar{p}) = 0.012$ at $\bar{p} = 1.27$, so a menu cost around empirical estimates as a share of revenue would, in this static game under the calibrated parameters of the model, guarantee a Type-I equilibrium.

Figure A6 plots various features of this profit function, varying p_2. Under the profit function derived from CES preferences, it is not true that $\pi_{12} > 0$ everywhere, but this is true at $(p_1, p_2) = (1.3, 1.3)$, so around the average markup in the calibrated model.[73]

Summary From this exercise, the following is a heuristic understanding of the dynamic model. Nominal rigidity allows firms to fluctuate around a markup which is larger than the frictionless Nash equilibrium. However, this is constrained by the size of the menu cost, which is pinned down by the average frequency of price change. Given a menu cost ξ, firms choose reset prices

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[72] Recall that the *Alt III* calibration of the monopolistically competitive model set $\eta = 6$ to deliver this as a frictionless markup.

[73] An unusual property of the CES profit function is that profits are always positive for $p > 1$, regardless of price. This implies, as shown in Panel C, that the second derivative must, for high prices, become positive.

around a real price $\bar{p}$ that supports a Type-I equilibrium, but not so high as to risk a Type-II equilibrium. Idiosyncratic shocks force the firms' real prices apart, but the firms keep on adjusting their prices so as to not let them get too far away from $\bar{p}$. Prices that are too high invite undercutting, and prices that are too low reduce profitability. Menu costs in the range of empirical estimates can sustain markups in the range of empirical estimates. Finally, getting to these high prices requires firms to reduce profit in the short run in order to lay the incentives for their competitor to choose a price that maintains high long run profits for the sector.

Calvo model Finally, consider a Calvo version of the static model, where each firm changes its price with probability α. Let $\tilde{p}$ be the optimal reset price of the firm. Then a Nash equilibrium requires that each firm's first order condition be satisfied at $\tilde{p}$:

$$\alpha \pi_1(\tilde{p}, \tilde{p}) + (1 - \alpha)\pi_1(\tilde{p}, \bar{p}) = 0.$$

It is straightforward to show that $\tilde{p} < p^*(\bar{p})$. A sufficient condition is that $\pi_1(\tilde{p}, \bar{p}) < 0$, since $\pi_1(p^*(\bar{p}), \bar{p}) = 0$. The first order condition implies that this is true if $\pi_1(\tilde{p}, \bar{p}) > \pi_1(\tilde{p}, \tilde{p})$, which is true due to complementarity and $\bar{p} > \tilde{p}$. Note that as $\alpha \to 1$, then $\tilde{p} \to p^*$.

Proof For the Type-III equilibrium to exist, conditions ($C5$) and ($C6$) must hold simultaneously, requiring that

$$\pi(p^{**}(\bar{p}), p^*(\bar{p})) - \pi(\bar{p}, p^*(\bar{p})) \le \pi(p^*(\bar{p}), \bar{p}) - \pi(\bar{p}, \bar{p}).$$

I prove that the negation of this inequality always holds. Note that the expression on the left hand side can be decomposed as follows:

$$
\begin{aligned}
\pi(p^{**}(\bar{p}), p^*(\bar{p})) - \pi(\bar{p}, p^*(\bar{p})) &= \left[\pi(p^{**}(\bar{p}), p^*(\bar{p})) - \pi(p^*(\bar{p}), p^*(\bar{p}))\right] \\
&\quad + \left[\pi(p^*(\bar{p}), p^*(\bar{p})) - \pi(\bar{p}, p^*(\bar{p}))\right].
\end{aligned}
$$

Since the best response function is upward sloping, then $p^{**}(\bar{p}) < p^*(\bar{p}) < \bar{p}$, and the profit function $\pi(p, p^*(p))$ is downward sloping for $p > p^{**}(\bar{p})$. This implies that each of the two terms on the right-hand side is positive. A sufficient condition for the non-existence of a Type-III equilibrium is therefore

$$\pi(p^*(\bar{p}), p^*(\bar{p})) - \pi(\bar{p}, p^*(\bar{p})) \ge \pi(p^*(\bar{p}), \bar{p}) - \pi(\bar{p}, \bar{p}).$$

Noting that $p^*(\bar{p}) < \bar{p}$, then the fundamental theorem of calculus can be used to express this condition as

$$\int_{p^*(\bar{p})}^{\bar{p}} \pi_1(u, p^*(\bar{p})) \, du \leq \int_{p^*(\bar{p})}^{\bar{p}} \pi_1(u, \bar{p}) \, du.$$

Since $p^*(\bar{p}) < \bar{p}$ and the firms' prices are complements, then $\pi_1(u, p^*(\bar{p})) \leq \pi_1(u, \bar{p})$ for all $u \in [p^*(\bar{p}), \bar{p}]$, so this condition holds.

D   Discussion of model assumptions

1. CES demand structure   An alternative formulation of the demand system could have been chosen. A pertinent example is a nested logit system commonly used in structural estimation of demand systems. However, as shown by Anderson, de Palma, and Thisse (1992), the nested CES structure is isomorphic to a nested logit with a population of consumers that each choose a single option at each stage.[74] That is, consumers may have identical preferences for Kraft and Hellman's mayonnaise, up to an *iid* taste shock that shifts each consumer's tastes toward one or the other each period. A CES structure with equal weights will deliver the same market demand functions under an elasticity of substitution that reflects the distribution of taste shocks and reduced form elasticity of indirect utility to price.[75]

2. Random menu costs   Random menu costs serve two purposes in the model. First, they generate some small price changes. Some firms, having recently changed their price and accumulating little change in sectoral productivity, draw a small menu cost and again adjust their price. Figure 9 shows that a monopolistically competitive model with random menu costs gives a distribution of price changes that appear as smoothed versions of the bimodal spikes of Golosov and Lucas (2007). Midrigan (2011) explicitly models multiproduct firms and shows that the implications for aggregate price and quantity dynamics are—when calibrated to the same price-change data—the same as in a model with random menu costs. What is important for these dynamics is that the model generates small price changes—which dampen the extensive margin effect—leading to the statement that the conclusions drawn are not sensitive to the exact mechanism used to generate small price changes. In this sense, one can think of the random menu costs in my model as stand-

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[74]I thank Colin Hottman for making this point and take its presentation from Hottman (2016).

[75]For estimation of alternative static demand systems using scanner data similar to that used in this paper see Beck and Lein (2015) (nested logit), Dossche, Heylen, and den Poel (2010) (AIDS), and Hottman, Redding, and Weinstein (2014) (nested CES). Only the latter studies an equilibrium, imperfectly competitive model.

ing in for an unmodeled multiproduct pricing problem.

Second, and most important, random menu costs that are private information allow me to avoid solving for mixed-strategy equilibria. This technique I borrow from Doraszelski and Satterthwaite (2010), who use it to address the computational infeasibility of solving the model of Ericson and Pakes (1995), which has potential equilibria in mixed strategies as well as issues with existence of any kind of equilibrium.[76] One could imagine solving the model under mixed strategies with fixed menu costs. Given the values of adjustment and non-adjustment and a fixed menu cost ξ, the firm may choose its probability of adjustment

$$\gamma_i(s, \mathbf{S}) = \arg\max_{\gamma_i \in [0,1]} \gamma_i \left[v_i^{adj}(s, \mathbf{S}) - \xi \right] + (1 - \gamma_i) v_i^{stay}(s, \mathbf{S}).$$

If firm $-i$ follows a mixed strategy such that $v_i^{adj}(s, \mathbf{S}) - \xi = v_i^{stay}(s, \mathbf{S})$, then a mixed strategy is a best-response of firm i. If one believes that menu costs are fixed, then this provides an alternative rationale for small price changes. Some firms may not wish to adjust prices this period, yet their mixed strategy over adjustment leads them to change prices nonetheless. However, the solution of this model would be vastly more complicated and at this stage infeasible. Appendix C proves that even in a simple static game of price adjustment with menu costs, such multiple equilibria may arise.

3. Information I assume that the evolution of product demand within the sector (z_{1j}, z_{2j}) is known by both firms at the beginning of the period and only menu costs are private information. An alternative case is that menu costs are fixed, but firms know only their own productivity and the past prices of both firms. This would add significant complexity to the problem. First, if productivity is persistent, then firms would face a filtering problem and a state vector that includes a prior over their competitor's productivity. Second, computation is still complicated even if productivity is *iid*. From firm 1's perspective z_{2j} would be given by a known distribution, which firm 1 must integrate over when computing expected payoffs. Integrating over firm 2's policy functions—which depend on z_{2j}—would be computationally costly. Since the menu cost is sunk, I avoid these issues.

4. Idiosyncratic shocks Three key assumptions are made regarding idiosyncratic shocks, they (i) follow a random walk, (ii) move both marginal revenue and marginal productivity schedules

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[76]This technique is also used by Nakamura and Zerom (2010) and Neiman (2011) in menu cost models.

of the firm, and (iii) are idiosyncratic rather than sectoral. These are made for tractability but are not unrealistic.

The first is plausible given that the model is solved monthly. It achieves tractability in that future states depend on growth rates of z_{ij}, which are *iid*. An alternative assumption deployed in similar studies is a random walk in money growth and AR(1) in firm-level shocks, which reduces the *aggregate* state variables of a monopolistically competitive model in the same way.[77] In the duopoly model, this would leave the overall state vector with five elements

$$ s_{ijt} = \left(p_{ijt-1}, p_{-ijt-1}, z_{ijt}, z_{-ijt}, \mu_t \right), $$

with four state variables in the sectoral problem which is infeasbible. The random walk assumptions on z_{ijt} and AR(1) in money growth implies $s_{ijt} = \left(\mu_{ijt}, \mu_{-ijt}, g_t, \mu_t \right)$, with two state variables in the sectoral problem which is feasbible. Additionally, since at a monthly frequency the estimated persistence of money growth is significantly less than one ($\rho_g = 0.61$, see Section 4), this is preferred.

The second seems acceptable if one does not hold a strong view on whether demand or productivity shocks drive firm price changes, a reasonable stance given that only revenue productivity is observed in the data for all but a small number of sectors. Midrigan (2011) interprets ε_{ij}'s as shocks to "quality": the good has higher demand but is more costly to produce. This assumption is necessary—along with random walk shocks—to express the sectoral state vector in two rather than four states.

The third assumption is not for tractability of the duopoly model but the monopolistically competitive model. The latter with sectoral shocks would introduce two additional state variables to the firm's problem: the sectoral markup and sectoral shock. Firms would require forecasting rules for *both* of these on top of forecasting rules for the aggregate markup. This would render the problem infeasible. In addition, the existing literature does not take this approach.

Empirically, I offer some new evidence from a decomposition of firm revenue in the IRI data that suggests this is also a good approximation. Changes in firm f revenue r_{fpst} can expressed as:

$$ \Delta \log r_{fpst} = \Delta \log \left(\frac{r_{fpst}}{r_{pst}} \right) + \Delta \log \left(\frac{r_{pst}}{r_{st}} \right) + \Delta \log r_{st}. \tag{D1} $$

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[77]Specifically, such an assumption would allow the aggregate state—following the Krusell-Smith approximation—to be captured by only the aggregate markup.

The first component is the change in expenditure on firm f relative to the market, the second component is the change in expenditure on product p relative to total expenditure in the region, and the final term is due to changes in total expenditure in the region. Taking the time series variance of this equation admits the following identity for each pair of product p and state s:

$$1 = \underbrace{\frac{var\left(\Delta\log\left(\frac{r_{fpst}}{r_{pst}}\right)\right)}{var\left(\Delta\log r_{fpst}\right)}}_{\text{(1) Firm share in market}} + \underbrace{\frac{var\left(\Delta\log\left(\frac{r_{pst}}{r_{st}}\right)\right)}{var\left(\Delta\log r_{fpst}\right)}}_{\text{(2) Market share in state}} + \underbrace{\frac{var\left(\Delta\log r_{st}\right)}{var\left(\Delta\log r_{fpst}\right)}}_{\text{(3) State expenditure}} + \underbrace{\frac{\text{Cov. terms}}{var\left(\Delta\log r_{fpst}\right)}}_{\text{(4) Covariance terms}}. \tag{D2}$$

I compute this decomposition for the largest firm in each market. Figure A5 plots the first three elements of equation (D2) against each other. Table A2 provides the average for each of these elements. The first column is a simple average across all pairs ps, and the second is weighted by average revenue $\bar{r}_{pr}$. Both point to fluctuations in the revenue share of the firm within the market as the most important in accounting for fluctuations in firm-level revenues, followed by fluctuations in the revenue share of the product within the state and finally fluctuations in total state expenditure.

The majority of fluctuations in the revenue of large firms are due to changes in the firm's share of expenditures within their product-state market, and not changes in the product's share of state expenditure or changes in the state's share of national expenditure. These results are robust to whether the second, third, or fourth largest firm in a market is used in the computation. As an initial approximation, firm rather than sectoral shocks seems satisfactory.

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Tables

Table 1: Parameters in the duopoly (Duo) and monopolistically competitive (MC) models

		Baseline		Alternative MC models		
		Duo_I	MC_I	MC_{II}	MC_{III}	MC_{IV}
A. Parameters						
Within-sector elasticity of demand	η	10.5	4.5	10.5	6	10.5
Upper bound of menu cost distribution	$\xi \sim U[0, \bar{\xi}]$	0.17	0.21	0.17	0.29	0.42
Size of shocks (percent)	σ_z	3.8	4.0	3.8	4.1	4.3
B. Moments						
Markup	$\mathbb{E}\left[\mu_{it}\right]$	1.30	1.30	1.12	1.22	1.13
Frequency of price change	$\mathbb{E}\left[\mathbf{1}\{p_{it} \neq p_{it-1}\}\right]$	0.13	0.13	0.19	0.13	0.13
Log abs. price change	$\mathbb{E}\left[\left|\log(p_{it}/p_{it-1})\right|\right]$	0.10	0.10	0.05	0.10	0.10
C. Results						
Std. deviation consumption (percent)	$\sigma\left(\log C_t\right)$	0.31	0.13	0.06	0.13	0.13
Average minus frictionless markup	$\mathbb{E}\left[\mu_{it}\right] - \mu^*$	0.10	0.02	0.01	0.02	0.02

Notes: (i) The table presents three alternative calibrations of the monopolistically competitive model. MC_{II} has the same parameters as the baseline duopoly calibration. MC_{III} has a value of η chosen such that it delivers the same frictionless markup as the duopoly model. MC_{IV} has a value of η equal to the duopoly model. Under MC_{III} and MC_{IV}, the values of $\bar{\xi}$ and σ_z are chosen to match the frequency and size of adjustment. (ii) Given that $\log z_{ij}$ follows a random walk, σ_z measures percentage innovations to z_{ij}. (iii) Average log absolute price change is computed conditional on a non-zero price change.

Table 2: Market structure and the composition of monetary non-neutrality

		1. Intensive	2. Extensive	3. Covariance
A. Fraction of inflation accounted for by each margin				
Monopolistic competition	π_t^{mc}	0.40	0.55	0.05
Duopoly	π_t^d	0.41	0.58	0.01
B. Fraction of the difference in inflation accounted for by each margin				
Monopolistic competition minus duopoly	$\left(\pi_t^{mc} - \pi_t^d\right)$	0.36	0.45	0.19
C. Fraction of the difference in each margin accounted for by regions of the distribution of markups				
Both markups below the median	$\left(\mu_i^L, \mu_j^L\right)$	-0.90	-0.73	-0.50
One below, one above the median	$\left(\mu_i^L, \mu_j^H\right)$	1.81	1.65	1.05
Both markups above the median	$\left(\mu_i^H, \mu_j^H\right)$	0.09	0.08	0.45

Table 3: Market structure, monetary non-neutrality and price-setting technologies

| | Fixed menu cost | Random menu cost | | Calvo | |
	Mon. Comp.	Duopoly	Mon. Comp.	Duopoly	Mon. Comp.
$\sigma(\log(C_t)) \times 100$	**0.08**	0.31	**0.13**	0.41	**0.38**
Relative $\sigma(\log(C_t))$					
Duopoly vs Mon.Comp		2.38	-	1.07	-
Calvo vs Menu Cost		-	-	1.32	**2.92**

Notes: (i) Menu cost model results are from Table 1: Duo_I and MC_I. (ii) Calvo model frequency of price change $\alpha = 0.13$ and size of shocks $\sigma_z = 0.05$ are chosen to match the same frequency and average size of absolute price change as the menu cost model. (iii) Note, the same σ_z is able to be used in both the duopoly and monopolistically competitive Calvo models due to the lack of pricing complementarity under Calvo. (iv) Relative $\sigma(\log(C_t))$ is the ratio of $\sigma(\log(C_t))$ for the relevant comparison.

Table 4: Moments of the distribution of price changes: $x_{it} = \log\left(p_{it}/p_{it-1}\right)$

Model		Std.	Skew.	Kurt.	$p10$	$p25$	$p75$	$p90$	Increases
Monopolistic competition	MC_I	0.11	-0.26	1.88	-0.14	-0.10	0.09	0.12	0.58
Duopoly	Duo_I	0.11	-0.06	1.79	-0.15	-0.10	0.10	0.14	0.54

Notes: (i) All moments are from the distribution of price changes. (ii) pX give the percentiles of the price change distribution. (ii) *Increases* gives the fraction of prices changes that are positive.

Table 5: Market structure and output losses due to nominal rigidity

			Mon. Comp. MC_I	Duopoly Duo_I
(1)	Output under no distortions $\bar{\xi} = 0$	$\mu_{it} = \mu^*$	0.78	0.83
(2)	Output under no dispersion (level only)	$\mu_{it} = \mathbb{E}[\mu_{it}]$	0.77	0.77
(3)	Output in full model (level + dispersion)		0.76	0.75
(1)-(3)	Total output loss due to nominal rigidity		2.6%	9.6%
(1)-(2)	... due to level of markups		0.49	0.77
(2)-(3)	... due to dispersion in markups		0.51	0.23

Notes: (i) Calibration of both models is as in Table 1, MC_I and Duo_I. Recall that these calibrations are such that $\mathbb{E}[\mu_{it}]$ is the same in both models. (ii) When the markups of all firms are equal $\mu_t = \mu_{it}$, so under $P_t Y_t = M_t$, then $Y_t = M_t / P_t = 1/\mu_t$. This is used to simply compute output under the counterfactuals in rows (1) and (2). Row (3) takes average output from simulations of the model with aggregate shocks.

Additional and appendix tables

Table A1: Existing results

(1)	(2)	Ref. (3)	Peak IRF $\frac{\Delta \log Y_t}{\Delta \log M_t}$ (4)	Slope PC $\lambda = \frac{\pi_t}{\widehat{mc}_t}$ (5)	Freq. α (6)	Dur. $1/\alpha$ (7)
Panel A.						
Golosov-Lucas	Menu-cost	Fig. 4a	**0.42**	1.36	0.67	1.49
Nakamura-Steinsson	14-sector	Fig. VIII	**0.50**	1.00	0.62	1.62
	+ Round-a-bout*	Fig. IX	**0.80**	0.25	0.39	2.56
Gertler-Leahy	Baseline	Fig. 2	**0.45**	1.22	0.65	1.53
	+ sectoral labor**	Fig. 3	**0.75**	0.33	0.43	2.30
Burstein-Hellwig	Baseline	Fig. 5	**0.34**	1.94	0.73	1.37
	+ DRS**	Fig. 5	**0.56**	0.79	0.58	1.73
	+ Wage rigidity*	Fig. 5	**0.70**	0.43	0.47	2.11
Klenow-Willis	Baseline	Fig. 4	-	**0.51**	0.50	1.99
	+ Kimball**	Fig. 4	-	**0.40**	0.46	2.16
This paper	Monopolistic comp.	Fig. 5	**0.42**	1.38	0.67	1.49
	Duopoly**	Fig. 5	**0.74**	0.36	0.45	2.25
Forms of pricing complementarity: $*$ = 'macro'-complementarity, $**$ = 'micro'-complementarity						
Panel B.						
Calvo model	Bils-Klenow	Tab. 1	0.967	0.167	0.22	**4.55**
	6 month price duration		0.967	0.033	0.17	**6**
	9 month price duration		0.986	0.014	0.11	**9**
	12 month price duration		0.992	0.008	0.08	**12**

Notes: Column (4) provides my calculation of the ratio of the peak output response $\Delta \log Y_t$ to the size of a monetary shock $\Delta \log M_t$, as inferred from the impulse response provided in the referred to paper (column 1), and figure (column 3). For example, Fig. VII of Nakamura and Steinsson (2010) shows a peak response of $\Delta \log Y_t = 0.005$, in response to $\Delta \log M_t = 0.010$. The models referred to are as follows. In Nakamura and Steinsson (2010), the round-a-bout production technology with an intermediate share of 0.70. In Gertler and Leahy (2008), the sectoral labor supply model with a unit Frisch elasticity of labor supply. In Burstein and Hellwig (2007) "+DRS" refers a decreasing returns production technology (labor share equal to 0.55), "+ Wage rigidity" refers to aggregate nominal wage rigidity: $W_t = Y_t^{-0.8} M_t$. In Klenow and Willis (2016), the model with Kimball (1995) preferences and super-elasticity of demand $\theta = 10$. Now consider a New-Keynesian model with constant returns to scale in production, no idiosyncratic shocks, and Calvo price adjustment. In this model, output is proportional to real marginal cost, and the response of prices to changes in real marginal cost $(\pi_t / \widehat{mc}_t)$ would be given by $\lambda = (1 - x)/x$, where x is the value in column (4). Here, λ is the slope of the Phillips curve. In this model, λ would obtain under the monthly frequency of price change α given in Column (6): $\lambda = (1 - \beta\theta)(1 - \theta)/\theta$, where $\theta = 1 - \alpha$. Column (7) provides the average duration of prices implied by α, interpretable as *"the average duration of prices in a baseline New-Keynesian model that would deliver the same relationship between real marginal cost and inflation following monetary shocks, implied by the given model in column (2)"*. **Panel B**, proceeds backward, starting with an average duration of price change in column (7). Christiano, Eichenbaum, and Trabandt (2015) estimate a 12 month average price duration. Smets and Wouters (2007) estimate a 6 month average price duration in a model with strong complementarities and sticky wages.

Table A2: Decomposing changes in firm revenue

	Unweighted	Revenue weighted
(1) Firm share in market	1.27	1.07
(2) Market share in state	0.72	0.40
(3) State expenditure	0.20	0.13
(4) Covariance terms	-1.20	-0.61

Notes: Table gives the averages of the elements of equation $(D2)$, computed for each product p, region r, where the firm f has the largest revenue in market pst. There are $1,333$ observations (31 products and 43 regions). Since these are averages, each column does not necessarily sum to one.

Figures
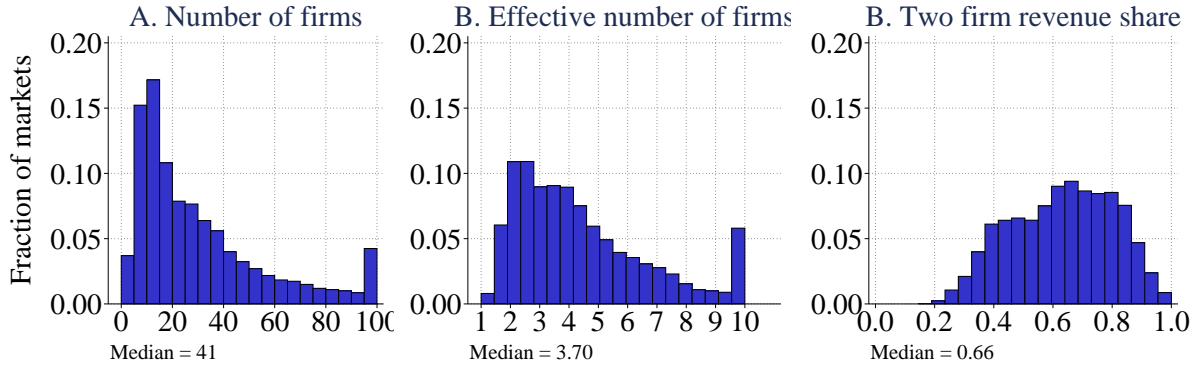
Figure 1: Wholesaler market concentration in the IRI data

<u>Notes:</u> (i) A market is defined as an IRI product category p within state s in quarter t giving $191,833$ observations. (ii) A firm i is defined within a pst market by the first 6 digits of a product's bar code, which identifies the wholesale firm. (iii) Revenue r_{ipst} is the sum over the revenue from all products of firm i in market pst. See Appendix A for more details on the data. (iv) Medians reported in the figure are revenue weighted. Unweighted medians are A. 21, B. 3.88, C. 0.64. (v) Each histogram has 20 bins. **Panel A**: Number of firms is the total number of firms with positive sales in market pst. **Panel B**: Effective number of firms is given by the inverse Herfindahl index h_{pst}^{-1}, where the Herfindahl index is the revenue share weighted average revenue share of all firms in the market, $h_{pst} = \sum_{i \in \{pst\}} (r_{ipst}/r_{pst})^2$. **Panel C**: Two-firm revenue share is the share of total revenue in market pst accruing to the two firms with the highest revenue.
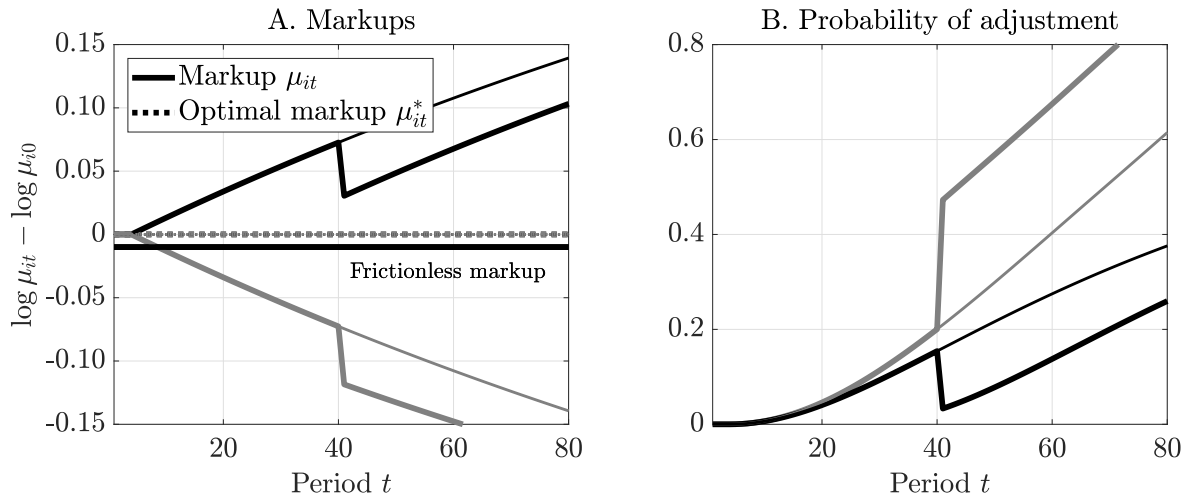
Figure 2: Example - Positive monetary shock in monopolistically competitive model

<u>Notes:</u> Thin solid lines give exogenous evolution of markups for two firms *within the same sector* absent a monetary shock. Thin dashed lines give corresponding optimal markups conditional on adjustment, where $\mu_1^* = \mu_2^*$. Thick solid lines include a monetary shock in period 40 which decreases both firms' markups. Thick dashed lines—which lie on top of the thin dashed lines before period 40—give the corresponding optimal markups. The model is solved in steady state, and the monetary shock is a one-time unforeseen level increase in money. The parameters of the model are as in Table 1. The y-axis in panel A describes the log deviation of markups from the value chosen when realizations of shocks and menu costs are zero, $\bar{\mu} = 1.30$, which is equal to the average markup.
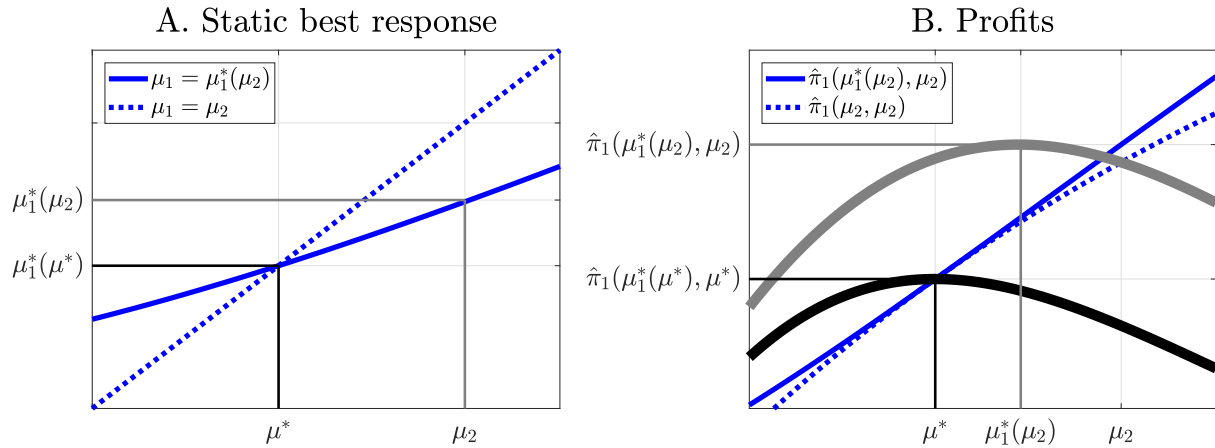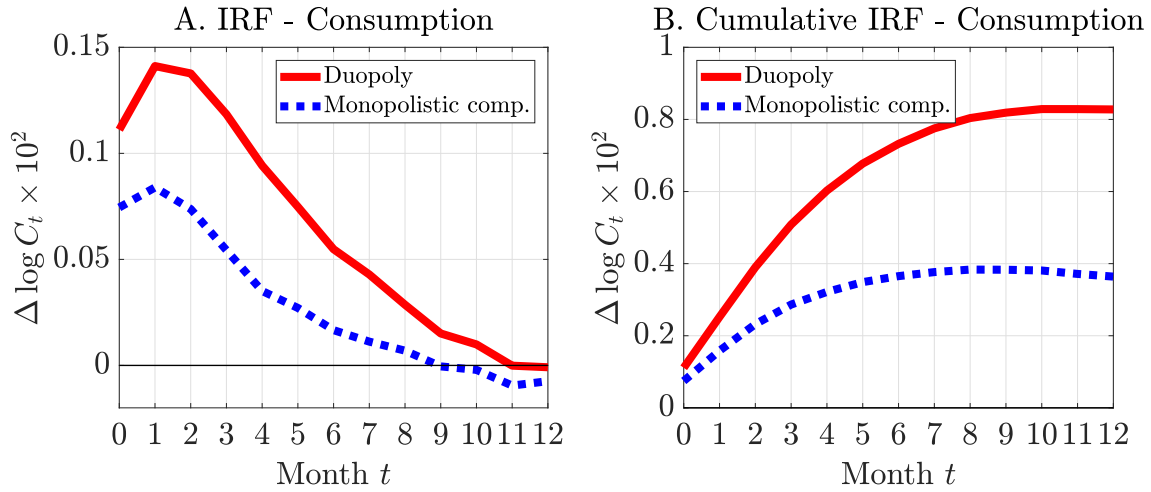
Figure 3: Static complementarity

Notes: Thick curves in panel B plot the component of firm 1's profit function due to the two firms' markups: $\hat{\pi}_1(\mu_1, \mu_2)$ from the normalized profit function in equation (8). The only parameters that enter this function are η and θ, which are set to their calibrated values of 10.5 and 1.5 (see Table 1). The upper (grey) curve describes firm 1 profits when $\mu_2 = 1.30$, which equals the average markup under the baseline calibration. The lower (black) curve describes firm 1 profits when $\mu_2 = 1.20$, which equals the frictionless Nash equilibrium markup under the baseline calibration. Given a value of μ_2 on the x-axis, the solid thin line describes $\hat{\pi}_1(\mu_1^*(\mu_2), \mu_2)$, under firm 1's static best response. The static best response $\mu_1^*(\mu_2)$, is plotted in panel A. Given a value of μ_2 on the x-axis, the dotted thin line describes $\hat{\pi}_1(\mu_2, \mu_2)$, under firm 1 setting its markup equal to firm 2's.
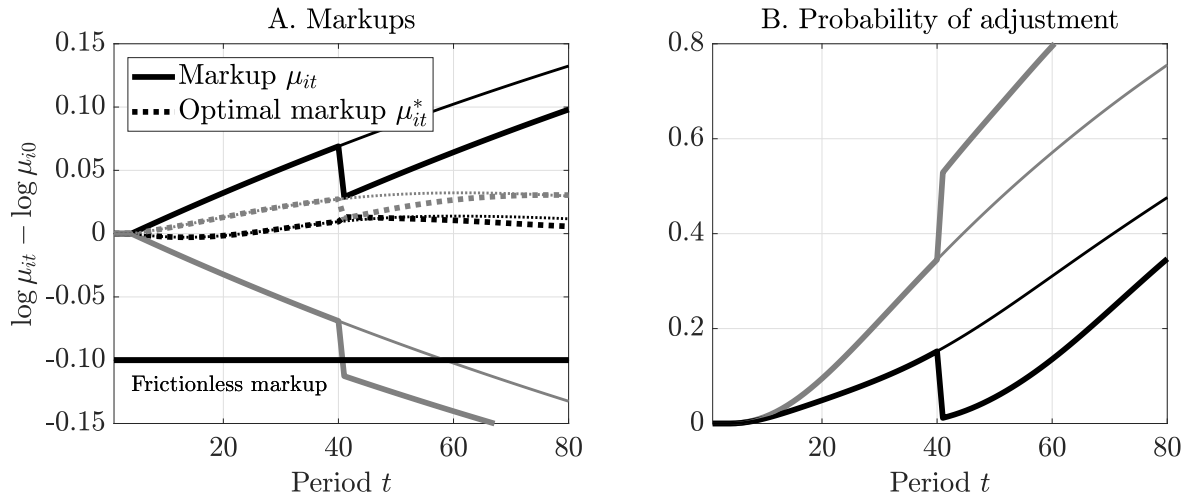
Figure 4: Example - Positive monetary shock in duopoly model

Notes: Thin solid lines give exogenous evolution of markups for two firms *within the same sector* absent a monetary shock. Thin dashed lines give corresponding optimal markups conditional on adjustment $\mu_1^*(\mu_1, \mu_2)$ and $\mu_2^*(\mu_1, \mu_2)$. Thick solid lines include a monetary shock in period 40 which decreases both firms' markups. Thick dashed lines—which lie on top of the thin dashed lines before period 40—give the corresponding optimal markups. The model is solved in steady state, and the monetary shock is a one-time unforeseen level increase in money. The parameters of the model are as in Table 1. The y-axis in panel A describes the log deviation of markups from the value chosen when realizations of shocks and menu costs are zero, $\bar{\mu} = 1.30$, which is equal to the average markup.

68

Figure 5: Monetary non-neutrality in the duopoly and monopolistically competitive models

Notes: Parameters for both models are as in Table 1 (Duo_I, MC_I). Impulse response functions computed by local projection (see footnote 39). The response function plotted IRF_τ for $\Delta \log C_t$ is multiplied by the standard deviation of innovations to money growth $\sigma_g = 0.0019$. This is then multiplied by 100, such that units are log points. The peak response elasticity is therefore $(0.0014/0.0019) = 0.74$.
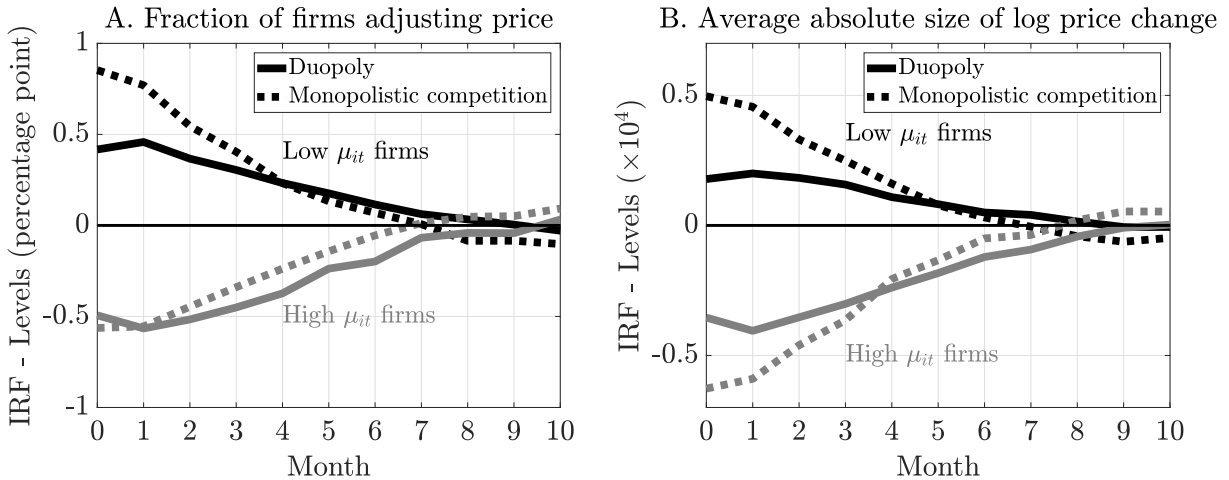
Figure 6: Impulse responses of frequency and size of adjustment to a positive monetary shock

Notes: Impulse response functions are computed by local projection (see footnote 39). For panel A, the dependent variable is the change in the fraction of firms adjusting price. For panel B, the dependent variable is the change in the average absolute size of log price changes. To isolate the effect of a positive monetary shock, only positive innovations to money growth $\varepsilon_t^g > 0$ are included in the regressions. Black (grey) lines correspond to low (high) markup firms. In the duopoly model, firms are assigned to the low-markup group if, within their sector, they have the lowest markup. In the monopolistically competitive model, pairs of firms are drawn at random and assigned to the low-markup group if their markup is the lowest in the pair.
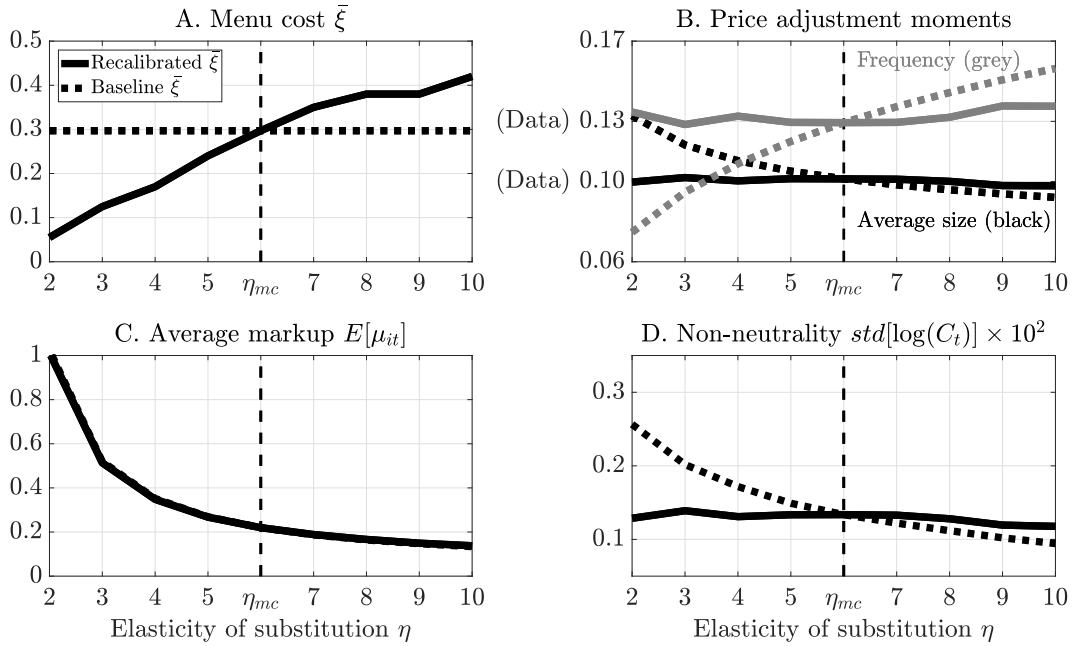
Figure 7: Elasticity of substitution comparative statics and monopolistic competition

<u>Notes:</u> Solid lines denote values for the monopolistically competitive model under $\sigma_z = 0.041$ and the recalibrated values of $\bar{\bar{\xi}}$ given by the solid line in panel A. These values of $\bar{\bar{\xi}}$ are chosen to best match data on both the frequency and size of price change (panel B). Dashed lines denote values for the monopolistically competitive model under $\sigma_z = 0.041$, with $\bar{\bar{\xi}}$ fixed at its value from calibration MC_{III} of Table 1. The vertical black lines mark the value of $\eta_{mc} = 6$ under this calibration. In panel C, the dashed line lies imperceptibly above (below) the solid line to the left (right) of $\eta_{mc} = 6$. For low values of η, and fixed $\bar{\bar{\xi}}$, frequency of price change is lower (panel B, grey dashed line), leading firms to choose higher markups for precautionary reasons. These effects on the average markup are, however, very small: the average markup is dominated by η.
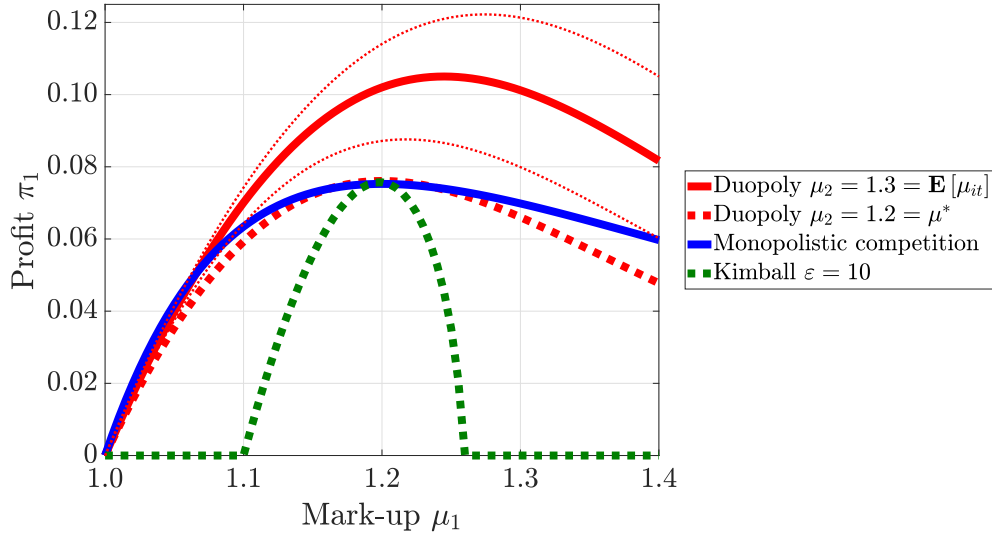
Figure 8: Market structure and the profit function of a firm

Notes: (i) In all three models, the frictionless optimal markup is $\mu^* = 1.20$, with $\eta_d = 10.5$ (Duo_I) and $\eta_m = 6$ (MC_{III}). (ii) The solid upper (red) line describes $\pi_1(\mu_1, \mathbb{E}[\mu_{it}])$, the flow profit of firm 1 when the markup of firm 2 is equal to the average markup in the duopoly model, which is 1.30. Its maximum $\mu_1^*(\mu_2) = \arg\max_{\mu_1} \pi_1(\mu_1, \mu_2)$ is obtained at 1.24. (iii) The thin dashed lines describe the same profit function when μ_2 is one standard deviation above and below $\mathbb{E}[\mu_{it}]$. (iv) The thick dashed red line describes $\pi_1(\mu_1, \mu^*)$, the flow profit of firm 1 when the markup of firm 2 is equal to the frictionless optimal markup μ^*, which is 1.20.
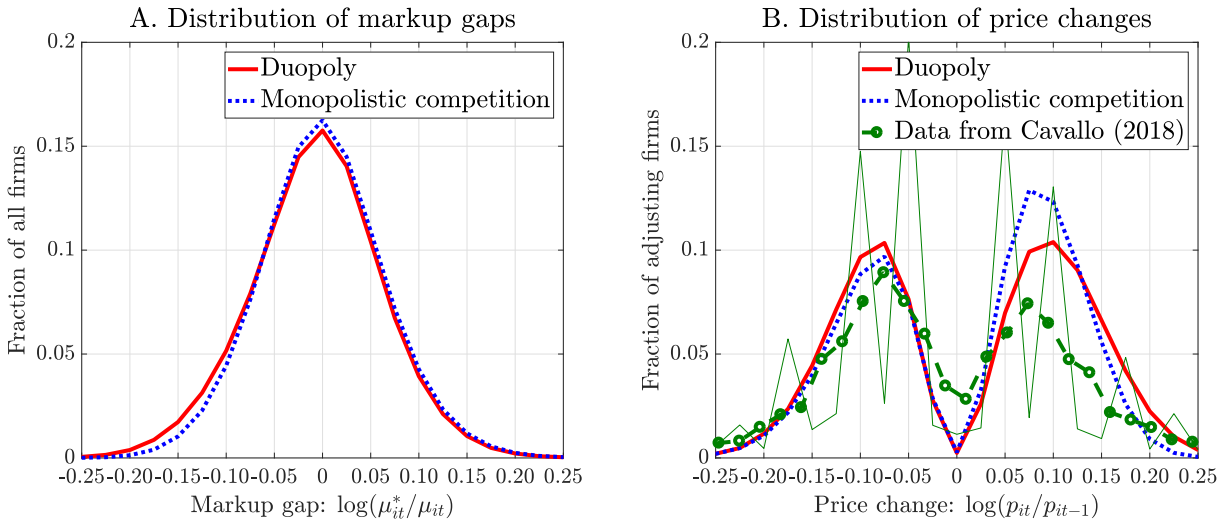
Figure 9: Distributions of markup gaps and price changes

Notes: The markup gap $\log\left(\mu_{it}^* / \bar{\mu}_{it-1}\right)$ is defined with respect to the markup that would occur if the firm does not change its price, and the optimal markup μ_{it}^*. The distribution of price changes is equal to the distribution of markup gaps conditional on a price change $\log\left(p_{it}/p_{it-1}\right) = \log\left(\mu_{it}^*/\bar{\mu}_{it}\right)$. For a derivation see Appendix B.1. Firms are binned in 0.025 intervals of the values on the x-axis. Raw data from Cavallo (2018) are prices p_{it} and p_{it-1} conditional on price change, from which I compute $\log\left(p_{it}/p_{it-1}\right)$. Thin line gives the raw histogram of price changes binned in 0.025 intervals. Thick line with circle markets gives kernel density plot with bandwidth of 0.025.
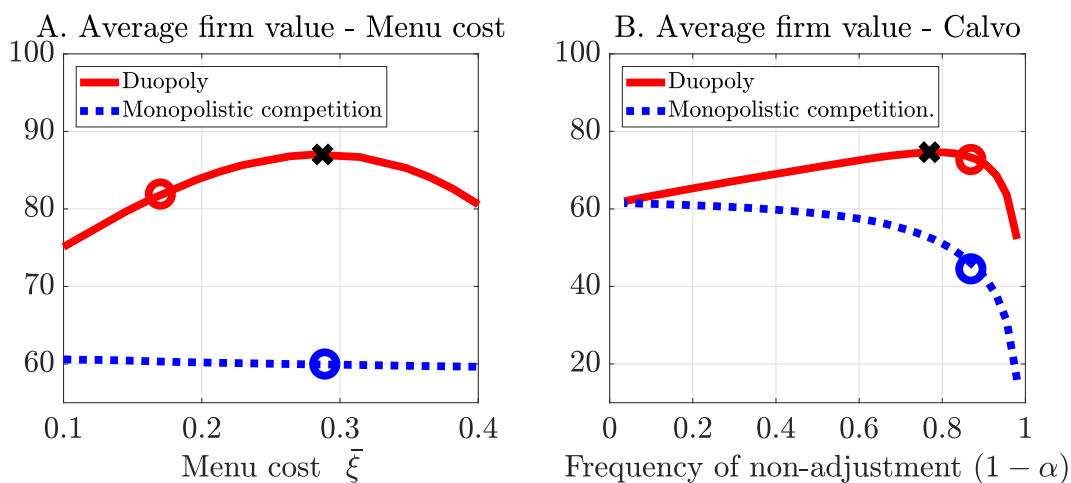
Figure 10: Comparative statics: Markups and firm value

Notes: (i) Figures plot comparative statics of the average firm value—in real terms—given by Bellman equation (9), with respect to changes in the size of nominal rigidity in the menu cost model (panel A) and Calvo model (panel B). (ii) The models are calibrated according to Table 1, Duo_I and MC_{III}, they therefore have the same markup and same real average value under no pricing frictions (see footnote to Table 1. (iii) The cross mark gives the size of the friction that maximizes firm value in the duopoly model. (iv) Panel A is truncated on the *x*-axis due to computational issues associated with approximating policy functions under very small and very large menu costs, when all other parameters are fixed: as the frequency of price change becomes too low or too high, the approximating nodes required change, while for the purposes of comparative statics these remain fixed. (v) Note that the scale of the *y*-axis differs. This is because the menu cost and Calvo models are not comparable in terms of firm value *in the presence of pricing frictions*. For a given frequency of price change, firm value is larger in the menu-cost model due to the ability to time price changes. This added value more than offsets the losses due to the small menu cost.
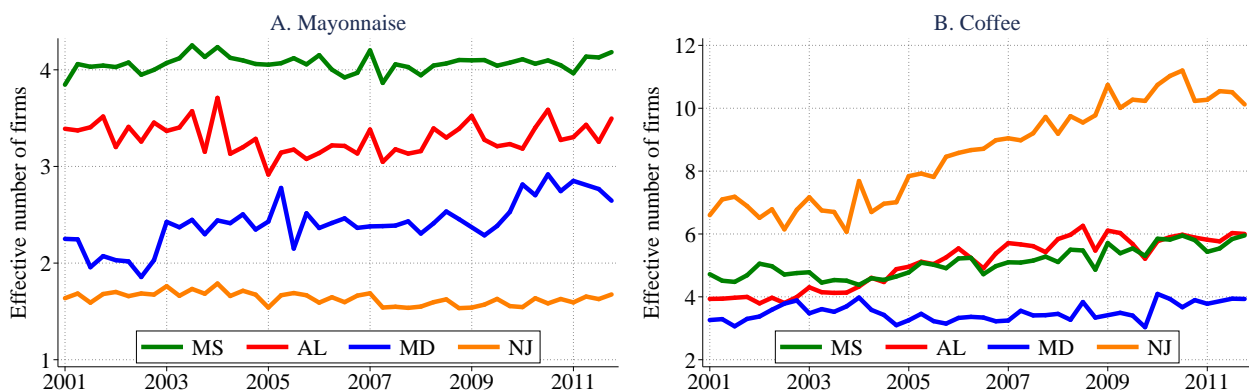

Figure 11: Within-product, Across-region variation in market concentration

Notes: For construction of the *Effective number of firms* measure see the notes to Figure 1.
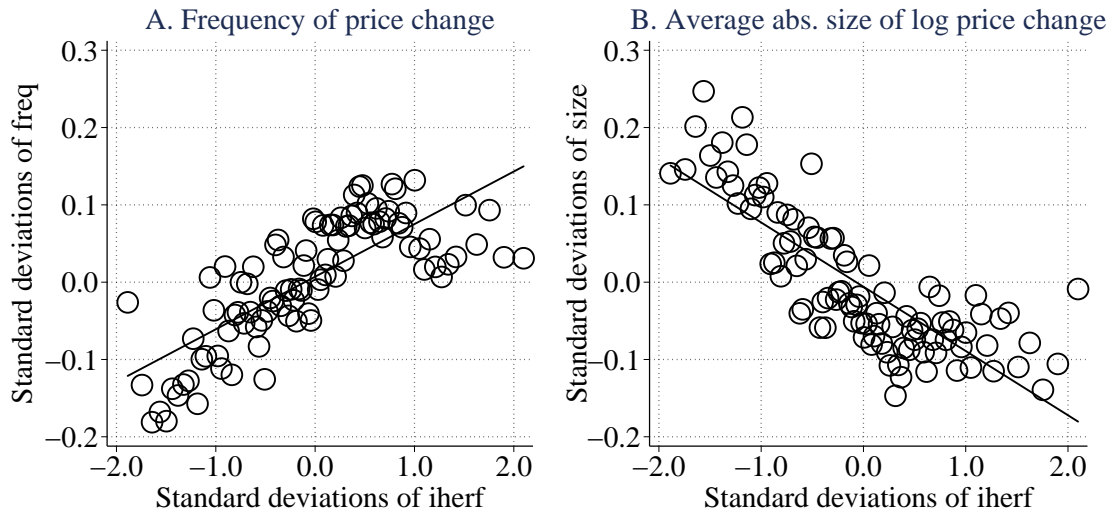
Figure 12: Empirical relationship between market concentration and price flexibility

<u>Notes:</u> Data are at good-p, state-s, quarter-t level ($61,884$ observations, 31 products, 43 states, 2001-2011). Concentration is measured by the effective number of firms implied by the inverse Herfindahl index (large is more equally sized firms, so less concentrated), computed from wholesale firm revenue shares in market-pst: $iherf_{pst}$ (see footnote to Figure 1). Frequency of price change $(freq_{pst})$ is the fraction of goods changing price, size of price change $(size_{pst})$ is the average absolute log price change (conditional on price change). For each measure x_{pst}, I first remove joint product-time-pt fixed effects using a regression that also controls for total market revenue rev_{pst}, and number of firms with positive sales $Nfirms_{prt}$. Residuals $\tilde{x}_{pst}$ are then scaled by the within-pt standard deviation: $\tilde{x}'_{pst} = \tilde{x}_{pst}/\text{std}[\tilde{x}_{pst}]$. I then bin markets into percentiles of $\widetilde{iherf}'_{pst}$, and compute within bin means of $\widetilde{freq}'_{pst}$, $\widetilde{size}'_{pst}$, and $\widetilde{iherf}'_{pst}$. These binned means are then used in the figure, with the within bin mean of $\widetilde{iherf}'_{pst}$ on the x-axis. Note that since results are *within-product-quarter*, then the x-axis can only be read as a measure of *relative* competitiveness of the state s market for good p at date t relative to other states s' at date t (e.g. in absolute terms some markets with low values of $\widetilde{iherf}'_{pst}$ may have high or low values of $iherf_{pst}$ relative to all markets).

Additional and appendix figures

A. Intensive: Still increase prices, and increase them by more
B. Extensive + Covariance: More firms increase prices, and increase them by more
C. Extensive: No longer decrease prices
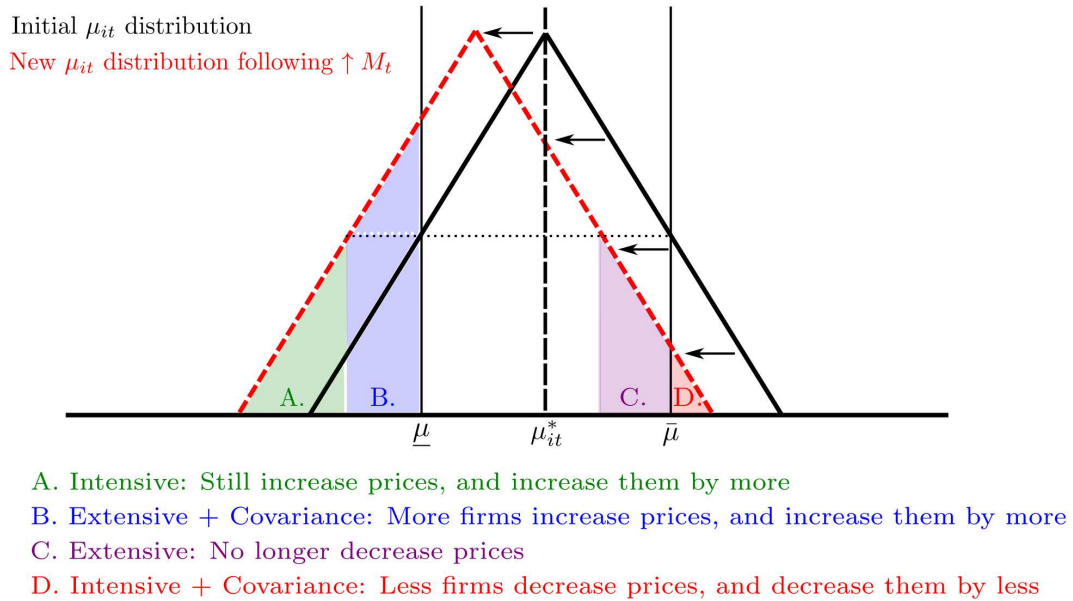D. Intensive + Covariance: Less firms decrease prices, and decrease them by less

Figure A1: Decomposing markup adjustment in a monopolistically competitive, menu cost model

Notes: Vertical solid lines give the thresholds for adjustment $\underline{\mu} < \bar{\mu}$. Following an increase in the money supply, all markups decrease by the same amount, as given by the leftward shift in the distribution. For a permanent one-time increase in the money supply, the optimal markup μ_{it} and thresholds for adjustment are not affected by the shock.
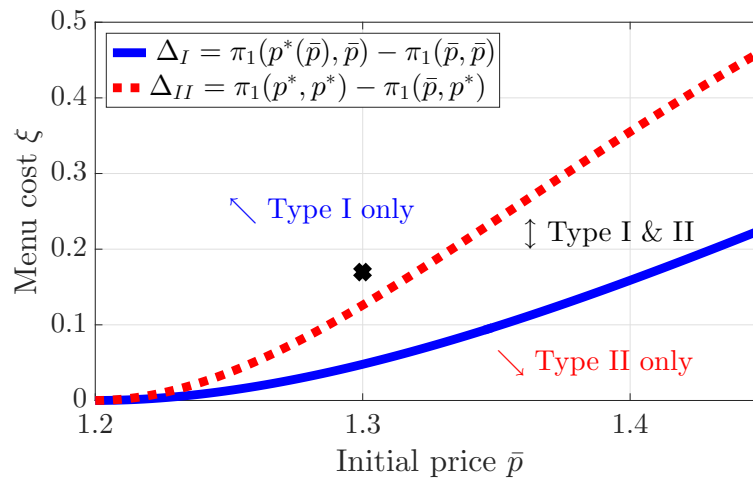
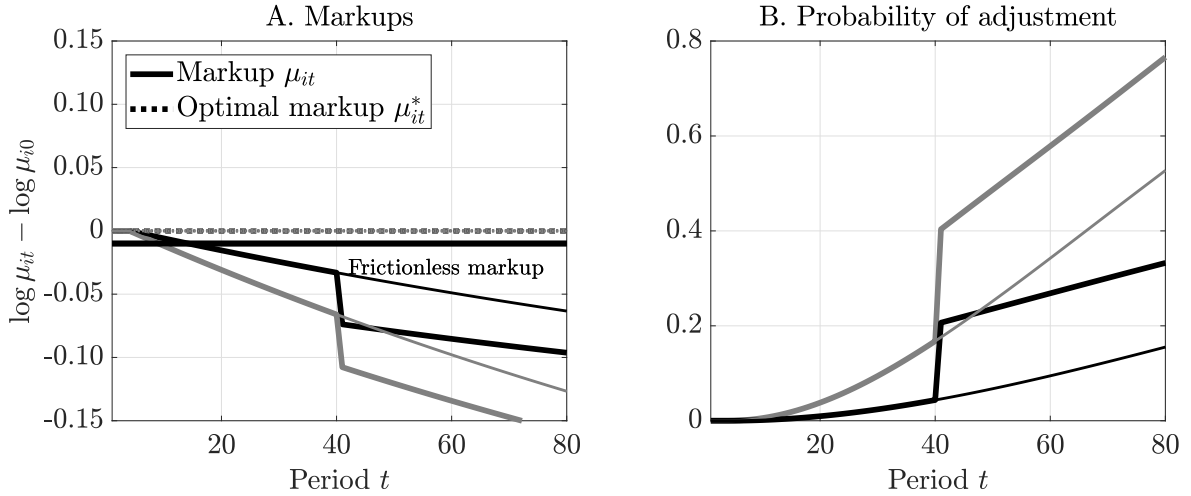Figure A2: Regions of equilibria in a static price setting game

Figure A3: Positive monetary shock in monopolistically competitive model - Low markup firms

Notes: Thin solid lines give exogenous evolution of markups for two firms absent a monetary shock. Thin dashed lines give corresponding optimal markups conditional on adjustment $\mu'_1 = \mu^*$ and $\mu'_2 = \mu^*$. Thick solid lines include a monetary shock in period 40, which decreases both firms' markups. Thick dashed lines (which lie on top of the thin dashed lines) give the corresponding optimal markups. The model is solved in absence of *aggregate* uncertainty and the monetary shock is a one-time unforeseen level increase in money. The *y*-axis in panel A describes the log deviation of markups from the value chosen when shocks and menu costs are zero, $\bar{\mu} = 1.30$, which is equal to the average markup.
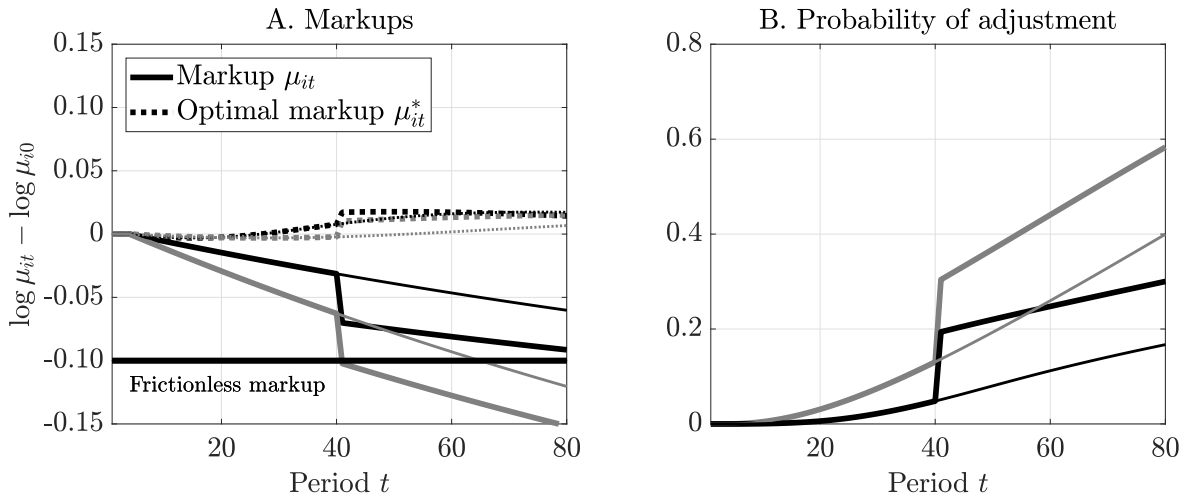

Figure A4: Positive monetary shock in duopoly model - Low markup firms

Notes: Thin solid lines give exogenous evolution of markups for two firms *within the same sector* absent a monetary shock. Thin dashed lines give corresponding optimal markups conditional on adjustment $\mu'_1 (\mu_1, \mu_2)$ and $\mu'_2 (\mu_1, \mu_2)$. Thick solid lines include a monetary shock in period 40, which decreases both firms' markups. Thick dashed lines (which lie on top of the thin dashed lines) give the corresponding optimal markups. The model is solved in the absence of *aggregate* uncertainty and the monetary shock is a one-time unforeseen level increase in money. The *y*-axis in panel A describes the log deviation of markups from the value chosen when shocks and menu costs are zero, $\bar{\mu} = 1.30$, which is equal to the average markup.
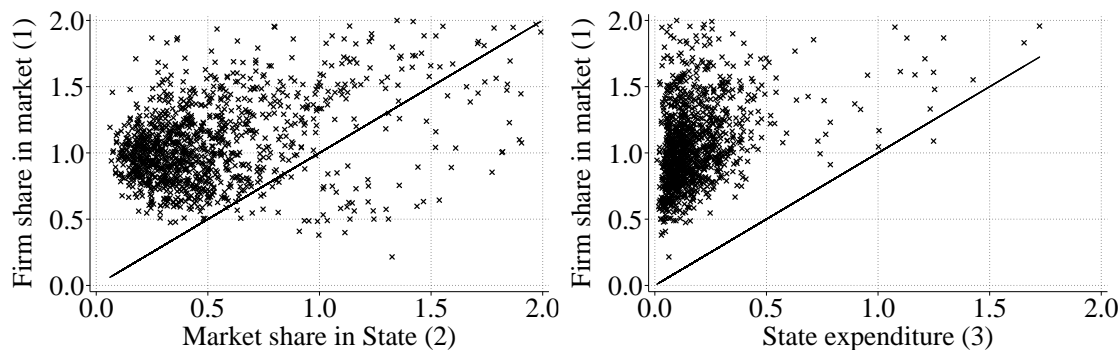
Figure A5: Decomposition of the variance of largest firm revenue changes

Notes: Figures plot the elements of equation $D2$, computed for each product p, region r, where the firm f has the largest revenue in market pst. There are $1,333$ observations (31 products and 43 regions).

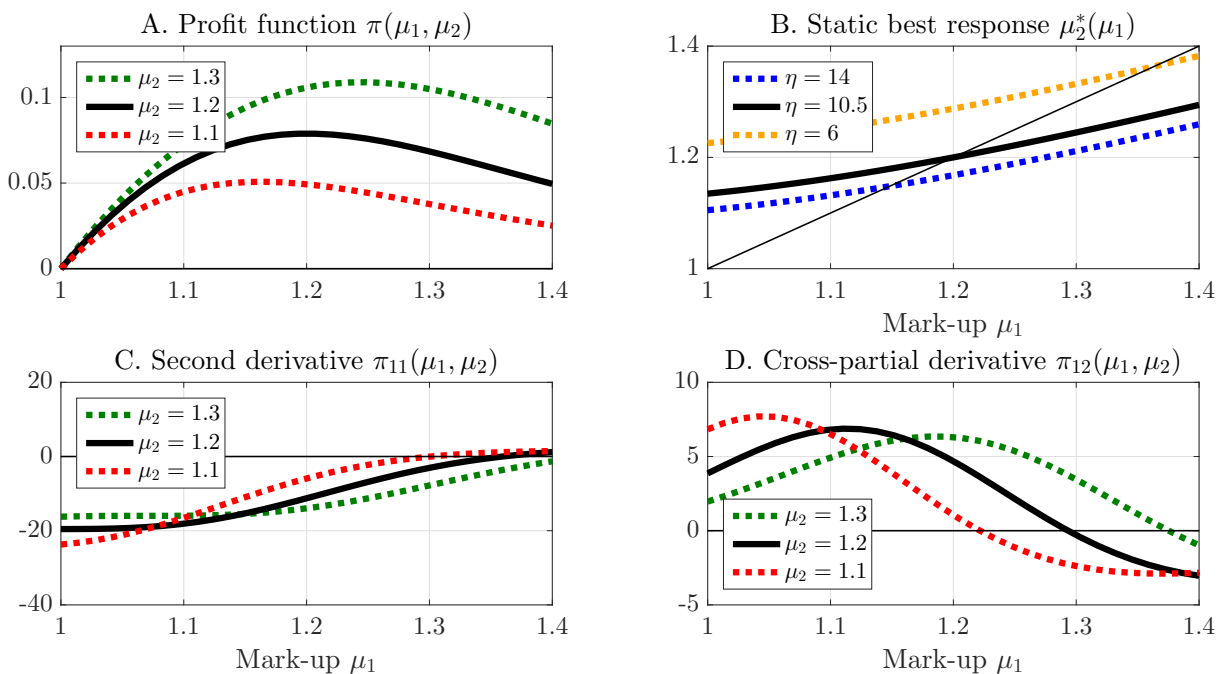
Figure A6: Properties of firm profit functions

Notes: Panels A, C, and D display features of the duopoly profit functions under $\theta = 1.5$, $\eta = 10.5$ as in Table 1. Given these parameters, the frictionless Nash-Bertrand markup is 1.20 due to an effective elasticity of demand of $\varepsilon = (1/2)(\theta + \eta)$ and a symmetric equilibrium. Panel B plots the static best response function $\mu_i^*(\mu_j)$ under $\theta = 1.5$ and different values of η. Higher values of η reduce the Nash equilibrium markup—given by the intersection of the best response with the 45-degree line—and increase the slope of the best response function.