Precautionary price stickiness

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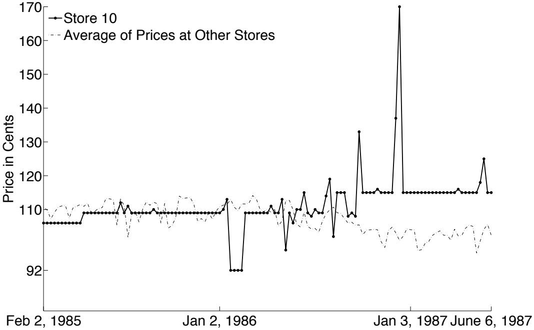
Many individual prices are "sticky"

Figure 1: The Price of Fleischmann's Margarine[(i)]



Source: Campbell and Eden (2010)

Motivating questions

1. What causes the "stickiness" of individual prices?
2. Does the rigidity of individual prices matter for aggregate business cycle fluctuations?

Implications for macroeconomic performance and for policy

Existing explanations

1. Why are prices sticky? – Technological constraints:

- "Menu" costs of changing price tags
  - Fixed
  - Stochastic
  - Calvo: 0 with prob. p, and ∞ with prob. $(1-p)$
- "Observation" or "information" costs

Existing explanations

2. Individual price stickiness $\Rightarrow$ rigidity of the aggregate price level?

- Calvo (1983): constant adjustment probability
  - Monetary shocks have large and persistent real effects
- Golosov-Lucas (2007): fixed "menu" cost + idiosyncratic shocks
  - Strong selection effect $\Rightarrow$ near-neutrality of money

Idea

- Suppose that price changing is risky: occasionally, firms may inadvertently set a price which is worse than the current one
- We assume the probability of setting any given price is proportional to the exponent of the value of having that price
- Firms can reprice *costlessly* in any given period

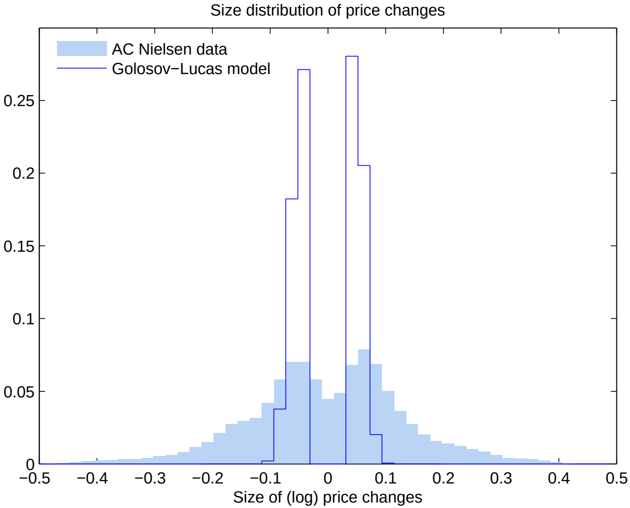
Preview of the main micro findings: stickiness

- The riskiness of changing prices implies price stickiness:
  - Firms change prices only when they are far from the optimum
  - When prices are close to optimal, firms leave them unchanged

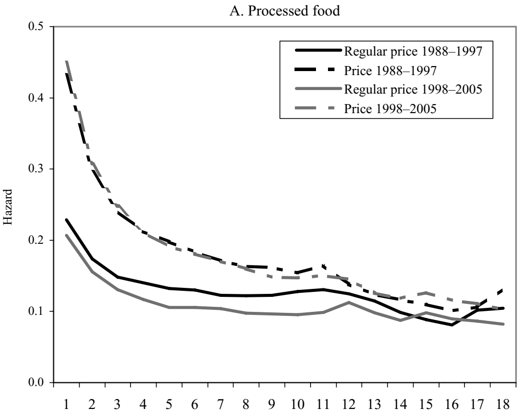
Preview of the main micro findings: four facts

- A single new parameter controls the degree of precision; we calibrate it to match the frequency of price changes
- We reproduce four “puzzling” features of the micro evidence:
  1. Co-existence of price changes of various sizes (Midrigan, forthcoming)
  2. Declining adjustment probability in price age (Klenow-Malin, 2009)
  3. Average size of price changes roughly constant in the price age (Ibid.)
  4. Extreme prices are young (Campbell-Eden, 2010)

Histogram of price changes: data vs. menu cost model



Declining price adjustment hazard

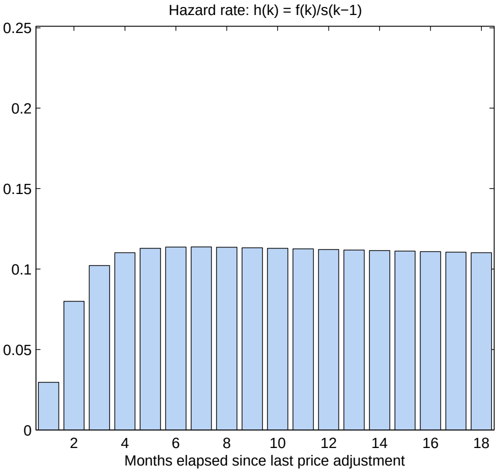


Months since the last price change

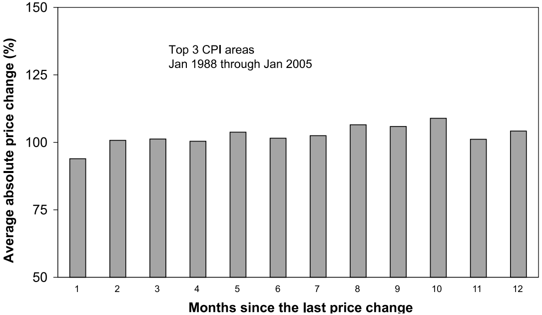
Source: Nakamura-Steinsson (2008)

Typical price adjustment hazard in the menu cost model

Idiosyncratic shocks with positive persistence

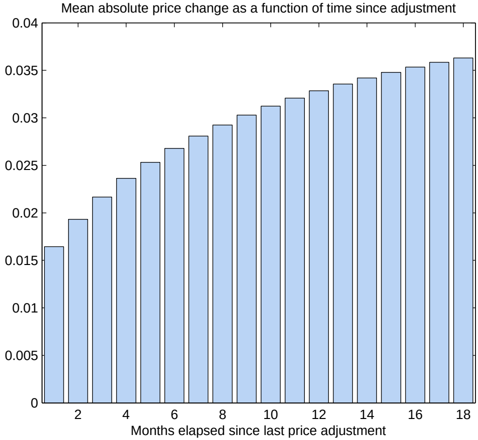


Average size of price changes as a function of price age



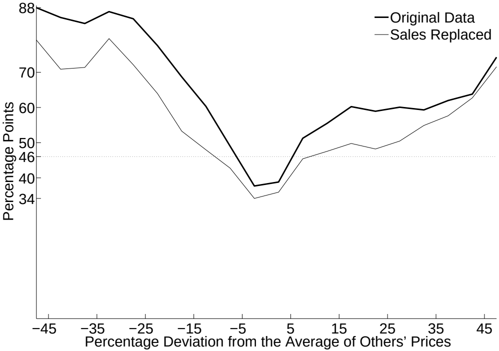
Source: Klenow-Kryvtsov (2008)

Average size of price changes in the Calvo model



Extreme prices are young in the data

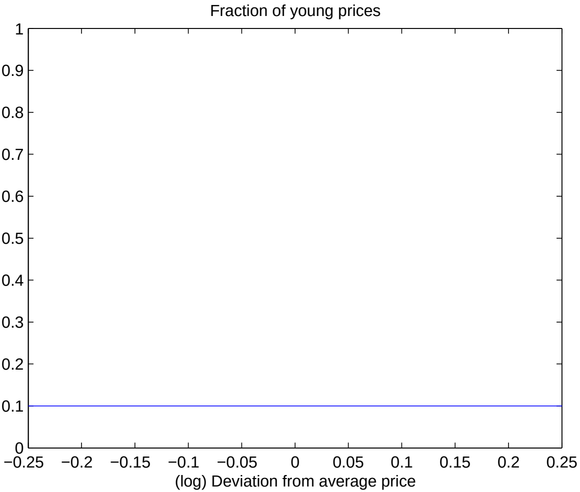
Figure 7: The Fraction of Young Prices by Relative Price(i)



Note: (i) Young prices are those with ages less than four weeks. The plotted fractions exclude prices one week old from both the numerator and denominator.

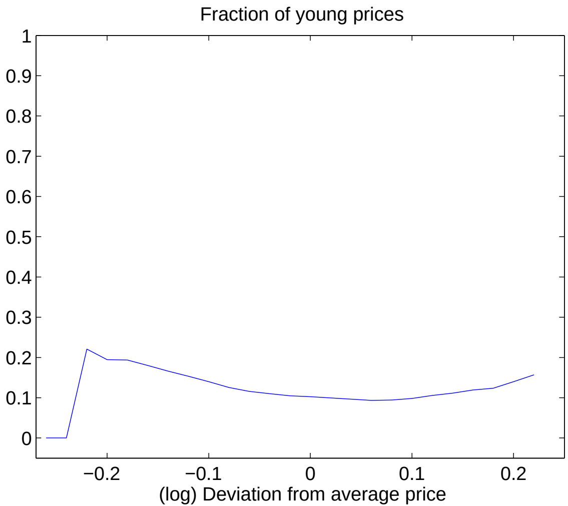
Source: Campbell-Eden (2010)

Extreme prices in the Calvo model



Extreme prices in the menu cost model

2% trend inflation



Preview of the main macro findings

- The model predicts well the effects of positive trend inflation on the frequency and size of price changes
- A powerful selection effect is at work, similar to the menu cost model
- The real effects of nominal shocks are much smaller than in the Calvo model, but nonetheless are twice as large as in the menu cost model
- Noise in the *timing* of repricing more easily delivers money non-neutrality than noise in reset prices themselves

Outline of the talk

1. Related literature
2. Model
3. Calibration
4. Computation
5. Results
6. Conclusions

Related literature: state-dependent pricing

- Previous work obtained solutions by limiting the scope of analysis
  - Partial equilibrium (Caballero-Engel, 2007; Klenow-Kryvtsov, 2008)
  - No idiosyncratic shocks, only aggregate (Dotsey-King-Wolman, 1999)
  - Strong assumptions on idiosyncratic process (Gertler-Leahy, 2005)
- But large idiosyncratic shocks are frequent (Klenow-Kryvtsov, 2008)
- Golosov-Lucas (2007): menu cost + large firm-level shocks
  - Striking near-neutrality result, but model's fit to price data questionable

Related literature: size distribution of price changes

Proposals to "fix" the distribution:

- Sectoral heterogeneity in fixed menu costs (Klenow-Kryvtsov, 2008)
- Multiple products on the same "menu" + leptokurtic technology shocks (Midrigan, 2010)
- Costain-Nakov (JMCB forthcoming): the probability of adjustment increases *smoothly* with the gain from adjustment
  - We match the distribution better with less free parameters

Related literature: bounded rationality, model uncertainty, information constraint

- "Bounded rationality": Akerlof-Yellen (1985)
  - Assume a fraction of non-maximizing agents
  - In our case *all* firms are close to, but not quite, rational
- "Model uncertainty": Hansen and Sargent (2010)
  - Looking for decision rules robust to local model misspecification
  - Entropy penalty constraining the set of alternative models
- "Information constraint": Sims (2003)
  - Constraint on information flow from environment to decision-maker
  - Our decision-maker has complete information but faces an implementation constraint

Related literature: "logit equilibrium"

- McKelvey and Palfrey (1995): a statistical generalization of Nash equilibrium which allows for noisy optimizing behavior
- Successful at explaining play in many games where Nash performs poorly (e.g. centipede game, Bertrand competition)
- A single-parameter generalization: imposes substantial discipline

Model: monopolistic firms

- Firm output: $Y_i = A_i N_i$
- Idiosyncratic productivity: $\log A_{it} = \rho \log A_{it-1} + \varepsilon^a_{it}$
- Profits: $U = P_i Y_i - W N_i$
- Firm value: $V(P_i, A_i, ...) = U + E[QV(P_i', A_i', ...)]$
- Optimal price choice: $P^*(A_i) = \arg\max_P V(P, A_i)$

Model: noisy optimization

- Instead, we assume *noisy optimization*
- The decision to change the price triggers a process, the outcome of which is uncertain
- The outcome is drawn from a logit distribution centered on P^*

$$\pi(P_i|A_i) = \frac{\exp(\xi V(P_i, A_i))}{\sum_P \exp(\xi V(P, A_i))}$$

- Precision parameter $\xi \in [0, \infty)$ controls the tightness around P^*

Model: precision parameter

Parameter $\xi \in [0, \infty)$ controls the "degree of precision":

- If $\xi = \infty$, firms choose the optimal price with $\pi(P^*|A_i) = 1$
- If $\xi = 0$, firms draw their price from a uniform distribution
- If $0 < \xi < \infty$, firms choose the optimal price with $\pi(P^*|A_i) < 1$

Model: adjustment decision

- Expected gain from adjustment

$$G = \sum_P \pi(P|A)V(P,A) - V(P,A) \gtrless 0$$

- Adjustment decision:
  - Change price if $G > 0$
  - Stay with current price if $G < 0$

- No randomness in the above timing decision

- Changing the price itself is costless

Model: (S,s) structure

- $G \gtrless 0$ depends on how far the current price is from the optimum
  - If the current price is far from the optimal, then $G > 0 \Rightarrow$ reset
  - If the current price is close to optimal, then $G < 0 \Rightarrow$ stay with current
- An (S,s) inaction band emerges endogenously as soon as $\xi < \infty$
- The width of the inaction band depends on the degree of precision ξ

Deriving logit choice from an entropy constraint

- Maximize the expected gain from adjustment

$$\max_{\lambda,\pi_i} \lambda \left(\sum_i \pi_i V_i - V - \xi^{-1} \sum_i \pi_i \log \pi_i \right)$$

subject to

$$\sum_i \pi_i = 1$$

- Optimality conditions:
  - $\pi_i = \exp(\xi V_i - \eta)$
  - $\lambda = \mathbf{1} \left(\sum_i \pi_i V_i - V > \xi^{-1} \sum_i \pi_i \log \pi_i \right)$

Model: the rest is standard

- Household utility: $\frac{C^{1-\gamma}}{1-\gamma} - \chi N + \nu \log(M/P)$ with discount β
- Period budget constraint:

$$P_t C_t + M_t + R_t^{-1} B_t = W_t N_t + M_{t-1} + T_t + B_{t-1} + \Pi_t$$

- Consumption bundle:

$$C_t = \left[\int_0^1 C_{it}^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}} \text{ with price } P_t \equiv \left[\int_0^1 P_{it}^{1-\epsilon} di \right]^{\frac{1}{1-\epsilon}}$$

- Money supply: $M_t = \mu \exp(z_t) M_{t-1}$, where $z_t = \phi_z z_{t-1} + \epsilon_t^z$

Model: aggregate consistency and aggregate state variable

- Labor market clearing: $N_t = \Delta_t C_t$
- Measure of price dispersion: $\Delta_t \equiv P_t^{\epsilon} \int_0^1 P_{it}^{-\epsilon} A_{it}^{-1} di$
- Balanced budget: $M_t = M_{t-1} + T_t$
- Bond market clears: $B_t = 0$
- Aggregate state variable: $\Omega_t \equiv (z_t, M_{t-1}, \mathbf{\Psi_{t-1}})$

Computation

- Challenge: need to keep track of the *distribution* of firms
- Reiter's (2009) method of "projection & perturbation"
- Appropriate for price-setting by firms: idiosyncratic shocks are relatively large; aggregate shocks are relatively small
- Two-step procedure, computing:
  1. Aggregate steady-state by non-linear projection on a finite grid
  2. Aggregate dynamics by linearization around each grid point

Computation: aggregate steady-state (projection)

Real prices converge to an ergodic distribution $\mathbf{\Psi}$

1. Guess real wage: w
2. Consumption: $C = (\chi/w)^{1/\gamma}$
3. Payoff at grid points: $U_{ij} = (p_i - w/A_j)\, Cp_i^{-\epsilon}$
4. Iterate on value matrix: $\mathbf{V} = \mathbf{U} + \beta \mathbf{R}' (\mathbf{V} + \mathbf{G})\, \mathbf{S}$
5. Iterate on distribution matrices:
   - $\tilde{\mathbf{\Psi}} = \mathbf{R\Psi S}'$
   - $\mathbf{\Psi} = (\mathbf{1}_{\#^p\#^a} - \mathbf{\Lambda}) \,.*\, \tilde{\mathbf{\Psi}} + \mathbf{\Pi}_{\#^p\#^a} \,.*\, \left(\mathbf{1}_{\#^p\#^p} * (\mathbf{\Lambda} .* \tilde{\mathbf{\Psi}})\right)$
6. Check if $\sum_{j=1}^{\#^p} \sum_{k=1}^{\#^a} \Psi_t^{jk} p_j^{1-\epsilon} = 1$, and adjust w until it holds

Computation: aggregate dynamics (perturbation)

- Dynamic Bellman equation:

$$\mathbf{V}_t = \mathbf{U}_t + \beta E_t \left[\frac{u'(C_{t+1})}{u'(C_t)} \mathbf{R}'_{t+1} \left(\mathbf{V}_{t+1} + \mathbf{G}_{t+1} \right) \mathbf{S} \right]$$

- Distributional dynamics:
  - $\tilde{\mathbf{\Psi}}_t = \mathbf{R}_t \mathbf{\Psi}_{t-1} \mathbf{S}'$
  - $\mathbf{\Psi}_t = \left(\mathbf{1}_{\#^p \#^a} - \mathbf{\Lambda}_t \right) .* \tilde{\mathbf{\Psi}}_t + \mathbf{\Pi}_t .* \left(\mathbf{1}_{\#^p \#^a} * \left(\mathbf{\Lambda}_t .* \tilde{\mathbf{\Psi}}_t \right) \right)$

- Collect variables in vector: $X_t = (vec(\mathbf{\Psi}_{t-1}), vec(\mathbf{V}_t), C_t, \pi_t, M_{t-1})$

- Model: $E_t \mathcal{F} \left(X_{t+1}, X_t, z_{t+1}, z_t \right) = 0$

- Linearization: $E_t \mathcal{A} \Delta X_{t+1} + \mathcal{B} \Delta X_t + E_t \mathcal{C} z_{t+1} + \mathcal{D} z_t = 0$

- Solve with Klein's QZ method for linear RE models

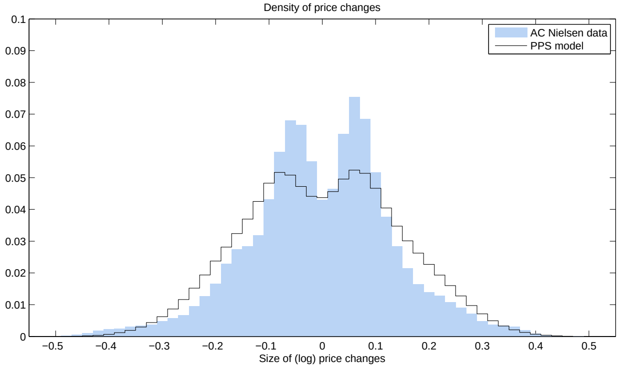
Calibration

Discount factor	$\beta^{-12} = 1.04$	Golosov-Lucas (2007)
CRRA	$\gamma = 2$	Ibid.
Labor supply	$\chi = 6$	Ibid.
MIUF coeff.	$\nu = 1$	Ibid.
Elast. subst.	$\epsilon = 7$	Ibid.
Money growth	$\mu = 1$	AC Nielsen dataset: zero inflation
Persistence	$\rho = 0.95$	Blundell-Bond (2000)
Std. dev. prod.	$\sigma = 0.06$	Eichenbaum et. al. (2009)
Precision	$\xi = 23.4$	Nakamura-Steinsson (2008): 10 months

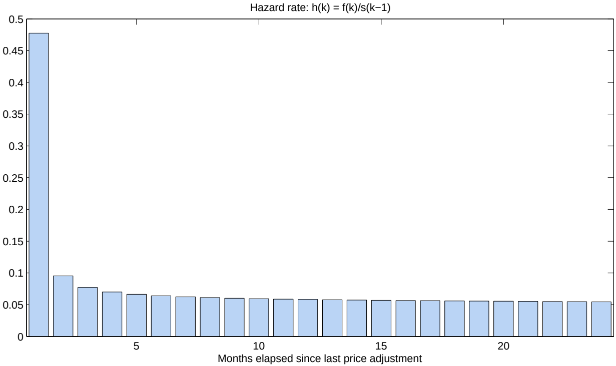
Note: noise $= 1/\text{precision} = 0.04$

Less noise than typically estimated in applied GT experiments

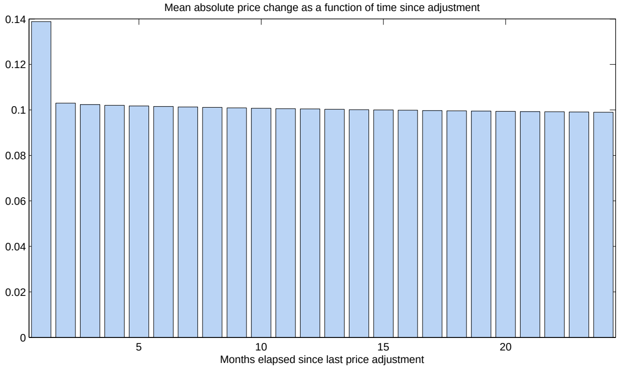
Histogram of price changes



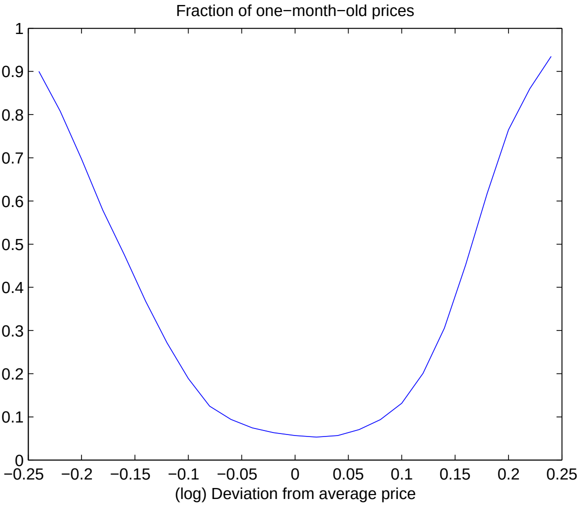
Price adjustment hazard



Size of price changes as a function of price age



Extreme prices are young in our model



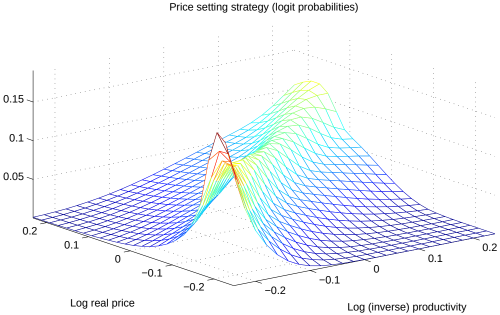
Summary steady-state statistics

Table 1. Model-Simulated Statistics and Evidence

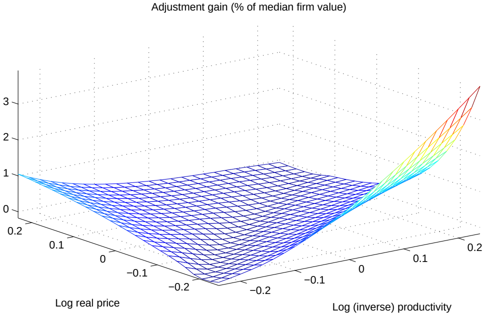
	Calvo	MC	PPS	Nested PPS	Data
Frequency of price changes	10	10	10	10	10
Mean absolute price change	2.8	5.5	11.9	10.4	10.4
Std of price changes	3.7	5.6	14.5	13.1	13.2
Kurtosis of price changes	4.2	1.2	2.6	2.8	3.5
Percent of price increases	48	51	50	50	50
% of abs price changes $\leq 2.5\%$	55	0	9.4	12.8	10
Mean loss due to errors (% of rev.)	0.6	0.1	0.5	1.9	

All statistics refer to regular price changes and are stated in percent.

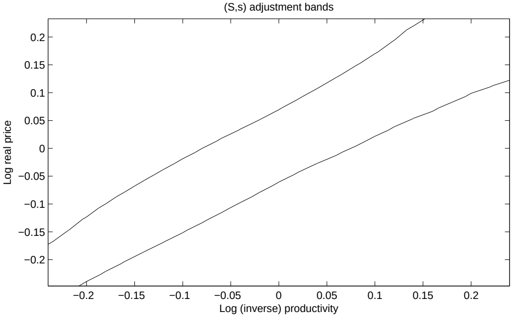
Price-setting strategy



Expected gain from adjustment

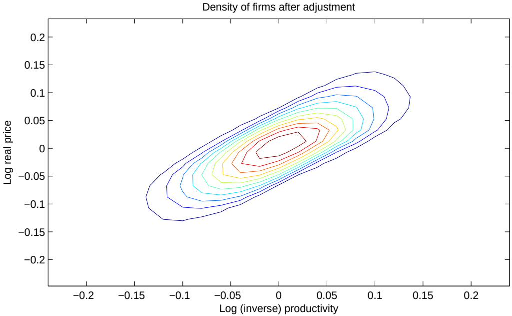


S,s bands

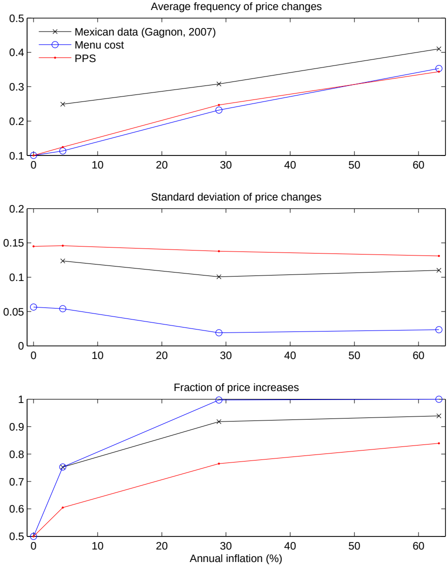


(S,s) adjustment bands
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
Log real price
−0.2
−0.15
−0.1
−0.05
0
0.05
0.1
0.15
0.2
Log (inverse) productivity

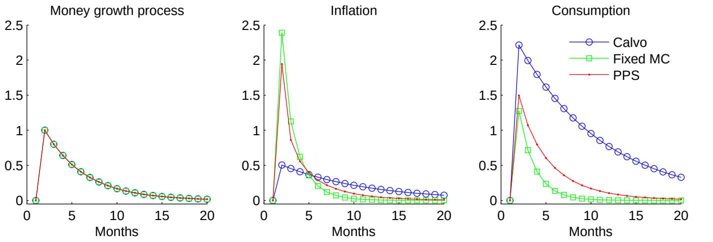
Stationary distribution of firms



Effects of positive trend inflation



Responses to a money growth shock



Inflation decomposition: Costain-Nakov (optimal pricing)

Inflation identity: $\pi_t \equiv \sum_{j=1}^{\#^p} \sum_{k=1}^{\#^a} x_t^{*jk} \lambda_t^{jk} \widetilde{\Psi}_t^{jk}$

where $x_t^{*jk} \equiv \log\left(\frac{p_t^*(a^k)}{p^j}\right)$ are firms' *desired* price changes

Decomposition:

$$\pi_t \equiv \bar{x}_t^* \bar{\lambda}_t + \sum_{j,k} x_t^{*jk} \left(\lambda_t^{jk} - \bar{\lambda}_t\right) \widetilde{\Psi}_t^{jk}$$

where $\bar{x}_t^* \equiv \sum_{j,k} x_t^{*jk} \widetilde{\Psi}_t^{jk}$ is the average *desired* price change

$$\Delta\pi_t \approx \bar{\lambda}\Delta\bar{x}_t^* + \bar{x}^*\Delta\bar{\lambda}_t + \Delta\sum_{j,k} x_t^{*jk} \left(\lambda_t^{jk} - \bar{\lambda}_t\right) \widetilde{\Psi}_t^{jk}$$

Inflation decomposition: Costain-Nakov (noisy pricing)

Inflation identity: $\pi_t \equiv \sum_{j=1}^{\#^p} \sum_{k=1}^{\#^a} (x_t^{*jk} + \epsilon_t^{jk}) \lambda_t^{jk} \widetilde{\Psi}_t^{jk}$

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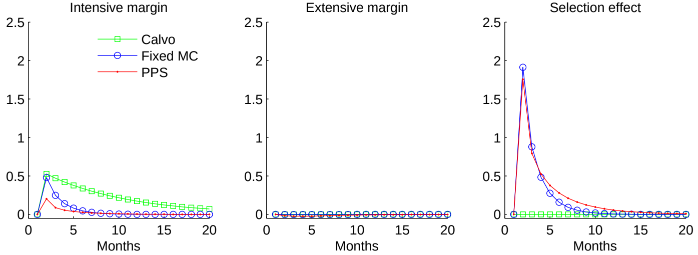
Decomposition:

$$\pi_t \equiv \bar{x}_t^* \bar{\lambda}_t + \sum_{j,k} x_t^{*jk} \left(\lambda_t^{jk} - \bar{\lambda}_t\right) \widetilde{\Psi}_t^{jk} + \bar{\epsilon}_t$$

where $\bar{\epsilon}_t \equiv \sum_{j,k} \epsilon_t^{jk} \lambda_t^{jk} \widetilde{\Psi}_t^{jk}$ is the average price error

$$\Delta\pi_t \approx \bar{\lambda}\Delta\bar{x}_t^* + \bar{x}^* \Delta\bar{\lambda}_t + \Delta \sum_{j,k} x_t^{*jk} \left(\lambda_t^{jk} - \bar{\lambda}_t\right) \widetilde{\Psi}_t^{jk} + \Delta\bar{\epsilon}_t$$

Selection effect is dominant at low trend inflation rates



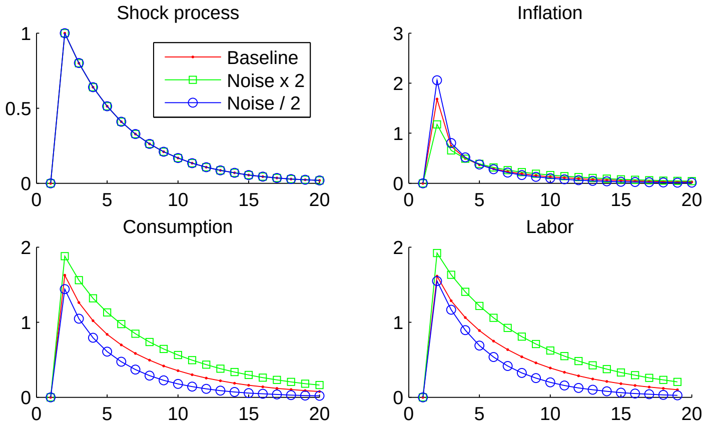
Estimated Phillips curve coefficients

Table 2. Variance decomposition and Phillips curves

Correlated money growth shock ($\phi_z = 0.8$)	Calvo	MC	PPS	Nested PPS	Data
Frequency of non-zero price changes (%)	10	10	10	10	10
Std of money shock (x100)	0.331	0.122	0.153	0.277	
Std of quarterly inflation (x100)	0.246	0.246	0.246	0.246	0.246
% explained by μ shock alone	100	100	100	100	
Std of quarterly output growth (x100)	1.08	0.195	0.310	0.874	0.510
% explained by μ shock alone	212	38.3	60.7	171	
Slope coeff. of Phillips curve*	1.1	0.149	0.273	0.848	
Standard error	0.070	0.012	0.006	0.035	
R^2 of regression	0.892	0.832	0.987	0.952	

The "slope coefficients" are 2SLS estimates of the effect of inflation on consumption
First stage: $\pi_t^q = \alpha_1 + \alpha_2 \mu_t^q + \epsilon_t$; second stage: $c_t^q = \beta_1 + \beta_2 \hat{\pi}_t^q + \varepsilon_t$, where the instrument μ_t^q is the exogenous growth rate of the money supply and the superscript q indicates quarterly averages.

Sensitivity to noise



Noise also in the timing of price changes

- So far, noise was allowed only in the decision of what price to set
- The decision *when* to change prices was fully rational
- What if the *timing* decision is noisy as well?

$$\lambda^{jk} = 1 - \exp\left(\frac{-\bar{\lambda}}{1 + \exp\left(-\xi G^{jk}\right)}\right)$$

- $\bar{\lambda}$ controls the *speed* at which decisions of accuracy ξ can be made
- ξ and $\bar{\lambda}$ are calibrated jointly to match:
  - the frequency of price changes
  - the average absolute size of price changes

Summary steady-state statistics

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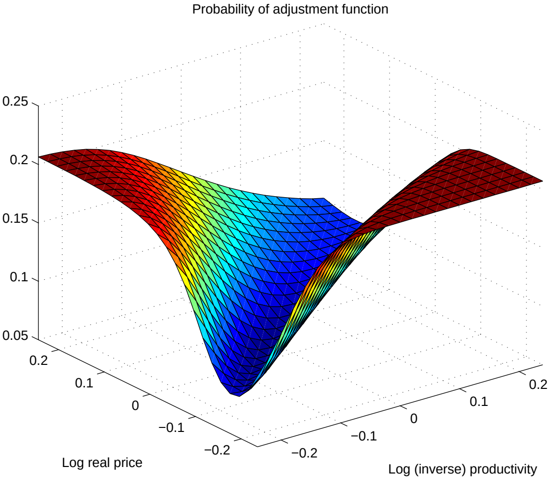
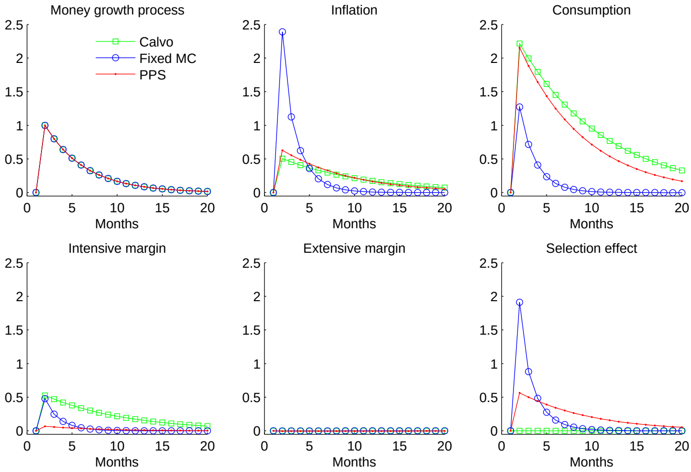
Adjustment probability smoothly increasing in the gain



Responses to money shock: nested logit model



Conclusions

- A model of price stickiness due to riskiness in the implementation
- Just one free parameter, controls the degree of precision
- Embed it into a standard DSGE framework
- Compute GE distributional dynamics

Conclusions

- The model successfully reproduces four puzzling facts
  - Co-existence of price changes of various sizes
  - Declining probability of adjustment in the age of a price
  - Roughly constant size of adjustment in the age of a price
  - Extreme prices are young
- Money shocks have relatively limited real effects due to a strong selection effect
- Allowing for noise also in the *timing* of price changes more easily delivers monetary non-neutrality closer to the Calvo model

Possible next steps

- More evidence about the story
  - Correlating size of price changes with repricing probability: very small or very large price changes are likely to end up outside the S,s bands
  - Implementation problems, noisy "chain of command": more likely in larger organizations?
  - Management literature: inaction due to implementation risk?
- Other applications: consumption or portfolio choice, communication