Strike while the Iron is Hot:

Optimal Monetary Policy under State-Dependent Pricing

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Motivation

- The recent inflation surge featured
  - Increase in the frequency of price changes (Montag and Villar, 2023) US
- Optimal monetary policy is mainly studied in models, in which the frequency is held constant (Galí, 2008; Woodford, 2003)
- What does optimal monetary policy look like with endogenous variation in frequency? How should CBs respond to a large inflation surge?

What do we do?

- We use a state-of-the-art state-dependent pricing model
  - Fixed menu cost with idiosyncratic quality shocks (Golosov and Lucas, 2007)
  - Strategic complementarities and fat-tailed quality shocks
  - Model to matches moments of price changes in normal times and high frequency in 2022
- Determine Ramsey optimal policy
  - Analytical analysis in a simplified model to gain intuition
  - Solve the non-linear model over the sequence space under perfect foresight using a new numerical algorithm
  - Contrast it to conventional results in Calvo (1983) time-dependent model

What do we find

- When cost-push shocks are small, business as usual.
- When cost-push shocks are large, more *hawkish* policy: "strike while the iron is hot."
  - Why? The Phillips curve is non-linear: it gets steeper as frequency increases.
  - Thus, stabilizing inflation is less costly in terms of output when inflation is high
- Divine coincidence holds for efficient shocks (e.g. TFP), either small or large.

Motivation: optimal policy in textbook Calvo framework

- New Keynesian Phillips Curve:

$$\pi_t = \beta \mathbb{E}_t[\pi_{t+1}] + \kappa x_t, \quad \text{where } \kappa = \frac{(1-\theta)(1-\beta\theta)}{\theta},$$

  where π_t is inflation, β is the discount factor, $1-\theta$ is the frequency of price changes, and x_t is the output gap

- Higher frequency raises the slope of the Phillips curve

$$\frac{\partial \kappa}{\partial (1-\theta) > 0}$$

- Why? Prices are more flexible

Motivation: Optimal policy in textbook Calvo framework, cont.

- Second-order approximation of utility:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\pi_t^2 + \frac{\kappa}{\varepsilon} x_t^2\right]$$

- Relative importance of inflation *decreases* with the slope of the Phillips curve κ
- Why? More flexible prices reduce the distortion caused by extra inflation
- Optimal policy: the two effects completely offset each other. Frequency no impact:

$$\pi_t + \frac{1}{\varepsilon} \Delta x_t = 0$$

- How does optimal policy respond to temporary frequency increases in Calvo and menu cost models?

Literature

- Endogenous frequency (Montag and Villar, 2023; Cavallo et al., 2024; Blanco et al., 2024b) implying a nonlinear Phillips curve
  - Microfounded by state-dependent price setting (Golosov and Lucas, 2007; Gertler and Leahy, 2008; Auclert et al., 2022)
  - In the presence of large aggregate shocks (Karadi and Reiff, 2019; Alvarez and Neumeyer, 2020; Costain et al., 2022; Alexandrov, 2020; Blanco et al., 2024a; Gagliardone et al., 2025)
- Optimal policy in a menu cost economy
  - Optimal inflation target - higher under menu costs (Burstein and Hellwig, 2008; Adam and Weber, 2019; Blanco, 2021)
  - Focus on aggregate shocks (unlike Caratelli and Halperin, 2023, who study *sectoral* shocks)
  - Small shocks, large shocks, optimal nonlinear target rule (comp. Galí, 2008; Woodford, 2003)

Overview of our state-dependent model

= Textbook New-Keynesian model with Calvo pricing (e.g. Galí, 2008)

– Calvo fairy

+ fixed costs of price adjustments η – state-dependent price setting

+ idiosyncratic, fat-tailed quality shocks $A_t(i)$ - large and leptokurtic price changes

+ intermediate goods in production (Basu, 1995) - realistic Phillips curve slope

= Heterogeneous-firm NK DSGE model.

Overview of the model

- Households: consume a Dixit-Stiglitz basket of goods, and work
- Firms: produce differentiated goods using labor only and are subject to aggregate TFP shocks and idiosyncratic "quality" shocks. They have market power and set prices optimally subject to a fixed cost (Golosov and Lucas, 2007)
- Monetary policy: sets interest rate to maximize household welfare under commitment

Households

- A representative household consumes (C_t), supplies labor hours (N_t) and saves in one-period nominal bonds (B_t).

- The household's problem is:

$$\max_{C_t,N_t,B_t} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\log\left(C\right)_t - N_t\right)$$

$$\text{s.t. } P_t C_t + B_t + T_t = R_{t-1}B_{t-1} + W_t N_t + D_t,$$

where P_t is the price level, R_t is the gross nominal interest rate, W_t is the nominal wage, T_t are lump sum transfers and D_t are profits

Consumption and labor

- Aggregate consumption C_t and the price level are defined as:

$$C_t = \left\{ \int \left[A_t(i) C_t(i) \right]^{\frac{\epsilon - 1}{\epsilon}} di \right\}^{\frac{\epsilon}{\epsilon - 1}}, \quad P_t = \left[\int_0^1 \left(\frac{P_t(i)}{A_t(i)} \right)^{1-\epsilon} di \right]^{\frac{1}{1-\epsilon}}$$

  where $A_t(i)$ is product quality, ϵ is the elasticity of substitution.

- Labor supply condition and Euler equation are given by:

$$W_t = P_t C_t, \quad 1 = \mathbb{E}_t \left[\beta \frac{u'\left(C_{t+1}\right)}{u'\left(C_t\right)} \frac{R_t}{\Pi_{t+1}} \right]$$

Monopolistic producers

- Production of good i is given by $Y_t(i) = A_t \dfrac{N_t(i)^{\alpha} M_t(i)^{1-\alpha}}{A_t(i)}$, where $M_t(i)$ are intermediate goods and quality follows a random walk with fat-tailed shocks

$$\log A_t(i) = \log A_{t-1}(i) + \varepsilon_t(i), \quad \varepsilon_t(i) \sim \begin{cases} N(0, \sigma_1^2) & \text{with prob } \hat{\omega} \\ N(0, \sigma_2^2) & \text{otherwise} \end{cases}$$

- Static cost minimization

$$\alpha P_t M_t(i) = (1-\alpha) W_t N_t(i), \quad Y_t(i) = \left(\frac{(1-\alpha) w_t}{\alpha} \right)^{1-\alpha} \frac{A_t N_t(i)}{A_t(i)}$$

Monopolistic producers, cont.

- Strategic complementarity - nominal marginal cost $MC_t(i)$:

$$MC_t(i) = \frac{A_t(i)}{A_t \alpha^{\alpha}(1-\alpha)^{1-\alpha}} W_t^{\alpha} P_t^{1-\alpha}. \tag{1}$$

- Firms profits

$$\Pi_t(i) = \frac{D_t(i)}{P_t} = \left[\frac{P_t(i)}{P_t} - (1-\tau_t)\frac{MC_t(i)}{P_t}\right] Y_t(i),$$

- Firms face a fixed cost η to update prices; τ_t is a labor subsidy (cost-push shock)

Quality-adjusted relative prices

- Let $p_t(i) \equiv \log P_t(i)/(A_t(i)P_t)$ be the quality-adjusted log relative price
- Real profit then is

$$\Pi(p_t(i), w_t, A_t) \equiv \frac{D_t(i)}{P_t} = C_t e^{p_t(i)(1-\epsilon)} - C_t \frac{(1-\tau_t)w_t^{\alpha}}{A_t \alpha^{\alpha}(1-\alpha)^{1-\alpha}} e^{p_t(i)(-\epsilon)}$$

where w_t is the real wage.

- When nominal price $P_t(i)$ stays constant, $p_t(i)$ evolves: $p_t(i) = p_{t-1}(i) - \sigma\varepsilon_t(i) - \pi_t$

Price gap

- Optimal policy follows and (S,s) rule
- Price gap x_t

$$x_t(i) \equiv p_t(i) - p_t^* = x_t(i) = x_{t-1}(i) - \varepsilon_t - \pi_t^*,$$

where p_t^* optimal reset price, which is constant across firms, and $\pi_t^* \equiv p_t^* - p_{t-1}^* + \pi_t$.

- Let $V(x)$ be the firm's value function

$$V_t(x) = \mathit{\Pi}_t(x) + \mathit{\Lambda}_{t,t+1} \int_{s_{t+1}}^{S_{t+1}} V_{t+1}(x')\, \hat{\phi}(x - x' - \pi_{t+1}^*)\, dx'$$
$$+ \mathit{\Lambda}_{t,t+1} \left[1 - \int_{s_{t+1}}^{S_{t+1}} \hat{\phi}(x - x' - \pi_{t+1}^*)\, dx'\right] \left[V_{t+1}(0) - \eta w_{t+1}\right],$$

Pricing decision

- Optimal price gap $x_t = 0$ and the (S,s) bands s_t and S_t need to satisfy

$$V_t'(0) = 0, \tag{2}$$

$$V_t(0) - \eta w_t = V_t(s_t), \tag{3}$$

$$V_t(0) - \eta w_t = V_t(S_t). \tag{4}$$

Monetary Policy

- The central banksets policy optimally, maximizing household utility under commitment
- Aggregate shocks: employment subsidy (τ_t), TFP (A_t)

$$\log(A_t) = \rho_A \log(A_{t-1}) + \varepsilon_{A,t} \quad \varepsilon_{A,t} \sim N(0, \sigma_A^2)$$

$$\tau_t - \tau = \rho_\tau(\tau_{t-1} - \tau) + \varepsilon_{\tau,t} \quad \varepsilon_{\tau,t} \sim N(0, \sigma_\tau^2).$$

Law of motion of the price gaps

- End of period price gaps g_t:

$$g_t(x) = g_t^c(x) + g_t^0 \delta(x),$$

where $g_t^c(x)$ is a continuous density and g_t^0 is a mass point (Dirac delta) at $x = 0$.

- Continuous term evolves

$$g_t^c(x) = \int_{s_{t-1}}^{S_{t-1}} g_{t-1}^c(x_{-1})\hat{\phi}(x_{-1} - x - \pi_t^*)\, dx_{-1} + g_{t-1}^0\, \hat{\phi}(-x - \pi_t^*)$$

for $x \in [s_t, S_t]$ and zero otherwise.

- The mass point is

$$g_t^0 = 1 - \int_{s_t}^{S_t} g_t^c(x)\, dx.$$

Aggregation and market clearing

- Aggregate price index

$$1 = \int_{s_t}^{S_t} e^{(x+p_t^*)(1-\epsilon)} g_t(x)\, dx.$$

- Labor market equilibrium

$$N_t = \left[\frac{\alpha}{(1-\alpha)w_t}\right]^{1-\alpha} \frac{\Delta_t}{A_t} Y_t + \eta g_t^0, \quad \Delta_t = \int_{s_t}^{S_t} \left(e^{-\epsilon(x+p_t^*)}\right) g_t(x)\, dx,$$

where Δ_t is price dispersion and g_t^0 is frequency.

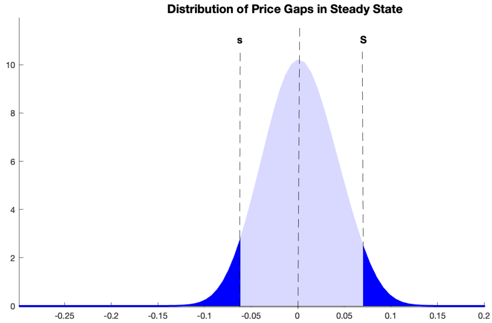
- Goods market clearing

$$Y_t = C_t d_t, \quad d_t = \left[1 - \left(\frac{(1-\alpha)w_t}{\alpha}\right)^{\alpha} \frac{\Delta_t}{A_t}\right]^{-1},$$

d_t is the Domar weight.

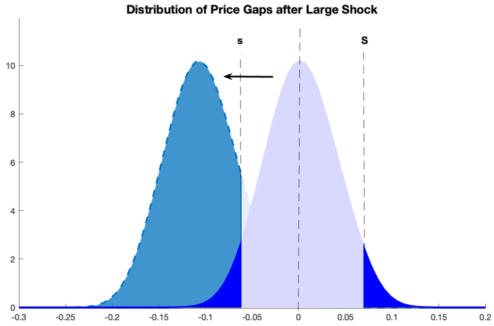
Model: Intuitive summary

- Each period, firm i chooses whether to reset its price and, if so, what new price to set
- The firm's optimality conditions define the reset price and the inaction region (S,s)
- Given the idiosyncr. shock, they endogenously determine the price distribution
- Let $p_t(i) \equiv \log(P_t(i)/(A_t(i)P_t))$ be the quality-adjusted log relative price
- Let $x_t(i) \equiv p_t(i) - p_t^*(i)$ be the difference of that price from the optimal price



Model under large shock

- Large aggregate shock: shifts the distribution of price gaps for all firms
- Limited impact on the (s,S) bands
- Pushes a large fraction of firms outside of the inaction region
- Large increase in the frequency of price changes and hence additional flexibility of the aggregate price level



Inspecting the mechanism: simple model

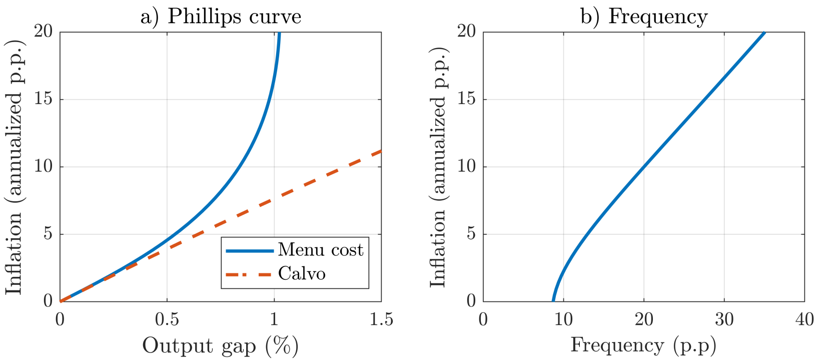
- In the Calvo model, we explain optimal policy as a choice of a planner selecting inflation and output to maximize quadratic welfare subject to the linearized Phillips curve
- To deliver a similar intuition but without linearization, we simplify the model by assuming that prices are reset each night
- Model becomes sequence of tractable static problems
- Simple expressions as function of π and y for
  - Phillips curve
  - Welfare

Planner's constraint: Phillips curve

- The model can be summarized by a single static equation relating inflation and output

$$1 = \left[\int_{s}^{S} e^{(p)(1-\epsilon)} \frac{1}{\sigma} \phi\left(\frac{p+\pi}{\sigma}\right) dp + \left(\frac{\varepsilon\,(1-\tau)}{\varepsilon - 1} Y\right)^{1-\epsilon} \left[1 - \int_{s}^{S} \frac{1}{\sigma} \phi\left(\frac{p+\pi}{\sigma}\right) dp\right]\right],$$

Planner's constraint: Phillips curve



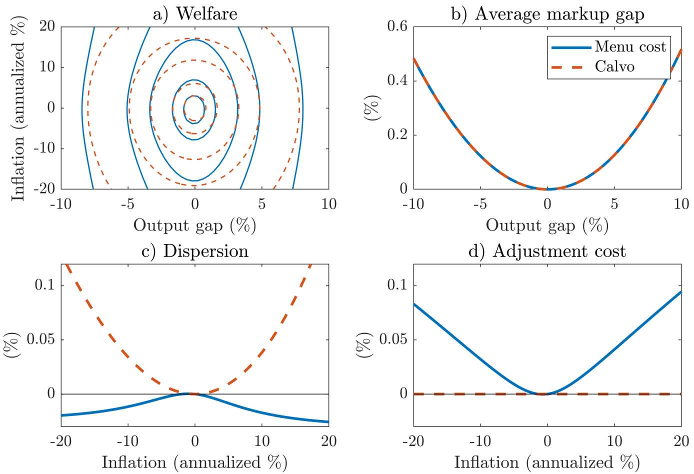
- Numerical calibration: match empirical frequency at normal times and at 10% inflation
- Phillips curve is nonlinear (close to linear under Calvo)
- Cheaper to disinflate at high inflation as price adjustments are more frequent

The planners objective: Welfare

- Welfare can be decomposed into three underlying distortions
- Each distortion depends on either output or inflation

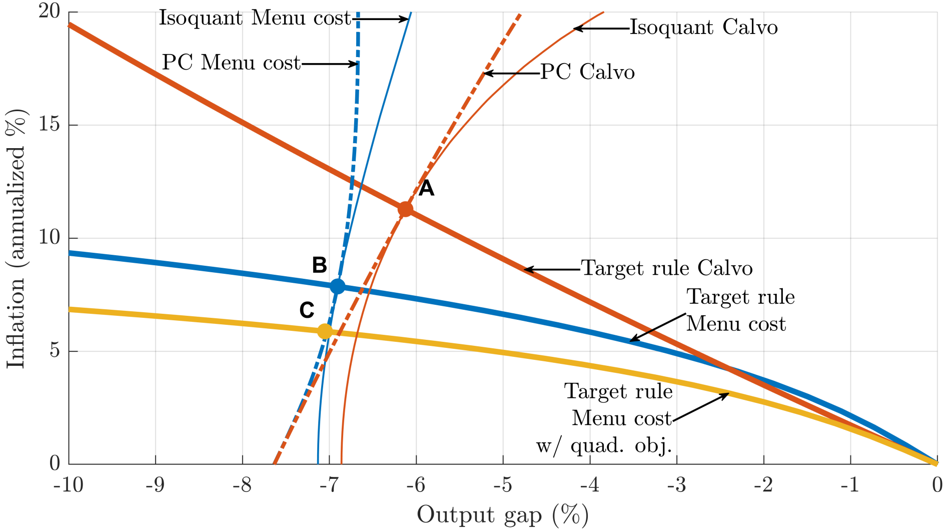
$$
\begin{aligned}
U - U^e \quad = \quad & \underbrace{\log(Y) - (Y-1)}_{\text{Average markup}} - \\
& \underbrace{Y\left(\int_s^S e^{p(-\epsilon)} \frac{1}{\sigma}\phi\left(\frac{p+\pi}{\sigma}\right)dp + \left(1 - \int_s^S \frac{1}{\sigma}\phi\left(\frac{p+\pi}{\sigma}\right)dp\right)e^{p^*(-\epsilon)} - 1\right)}_{\text{Markup dispersion}} - \\
& \underbrace{\eta\left[1 - \int_s^S \frac{1}{\sigma}\phi\left(\frac{p+\pi}{\sigma}\right)dp\right]}_{\text{Adjustment costs}}
\end{aligned}
$$

Planner's objective: Welfare



- Inflation is less costly in menu cost model, and for different reason

Optimal Policy



Optimal Policy

- Small shocks: Optimal policy similar to Calvo
- Large shocks: Optimal policy strikes while hot - exploiting cheaper disinflation, the planner stabilizes inflation more relative to output
- Reason: Nonlinear Phillips curve and near-quadratic utility
- This is not obvious. Remember: a change in the Calvo parameter doesn't affect optimal policy in the Calvo model

Full model: Calibration

	Baseline	Description	Reference
		Households and final producer	
β	$0.99^{1/3}$	Discount rate	Golosov and Lucas (2007)
χ	1	Utility weight on labor	Set so that $w = C$
ϵ	6	Elasticity of substitution	Gagliardone et al. (2025)
		Differentiated goods producers	
α	0.2	Labor share	Nakamura and Steinsson (2010)
η	0.064	Menu cost	Calibrated to match
σ	0.0306	Std dev. of quality shocks	moments of steady state
σ_1/σ_2	0.065	Ratio of low vs. high stdev	price change distribution
ϖ	0.934	Share of low volat. shock	at 2% inflation
		Aggregate shocks	
ρ_A	$0.95^{1/3}$	TFP shock persistence	Smets and Wouters (2007)
ρ_τ	$0.9^{1/3}$	Cost-push persistence	Smets and Wouters (2007)

Full model: Calibration, cont.

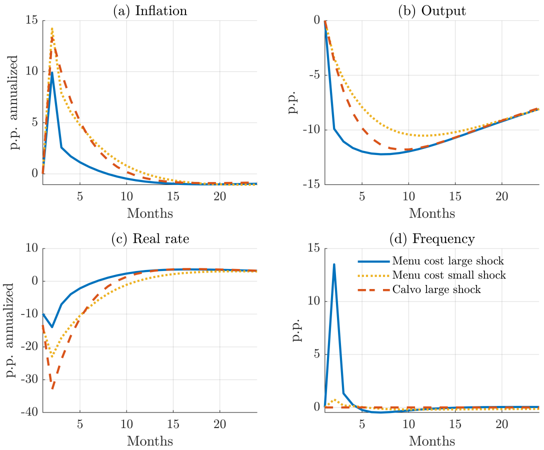
	Steady state at 2% inflation			Phillips curve	10% inflation	
	Frequency	Size	Kurtosis	slope	Freq. incr.	Shock size
Data	8.7%	8.5%	4	0.005-0.05	14pp	
Baseline	8.7%	8.5%	4	0.08	14pp	-2.89%

- Fat-tailed idiosyncratic shocks
  - The model is able to match the steady state frequency, size and kurtosis of price changes
  - The model is able to capture large increase in frequency at 10% inflation (comp. **?**)
- Roundabout production
  - The Phillips curve slope is high, but same order of magnitude as estimates
  - Shock size does not need to be extreme

Full model: Computation

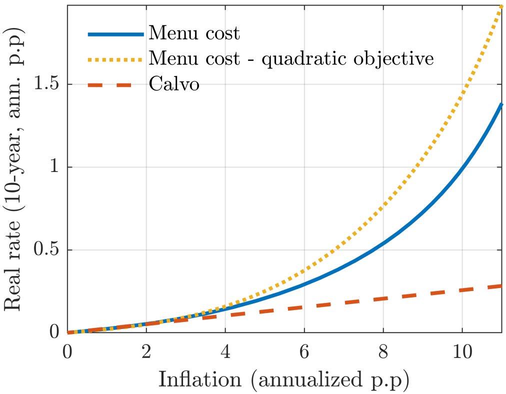
- Challenges
  - Price distribution $g_t(p_t)$ and value function $V_t(p_t)$ are infinite-dimensional objects
  - We need sufficient accuracy for optimal policy assessment
- New algorithm, in discrete time
  - Approximate distribution and value functions by piece-wise linear functions on grid.
  - Endogenous grid points: (S,s) bands and the optimal reset price.
  - Evaluate integrals analytically.
  - Solve non-linearly in the sequence space using Dynare's perfect foresight Ramsey solver.

Full model: Strike while the iron is hot



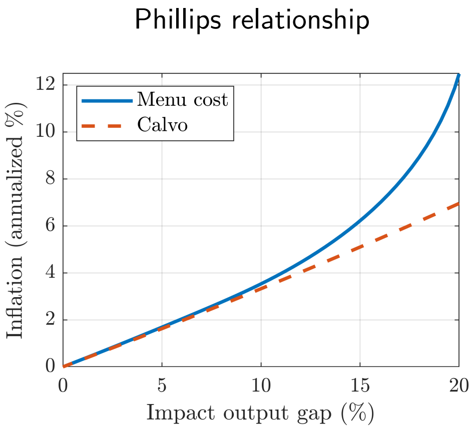
- Policy stance gets over-proportionally hawkish as inflation increases

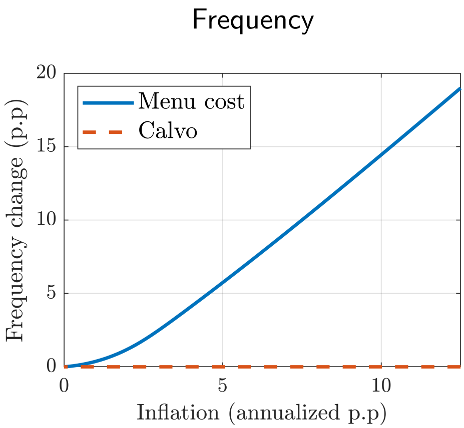
Full model: Strike while the iron is hot, cont.



- Policy stance gets over-proportionally hawkish as inflation increases

Full model





- Full model displays similar Phillips relationship and frequency as the simple model

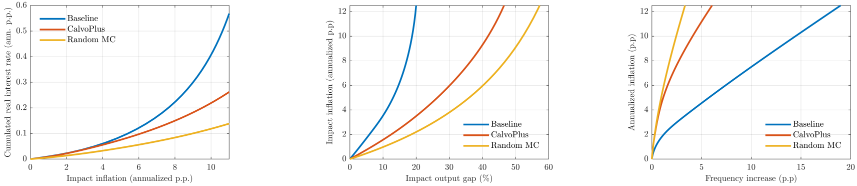
Robustness: alternative state-dependent models

- Menu cost is a random variable: (i) Calvo Plus (Nakamura and Steinsson, 2010), (ii) Random Menu Cost (Dotsey et al., 1999; Gagliardone et al., 2025)

$$(i) \quad \widetilde{\eta} = \begin{cases} \eta & \text{with prob } \alpha \\ 0 & \text{with prob } 1-\alpha \end{cases} \qquad (ii) \quad \widetilde{\eta} = \begin{cases} U[-\eta, \eta] & \text{with prob } \alpha \\ 0 & \text{with prob } 1-\alpha \end{cases}$$

- Strike-it relationship robust, weaker in alternatives, which underestimate frequency

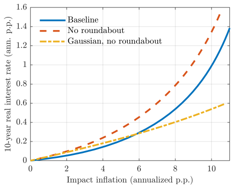
(a) Strike-it relationship (b) Phillips relationship (c) Frequency



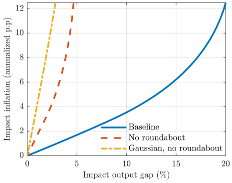
Robustness: Sensitivity to parameter choice

- Key components
  - Roundabout economy (labor share, $\alpha = 0.2$): More realistic slope of the Phillips curve
  - Fat tailed shocks (relative stddev, $\nu = 0.0625$): More realistic frequency response
- Strike-it relationship robust, weaker w/o fat tailed shocks, which underestimate frequency

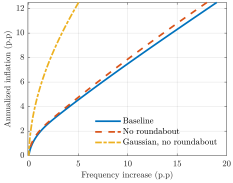
(a) Strike-it relationship



(b) Phillips relationship



(c) Frequency



Robustness: Calibration

	Baseline	CalvoPlus	Random MC	Description	Reference
			Households and final producer		
β	$0.99^{1/3}$	$0.99^{1/3}$	$0.99^{1/3}$	Discount rate	Golosov and Lucas (2007)
χ	1	1	1	Utility weight on labor	Set so that $w = C$
ϵ	6	6	6	Elasticity of substitution	Gagliardone et al. (2025)
	Differentiated goods producers				
α	0.2	0.2	0.2	Labor share	Nakamura and Steinsson (2010)
τ	0.1672	0.1685	0.1709	Labor subsidy in ss	$y = y^*$ in ss
θ	0	8.7%/2	8.7%/2	Share of 0 menu cost in ss	As in 2-product firms in Midrigan (2011)
η	0.064	0.468	2.40	Menu cost	Calibrated to match
σ	0.0306	0.0328	0.0365	Std dev. of quality shocks	moments of steady state
σ_1/σ_2	0.065	0.065	0.065	Ratio of low vs. high stdev	price change distribution
ϖ	0.934	0.926	0.9095	Share of low volat. shock	at 2% inflation
	Aggregate shocks				
ρ_A	$0.95^{1/3}$	$0.95^{1/3}$	$0.95^{1/3}$	TFP shock persistence	Smets and Wouters (2007)
ρ_τ	$0.9^{1/3}$	$0.9^{1/3}$	$0.9^{1/3}$	Cost-push persistence	Smets and Wouters (2007)

Robustness: Calibration

	Baseline	$\alpha = 1$	$\alpha = 1, \nu = 1$	Description	Reference
			Households and final producer		
β	$0.99^{1/3}$	$0.99^{1/3}$	$0.99^{1/3}$	Discount rate	Golosov and Lucas (2007)
χ	1	1	1	Utility weight on labor	Set so that $w = C$
ϵ	6	6	6	Elasticity of substitution	Gagliardone et al. (2025)
	Differentiated goods producers				
α	0.2	1	1	Labor share	Nakamura and Steinsson (2010)
η	0.064	0.013	0.035	Menu cost	Calibrated to match
σ	0.0306	0.0306	0.0252	Std dev. of quality shocks	moments of steady state
σ_1/σ_2	0.065	0.065	1	Ratio of low vs. high stdev	price change distribution
ϖ	0.934	0.934	0.934	Share of low volat. shock	at 2% inflation
	Aggregate shocks				
ρ_A	$0.95^{1/3}$	$0.95^{1/3}$	$0.95^{1/3}$	TFP shock persistence	Smets and Wouters (2007)
ρ_τ	$0.9^{1/3}$	$0.9^{1/3}$	$0.9^{1/3}$	Cost-push persistence	Smets and Wouters (2007)

Robustness: Calibration, cont.

	Steady state at 2% inflation				Phillips curve	10% inflation	
	Frequency	Size	Kurtosis	IQR	slope	Freq. incr.	Shock size
Data	8.7%	8.5%	4	10.8%	0.005-0.05	14pp	
Baseline	8.7%	8.5%	4	7.2%	0.08	14pp	-2.89%
CalvoPlus	8.7%	8.5%	4	10.8%	0.036	4.2pp	-3.32%
Random MC	8.7%	8.5%	4	10.5%	0.040		

Robustness: Calibration, cont.

	Steady state at 2% inflation			Phillips curve	10% inflation	
	Frequency	Size	Kurtosis	slope	Freq. incr.	Shock size
Data	8.7%	8.5%	4	0.005-0.05	14pp	
Baseline	8.7%	8.5%	4	0.08	14pp	-2.89%
$\alpha = 1$	8.7%	8.5%	4	0.42	13.72pp	-14.7%
$\alpha = 1, \nu = 1$	8.7%	8.5%	1.75	1.13	3.32pp	-6.15%

Efficient shocks: Dynamic "divine coincidence" holds

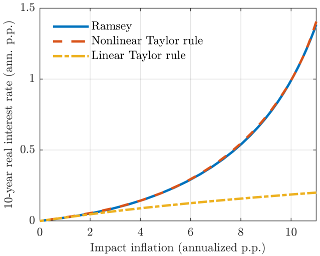
- In the standard NK model with Calvo pricing: divine coincidence holds after shocks affecting the efficient allocation: TFP (A_t).
- Optimal policy stabilizes inflation and closes the output gap.
- Same result holds in menu-cost models, regardless shocks are small or large.

Policy implications

- How would a Taylor rule need to be modified to approximate optimal policy?
- Inflation coefficient needs to increase with inflation

$$\log R_t = \rho \log R_{t-1} + (1-\rho)\left\{\left[\phi_\pi + \phi_F(\pi_t - \bar{\pi})^2\right](\pi_t - \bar{\pi}) + \phi_x(y_t - y_t^*)\right\}.$$

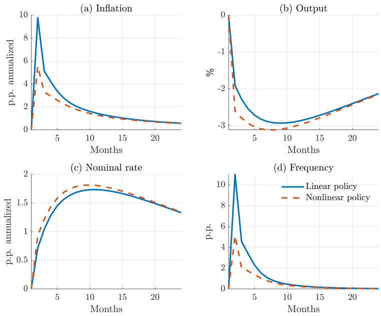
- We estimate the inflation coefficients (ϕ_π, ϕ_F) to match the strike-it figure



ρ	ϕ_π	ϕ_F	ϕ_x
$0.9^{1/3}$	2.22	135000	$0.5^{1/3}$

Policy implications, cont.

- Consider a policy maker that follows a linear rule (ignores the strike-it result, $\phi_F = 0$)
- It faces a cost-push (τ_t) shock that raises inflation to 10%. How would the outcome change if it followed the strike-it policy?



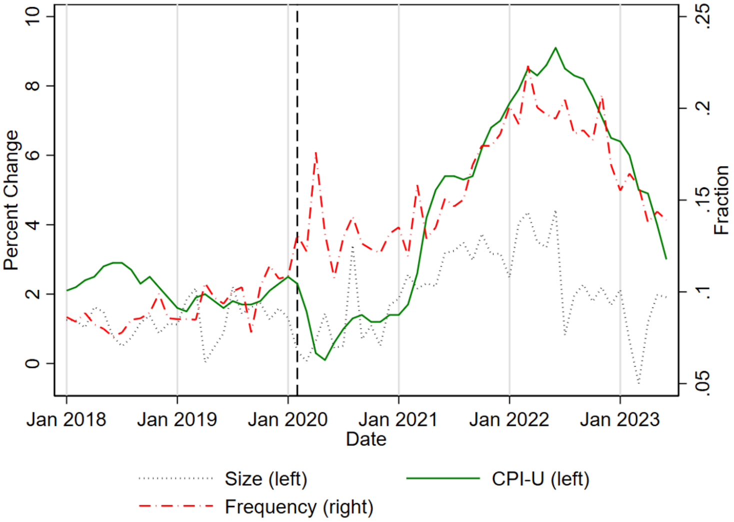
- Inflation would peak at 5.5%,
- Output would drop by 0.5%, petering out in a year
- 25bps persistently higher nominal rates
- Consumption-equivalent welfare higher by 35% relative to Ramsey
- Even more if also 'demand' shocks

Conclusion

We study optimal policy in a menu cost model.

- Optimal response to small cost-push shocks similar to Calvo (1983).
- Lean against frequency for large cost-push shocks: strike while the iron is hot!
- Divine coincidence holds for efficient shocks, either small or large.

CPI and frequency of price changes in the US, Montag and Villar (2023)



Back

The model in one slide, $x \equiv p - p^*$

$$\max_{\{g_t^c(\cdot), g_t^0, V_t(\cdot), C_t, w_t, p_t^*, s_t, S_t, \pi_t^*\}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\gamma}}{1-\gamma} - \upsilon \frac{C_t}{A_t} \left(\int e^{(x+p_t^*)(-\epsilon_t)} g_t^c(p)\, dx + g_t^0 e^{(p_t^*)(-\epsilon)} \right) - \upsilon \eta g_t^0 \right)$$

subject to

$$\begin{aligned}
1 &= \int e^{(x+p_t^*)(1-\epsilon)} g_t^c(x)\, dx + g_t^0 e^{(p_t^*)(1-\epsilon)}, \\
0 &= \Pi_t'(x) + \frac{1}{\sigma} \Lambda_{t,t+1} \int_{s_{t+1}}^{S_{t+1}} V_{t+1}(x') \frac{\partial \phi\left(\frac{x - x' - \pi_t^*}{\sigma}\right)}{\partial x} dx' \\
&+ \Lambda_{t,t+1} \left(\phi\left(\frac{S_{t+1} - \pi_t^*}{\sigma}\right) - \phi\left(\frac{s_{t+1} - \pi_t^*}{\sigma}\right) \right) (V_{t+1}(0) - \eta w_{t+1}), \\
V_t(s_t) &= V_t(0) - \eta w_t, \\
V_t(S_t) &= V_t(0) - \eta w_t, \\
w_t &= \upsilon C_t^{\gamma}, \\
V_t(x) &= \Pi(x, p_t^*, w_t, A_t) + \Lambda_{t,t+1} \frac{1}{\sigma} \int_{s_t}^{S_t} \left[V_{t+1}(x') \phi\left(\frac{(x - x') - \pi_{t+1}^*}{\sigma}\right) \right] dx' \\
&+ \Lambda_{t,t+1} \left(1 - \frac{1}{\sigma} \int_{s_t}^{S_t} \left[\phi\left(\frac{(x - x') - \pi_{t+1}^*}{\sigma}\right) \right] dx' \right) \left[(V_{t+1}(0) - \eta w_{t+1}) \right], \\
g_t^c(x) &= \frac{1}{\sigma} \int_{s_{t-1}}^{S_{t-1}} g_{t-1}^c(x_{-1}) \phi\left(\frac{x_{-1} - x - \pi_t^*}{\sigma}\right) dx_{-1} + g_{t-1}^0 \phi\left(\frac{-x - \pi_t^*}{\sigma}\right), \\
g_t^0 &= 1 - \int_{s_t}^{S_t} g_t^c(x) dx.
\end{aligned}$$

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