Optimal Monetary Policy with Informational Frictions

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We study optimal policy in a business-cycle setting in which firms hold dispersed private information about, or are rationally inattentive to, the state of the economy. The informational friction is the source of both nominal and real rigidity. Because of the latter, the optimal monetary policy does not target price stability. Instead, it targets a negative relation between the nominal price level and real economic activity. Such leaning against the wind helps maximize production efficiency. An additional contribution is the adaptation of the primal approach of the Ramsey literature to a flexible form of informational friction.

I. Introduction

In the last few years, a growing literature explores the macroeconomic implications of rational inattention (Sims 2003, 2010), sticky information (Mankiw and Reis 2002), and higher-order uncertainty (Morris and Shin

This paper extends, and subsumes, earlier drafts that concerned the same topic but contained a narrower methodological contribution (Angeletos and La'O 2008, 2011). We are particularly grateful to the editor, Harald Uhlig, and three anonymous referees for detailed and constructive feedback on the latest version. We thank Robert King and Philippe Bacchetta for discussing early versions of our paper and Karthik Sastry for research assistance. We also benefited from comments received in numerous conferences and seminars. Finally, Angeletos acknowledges that this material is based in part upon work supported by the National Science Foundation under grant SES-175719.

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1998, 2002; Angeletos and Lian 2016). Such frictions are not only a priori plausible but also consistent with survey evidence (Coibion and Gorodnichenko 2012, 2015). They help rationalize sluggish adjustment to shocks, myopia vis-à-vis the future, and nearly self-fulfilling waves of optimism and pessimism.[1] But do such phenomena affect the nature of the optimal monetary policy and in particular the desirability of price stability?

We address this question in a microfounded, business-cycle setting that allows firms to have dispersed private information about, or pay limited attention to, the state of the economy. The main lesson is a novel rationale for "leaning against the wind," that is, for a policy that targets a negative relation between the nominal price level and real economic activity. Such a policy is optimal because it provides firms with the right incentives for how to act on their information about the state of the economy as well as for how to collect such information in the first place.

This rationale is different from the one familiar from the textbook New Keynesian model. In that context, policies that lean against the wind are justified by assuming that the flexible-price allocations are suboptimal and by letting monetary policy substitute for missing tax instruments. Furthermore, such policies involve a trade-off between minimizing relative-price distortions and stabilizing the output gap. By contrast, none of these properties apply in our context.

Understanding these subtle points and the precise nature of the optimal policy requires a revision of the efficiency benchmark relative to which the output gap and the relative-price distortions ought to be measured. This brings us to the methodological contribution of our paper, which is to extend the primal approach of the Ramsey literature, and more specifically the methods of Correia, Nicolini, and Teles (2008), to a framework in which firms are informationally constrained.

A. Framework

Our setting features a representative household, centralized markets, and a continuum of monopolistic firms. Each such firm produces a differentiated commodity, which serves as an input into the production of a single final good, which in turn can be used for consumption and investment. A benevolent Ramsey planner sets jointly the monetary and fiscal policies, under full commitment. Lump-sum taxation is ruled out, but the tax system is otherwise rich enough to guarantee that monetary policy does not have to substitute for missing tax instruments.

[1] See, inter alia, Sims (2003), Woodford (2003), Mankiw and Reis (2006), Nimark (2008), and Mackowiak and Wiederholt (2009) for sluggishness; Angeletos and Lian (2018) for myopia; and Angeletos and La'O (2013), Angeletos, Collard, and Dellas (2018), and Benhabib, Wang, and Wen (2015) for belief waves.

These features make our framework comparable to, and indeed nest, those considered in Lucas and Stokey (1983), Chari, Christiano, and Kehoe (1994), and Correia et al. (2013). We depart from these benchmarks by letting firms make both their price-setting and their production choices on the basis of noisy, private signals of the aggregate state of the economy.

B. *Nominal versus Real Rigidity*

The informational constraint on a firm's price-setting choice represents a nominal rigidity. The constraint on its production choices introduces a real rigidity.

Although the literature has proposed the first feature as an appealing substitute to sticky prices and menu costs (Mankiw and Reis 2002; Woodford 2003; Mackowiak and Wiederholt 2009), this feature does not alone upset the key normative lessons of the New Keynesian paradigm. Indeed, a corollary of our analysis is that when only prices are subject to an informational constraint, the results of Correia, Nicolini, and Teles (2008) continue to apply: price stability remains optimal insofar as monetary policy need not substitute for missing tax instruments.

The second feature is therefore crucial. Because each firm conditions its choice of capital or other inputs on a noisy and idiosyncratic understanding of the state of the economy, production can no longer be perfectly coordinated across firms. As a result, the efficiency benchmark studied in Correia et al. (2013) and the existing literature more generally is inappropriate for gauging optimal policy in our environment. Instead, the relevant benchmark embeds the real information rigidity within the feasibility constraints of the planner. It is this element that is responsible for the novel lessons delivered in our paper.

C. *A Primal Approach*

We start by characterizing the entire set of the allocations that can be implemented as equilibria with the available policy instruments. To shed light on the role of monetary policy, we conduct this exercise under two scenarios. The one switches off the nominal rigidity by dropping the informational constraint on the firms' pricing decisions, and the other maintains it. This adapts the concepts of flexible-price and sticky-price allocations to our context.

We next solve a relaxed problem in which the planner faces only three constraints: resource feasibility, the absence of lump-sum taxation, and the real informational rigidity discussed above. Because of this rigidity, solutions to this problem can display positive cross-sectional dispersion in marginal products as well as business cycles that look like the product of animal spirits. These properties could be mistaken as obvious reasons for stabilization policy, and yet they are symptoms of the socially optimal use of the available information. This leads to our revision of the efficiency benchmark—a benchmark relative to which the concepts of the output gap and of relative-price distortions should be redefined.

The methodological part of our paper is completed by showing that the relaxed optimum is contained within the set of flexible-price allocations and by identifying the combination of taxes and monetary policy that implement it as a sticky-price allocation. As it turns out, the optimal taxes are similar to those found in Lucas and Stokey (1983) and Chari, Christiano, and Kehoe (1994); this is despite the fact that taxes play a novel role in our setting, namely, they may manipulate the decentralized use of private information. The optimal monetary policy is discussed next.

D. *Price Stability*

We now turn to the main applied contribution of our paper. In the New Keynesian framework, the optimal flexible-price allocation is typically replicated with a monetary policy that targets price stability (Correia, Nicolini, and Teles 2008). We instead show that price stability is inconsistent with replication of the optimal flexible-price allocation. Rather, optimality requires a negative relation between the nominal price level and real economic activity.

The intuition for this result is subtle, yet robust. Consider two firms with different beliefs, or different degrees of optimism, about the state of the economy. Because firms are rational, such belief differences reflect differential private information. Furthermore, it is socially optimal to let each firm condition its production on such private information (this is a key property of the efficiency benchmark identified above). As a result, it is optimal for the more optimistic firm to produce more than the less optimistic one. In short, efficiency requires that relative quantities vary with relative beliefs.

In equilibrium, this means that relative prices must also vary with relative beliefs; this is simply a consequence of downward-sloping demand. When nominal prices are flexible, the requisite comovement between relative prices and relative beliefs is trivially implementable. But now consider a world in which firms face informational constraints on their price-setting decisions. For the more optimistic firm to produce more and charge a lower relative price than the less optimistic firm, it has to be that the nominal price set by each firm is a decreasing function of her belief: more optimistic firms ought not only to produce more but also to fix lower prices.

Consider, then, a shock that causes a positive mass of firms to receive favorable private information about the underlying economic fundamentals and the likely level of aggregate demand. As explained above, efficiency requires that these firms produce more and set lower nominal prices. But since there is a positive mass of them, the aggregate level of real economic activity and the nominal price level have to move in opposite directions, which explains the result.

To sum up, the documented form of "leaning against the wind" derives from three basic properties: (1) firms have different information and different beliefs about the state of the economy; (2) there is social value in letting relative production vary with relative beliefs; and (3) nominal prices must move in the direction opposite to real quantities in order to implement the requisite movements in relative quantities and relative prices.

E. Rational Inattention

In the main text, the information structure is treated as exogenous. In online appendix A, it is endogenized as the product of a generalized form of rational inattention or of costly information acquisition. This allows monetary policy to influence how much information firms collect or how much attention they pay to the ongoing economic conditions—but it does not upset either the optimality of the flexible-price allocations or our rationale for a monetary policy that leans against the wind.

F. Relation to the Literature

Although a few other works have also touched on the question of how informational frictions affect optimal monetary policy (Ball, Mankiw, and Reis 2005; Adam 2007; Lorenzoni 2010), our paper remains the first to study this question in a setting in which such frictions are the source not only of nominal rigidity but also of real rigidity (in the sense defined above). As explained above, this feature is responsible for the novel lessons delivered in this paper. Barring that feature, the results of Correia, Nicolini, and Teles (2008) would have applied: the relevant efficiency benchmark would not have to be modified, and price stability would have remained optimal.

Another notable aspect of our contribution is the flexibility of our primal approach. Macroeconomic models with informational frictions can be hard to analyze because of the complexity in the dynamics of higher-order beliefs.[2] As a result, the literature typically takes one of two routes: either it imposes strong assumptions, including the absence of capital accumulation and specific signal structures, so as to solve for the equilibrium in closed form, or it resorts to numerical simulations. In contrast,

[2] See the discussions in Townsend (1983), Huo and Takayama (2015b), and Nimark (2017).

our approach bypasses these obstacles and delivers sharp theoretical results despite a flexible specification of the information structure. This approach builds a bridge between the Ramsey literature and the work of Angeletos and Pavan (2007, 2009), who study efficiency in a class of abstract incomplete-information games. Close, though less flexible, variants of such an approach appear in Angeletos and La'O (2008) and Lorenzoni (2010).

Finally, the extension developed in online appendix A builds a bridge between the methods of our paper and those of Angeletos and Sastry (2018), who prove a version of the welfare theorems for a class of economies with a generalized form of rational inattention. Related is also a paper by Paciello and Wiederholt (2014) that studies optimal monetary policy in an economy with rational inattention and inefficient business cycles but without the real rigidity that is at the core of our contribution.

G. *Layout*

Section II sets up our framework. Section III defines the appropriate concepts of sticky-price and flexible-price allocations. Section IV characterizes the set of allocations that can be implemented as decentralized equilibria in each of these two scenarios. Section V defines and characterizes the optimal allocation. Section VI presents our key results on optimal monetary policy. Section VII contains a simple, tractable example that helps illustrate the lessons of our paper more sharply. Section VIII concludes. The in-print appendix contains the proofs for our main results (those regarding optimality). The online appendixes contain the remaining proofs and the extension with endogenous information acquisition.

II. The Framework

In this section, we introduce our framework. We first describe the components of the environment that are invariant to the information structure. We next formalize the informational friction and its two roles (the nominal and the real).

A. *Preliminaries*

Periods are indexed by $t \in \{0, 1, 2, \dots\}$. There is a representative household, which pools all the income in the economy and makes consumption, capital accumulation, and labor supply decisions. There is a continuum of monopolistically competitive firms, indexed by $i \in I = [0, 1]$. These firms produce differentiated goods, which are used by a competitive retail sector as intermediate inputs into the production of a final good. The latter, in turn, can be used for three purposes: as consumption, as investment into capital, or as materials, that is, as intermediate input in the production of the differentiated goods. Finally, there is a government, which lacks lump-sum taxation but can levy a variety of distortionary taxes and can issue both a contingent and noncontingent debt.

B. *States of Nature*

In each period t, Nature draws a random variable s_t from a finite set S_t. This variable may contain not only innovations in the current fundamentals—namely, aggregate total factor productivity (TFP), government spending, and household preferences—but also news about future fundamentals (Beaudry and Portier 2006; Jaimovich and Rebelo 2009) or noise and sentiment shocks (Lorenzoni 2009; Angeletos and La'O 2013). The aggregate state of the economy, or the state of nature, in period t consists of the history of draws of s_τ for all $\tau \in \{0, \ldots, t\}$. The state is therefore an element of $S^t \equiv S_0 \times \ldots \times S_t$ and is henceforth denoted by $s^t \equiv (s_0, \ldots, s_t)$. Its unconditional probability is denoted by $\mu(s^t)$.

C. *Tax and Debt Instruments*

The government lacks access to both lump-sum taxation and firm-specific taxes. It can nonetheless impose four kinds of economy-wide taxes: a proportional tax on consumption at rate τ_t^c, a proportional tax on labor income at rate τ_t^ℓ, a proportional tax on capital income, net of depreciation, at rate τ_t^k, and a 100% tax on distributed profits. In addition, the government can issue two kinds of debt instruments. The first is a one-period, noncontingent debt instrument that costs 1 dollar in period t and pays out $1 + R_t$ dollars in period t, where R_t denotes the nominal interest rate between t and $t + 1$. The second is a complete set of state-contingent assets (or Arrow securities). These are indexed by $s \in S^{t+1}$, they cost $Q_{t,s}$ dollars in period t, and they pay out 1 dollar in period $t + 1$ if state s is realized and 0 otherwise. Their corresponding quantities are denoted by $D_{t,s}$ The quantity of the noncontingent debt, on the other hand, is denoted by B_t.

D. *The Household*

Let K_t denote the capital stock accumulated by the end of period t; L_t the labor supply in period t; r_t and w_t the pretax real values of the rental rate of capital and the wage rate in period t, respectively; C_t and X_t the period-t real levels of consumption and investment, respectively; and P_t the period-t price level (i.e., the nominal price of the final good). The household's period-t budget constraint can then be expressed, in nominal terms, as follows:

$$(1+\tau_t^c)P_tC_t + P_tX_t + B_t + \sum_{s\in S^{t+1}} Q_{t,s}D_{t,s} \\ = (1-\tau_t^\ell)P_tw_tL_t + (1-\tau_t^k)P_tr_tK_{t-1} + (1+R_{t-1})B_{t-1} + D_{t-1,s^t}.$$

The law of motion of the capital stock is given by

$$K_t = (1-\delta)K_{t-1} + X_t,$$

where $\delta \in [0,1]$ is the depreciation rate of capital. Finally, the household's preferences are given by her expectation of

$$\mathcal{U} = \sum_{t=0}^{\infty}\beta^t U(C_t, L_t, s^t),$$

where $\beta \in (0,1)$ and U is strictly increasing and strictly concave in $(C_t, -L_t)$.

E. The Firms

Consider monopolist i, that is, the firm producing variety i. Its output in period t is denoted by y_{it} and is given by

$$y_{it} = A(s^t)F(k_{it}, h_{it}, \ell_{it}),$$

where $A(s^t)$ is an aggregate productivity shock, k_{it} is the capital input, h_{it} is the final-good input (or "materials"), ℓ_{it} is the labor input, and F is a Cobb-Douglas production function.[3] The firm faces a proportional revenue tax, at rate τ_t^r. Its nominal profit net of taxes is therefore given by

$$\Pi_{it} = (1-\tau_t^r)p_{it}y_{it} - P_tr_tk_{it-1} - P_th_{it} - P_tw_t\ell_{it},$$

where p_{it} denotes the nominal price of the intermediate good i, P_t denotes the nominal price of the final good (also, the price level), and r_t and w_t denote, respectively, the real rental rate of capital and the real wage rate. The final good, in turn, is produced by a competitive retail sector, whose output, Y_t, is a CES (constant elasticity of substitution) aggregator of all the intermediate varieties:

$$Y_t = \left(\int_I (y_{it})^{(\rho-1)/\rho}\, di\right)^{\rho/(\rho-1)},$$

where $\rho > 1$. The profit of the retail sector is therefore given by $P_tY_t - \int_I p_{it}y_{it}\, di$, and its maximization yields the demand curves faced by the monopolists.

[3] The Cobb-Douglas restriction is with some, but not serious, loss of generality. A generalization was considered in an earlier version of our paper.

F. The Government

The government's period-t budget constraint, in nominal terms, is given by

$$(1 + R_{t-1})B_{t-1} + D_{t-1,s^t} + P_tG_t = B_t + \sum_{s\in S^{t+1}} Q_{t,s}D_{t,s} + T_t,$$

where $G_t = G(s^t)$ is the exogenous real level of government spending and T_t is the nominal level of tax revenue, given by

$$T_t = \tau_t^r P_t Y_t + \tau_t^c P_t C_t + \tau_t^\ell P_t w_t L_t + \tau_t^k P_t r_t k_t + \Pi_t,$$

where Π_t are the aggregate firm profits. With some abuse of notation, we let $D_t = (D_{t,s})_{s\in S^{t+1}}$ and $Q_t = (Q_{t,s})_{s\in S^{t+1}}$. The planner controls the vector $(\tau_t^r, \tau_t^\ell, \tau_t^k, \tau_t^c, B_t, D_t)$, along with R_t, the nominal interest rate. Finally, to simplify the exposition and keep the analysis comparable to that of Correia, Nicolini, and Teles (2008), we abstract from the zero lower bound on the nominal interest rate.

G. Market Clearing

Market clearing in the goods market is given by

$$C_t + H_t + X_t + G_t = Y_t,$$

where $X_t \equiv \int_I x_{it}\, di$ is aggregate investment and $H_t \equiv \int_I h_{it}\, di$ is the aggregate intermediate-input use of the final good. Market clearing in the labor market, on the other hand, is given by $\int_I \ell_{it}\, di = L_t$.

H. The Informational Friction

The scenario most often studied in the literature allows the firm-specific variables $(p_{it}, k_{it}, h_{it}, \ell_{it}, y_{it})$ to be measurable in s^t for all i and all t. We depart from this benchmark by requiring that each firm must act on the basis of a noisy, and idiosyncratic, signal of s^t. As in the related literature, the noise can be interpreted either as the product of imperfect observability of the state or as the product of rational inattention.

More specifically, the friction takes the following form. For every t, s^t, and i, nature draws a random variable ω_i^t from a finite set Ω^t according to a probability distribution φ. This variable represents the entire information ("signal") that firm i has in period t about the underlying state of nature. We denote with $\varphi(\omega^t, s^t)$ the joint probability of (ω^t, s^t), with $\varphi(\omega^t|s^t)$ the probability of ω^t conditional on s^t and with $\varphi(s^t|\omega^t)$ the probability of s^t conditional on ω^t. Conditional on s^t, the draws are i.i.d. (independently and identically distributed) across firms, and a law of large number applies, so that $\varphi(\omega^t|s^t)$ is also the fraction of the population that receives the signal ω^t.[4] Finally, we impose the following two measurability restrictions.

PROPERTY 1. There exist functions $\{h_t, k_t, \ell_t, y_t\}$ such that firm-level quantities satisfy

$$h_{it} = h_t(\omega_i^t), \quad k_{it} = k_t(\omega_i^t), \quad \ell_{it} = \ell_t(\omega_i^t, s^t), \quad y_{it} = y_t(\omega_i^t, s^t),$$

for all i, all t, and all realizations of uncertainty.

PROPERTY 2. There exist functions $\{p_t\}$ such that prices satisfy

$$p_{it} = p_t(\omega_i^t)$$

for all i, all t, and all realizations of uncertainty.

These properties constitute, in effect, a definition of informational feasibility. Property 2, which requires p_{it} to be measurable in ω_i^t rather than s^t, introduces the same kind of nominal rigidity as the one featured in Mankiw and Reis (2002), Woodford (2003), Mackowiak and Wiederholt (2009), and a growing literature that replaces Calvo-like sticky prices with an informational friction. Relative to this literature, the key novelty here is property 1. This adds a real friction by requiring that (k_{it}, h_{it}) be also measurable in ω_i^t. Finally, letting ℓ_{it} (and thereby also y_{it}) adjust to s^t guarantees that supply can meet demand and markets clear for all realizations of uncertainty.[5]

I. Interpretation and a Few Special Cases

Because no restriction is imposed on the dynamic structure of the signals, we can accommodate arbitrary learning dynamics or even the possibility of memory loss over time. Furthermore, ω_i^t may contain any arbitrary information: it may include information not only about fundamentals but also about the beliefs of other firms. That is, we can accommodate rich higher-order uncertainty.

This level of generality highlights the flexibility of our primal approach and the robustness of our lessons. It also permits us to nest a variety of specific cases found in the literature.

To start with, consider models with noisy Gaussian signals, as in Morris and Shin (2002), Woodford (2003), and Angeletos and La'O (2010). These may be nested by specifying the underlying aggregate TFP shock as a Gaussian random variable and letting each firm observe a pair of signals

[4] See Uhlig (1996) for an applicable law of large numbers with a continuum of draws.

[5] Although we make a specific modeling choice regarding which input choices are restricted to be contingent on ω_i^t, what is essential for our results is that some inputs are chosen on the basis of incomplete information, not the precise interpretation of these inputs. Moreover, the assumption that at least one input can adjust to the realized s^t is standard in both the New Keynesian literature and the recent literature on the informational foundations of nominal rigidity (Mankiw and Reis 2002; Woodford 2003; Mackowiak and Wiederholt 2009). Without this assumption, market clearing would not be possible, and some form of rationing would have to be introduced.

about it, one private and one public; see section VII for an example along these lines.

Alternatively, consider models with "sticky information," as in Mankiw and Reis (2002) and Chung, Herbst, and Kiley (2015). This specification is nested in our framework by letting φ assign probability μ to $\omega_i^t = (\omega_i^{t-1}, s^t)$ and probability $1 - \mu$ to $\omega_i^t = \omega_i^{t-1}$, where $\mu \in (0, 1)$ is the probability with which a firm updates its information set with perfect observation of the underlying state and $1 - \mu$ is the probability with which the firm is stuck with her old information set.

Finally, consider the different forms of rational inattention found in Sims (2003), Mackowiak and Wiederholt (2009), Myatt and Wallace (2012), and Pavan (2016) or the model of fixed observation costs found in Alvarez, Lippi, and Paciello (2011). For our purposes, these approaches boil down to allowing each firm to choose its own φ, the joint distribution of its signal and of the underlying state, and making different assumptions on the set of feasible φs and the associated cognitive costs. These possibilities are nested in the extension studied in online appendix A.

J. Relation to Ramsey and New Keynesian Literatures

When both the nominal and the real rigidity are assumed away (meaning that all prices and inputs can be measurable in s^t), our framework reduces to a prototypical Ramsey economy, such as those found in Lucas and Stokey (1983) and Chari, Christiano, and Kehoe (1994). More importantly, our framework nests the New Keynesian setting of Correia, Nicolini, and Teles (2008) by dropping the measurability constraint on $(h_{it}, k_{it}, \ell_{it}, y_{it})$, maintaining the measurability constraint on p_{it}, and letting $\omega_i^t = s^{t-1}$ with probability λ and $\omega_i^t = s^t$ with probability $1 - \lambda$, which means that a fraction λ of the firms must set their prices one period in advance while the rest can adjust their prices freely.

This nesting permits us to clarify three elementary points. First, the earlier results of Correia, Nicolini, and Teles (2008) directly extend to the alternative, information-based forms of nominal rigidity considered in Mankiw and Reis (2002), Woodford (2003), Mackowiak and Wiederholt (2009), and Alvarez, Lippi, and Paciello (2011). Second, these earlier results do not directly apply to our setting because, and only because, of the real rigidity formalized in property 1 above and of the associated imperfection in the coordination of production. And third, this imperfection is the sole source of our result regarding the optimality of monetary policies that lean against the wind. All of these points will be made clear in due course.

III. Sticky versus Flexible Prices: Definitions

The dual role of the informational friction as a source of both nominal and real rigidity is a defining feature of our framework. Accordingly, we are ultimately interested in the scenario in which both rigidities are present. To understand the role of monetary policy in this scenario, it is nevertheless instrumental to study the alternative scenario in which the nominal rigidity is artificially shut down by letting all prices be measurable in s^t. Borrowing, and paraphrasing, the terminology of the New Keynesian literature, we henceforth refer to the scenario that embeds the nominal rigidity as "sticky prices" and to the one that assumes it away as "flexible prices." In this section, we define the sets of allocations, prices, and policies that can be part of an equilibrium under each scenario.

To start with, we introduce some useful notation. We henceforth represent an allocation by a sequence $\xi \equiv \{\xi_t(\cdot)\}_{t=0}^{\infty}$, where

$$\xi_t(\cdot) \equiv \{k_t(\cdot), h_t(\cdot), \ell_t(\cdot), y_t(\cdot); K_t(\cdot), H_t(\cdot), L_t(\cdot), Y_t(\cdot), C_t(\cdot)\}$$

is a vector of functions that map the realizations of uncertainty to the quantities chosen by the typical firm (for the first four components of ξ_t) and the aggregate quantities (for the remaining five components). We similarly represent a price system by a sequence $\varrho \equiv \{\varrho_t(\cdot)\}_{t=0}^{t}$, where

$$\varrho_t(\cdot) \equiv \{p_t(\cdot), P_t(\cdot), r_t(\cdot), w_t(\cdot), Q_t(\cdot)\}$$

is a vector of functions that map the realizations of uncertainty to the price set by the typical firm, the aggregate price level, the real wage rate, the real rental rate of capital, and the prices of the Arrow securities. We finally represent a policy with a sequence $\theta = \{\theta_t(\cdot)\}_{t=0}^{t}$, where

$$\theta_t(\cdot) \equiv \left\{\tau_t^r(\cdot), \tau_t^\ell(\cdot), \tau_t^k(\cdot), \tau_t^c(\cdot), B_t(\cdot), D_t(\cdot), R_t(\cdot)\right\}$$

is a vector of functions that map the realizations of uncertainty to the various policy instruments.

Throughout our analysis, we let the domain of $K_t(\cdot)$, $H_t(\cdot)$, $L_t(\cdot)$, $Y_t(\cdot)$, $C_t(\cdot)$, $P_t(\cdot)$, $r_t(\cdot)$, $w_t(\cdot)$, $Q_t(\cdot)$, $\tau_t^r(\cdot)$, $\tau_t^\ell(\cdot)$, $\tau_t^k(\cdot)$, $\tau_t^c(\cdot)$, $B_t(\cdot)$, $D_t(\cdot)$, and $R_t(\cdot)$ be S^t. This reflects the fact that our analysis abstracts from informational frictions on the side of either the representative household or the government. In contrast, the informational friction of the firms is embedded in properties 1 and 2. We finally express the aggregate level of output and the aggregate price level as follows:

$$\begin{aligned} Y(s^t) &= \left[\sum_{\omega\in\Omega^t} (y(\omega, s^t))^{(\rho-1)/\rho} \varphi(\omega|s^t)\right]^{\rho/(\rho-1)}, \quad \text{and} \\ P(s^t) &= \left[\sum_{\omega\in\Omega^t} (p(\omega))^{\rho-1} \varphi(\omega|s^t)\right]^{1/(\rho-1)}. \end{aligned} \tag{1}$$

We can then define our notion of sticky-price equilibria as follows.[6]

DEFINITION 1. A *sticky-price equilibrium* is a triplet (ξ, ϱ, θ) of allocations, prices, and policies that satisfy properties 1 and 2 and are such that (i) $\{C(\cdot), L(\cdot), K(\cdot), B(\cdot), D(\cdot)\}$ solves the household's problem; (ii) $\{p(\cdot), k(\cdot), h(\cdot), \ell(\cdot), y(\cdot)\}$ solves the firm's problem; (iii) the quantity and the price of the final good are given by condition (1); (iv) the government's budget constraint is satisfied; and (v) all markets clear.

We next define our notion of flexible-price equilibria by dropping the measurability constraint on prices. Formally, we replace property 2 with the following property:

PROPERTY 2′. The prices satisfy

$$p_{it} = p_t(\omega_i^t, s^t)$$

for all i, all t, and all realizations of uncertainty.

Accordingly, we adjust the formula for the price level in condition (1) as follows:

$$P(s^t) = \left[\sum_{\omega\in\Omega^t} (p(\omega, s^t))^{\rho-1}\varphi(\omega|s^t)\right]^{1/(\rho-1)}. \tag{2}$$

We can then state the relevant definition as follows.

DEFINITION 2. A *flexible-price equilibrium* is a triplet (ξ, ϱ, θ) of allocations, prices, and policies that satisfy the same conditions as those stated in definition 1, except that property 2 is replaced by property 2′ and, accordingly, the price level is given by condition (2).

We let $\mathcal{X}^{\mathrm{f}}$ and $\mathcal{X}^{\mathrm{s}}$ denote the sets of the allocations that are part of a flexible-price equilibrium and a sticky-price equilibrium, respectively. We also let $\mathcal{X}$ denote the (super)set of all feasible allocations, by which we mean allocations that satisfy the economy's resource constraints along with property 1.

IV. Sticky versus Flexible Prices: Characterization and Replication

In this section we characterize, and compare, the sets of the allocations that can be part of either a flexible-price or a sticky-price equilibrium.

A. *Flexible-Price Allocations*

Consider any flexible-price equilibrium. The characterization of the household's problem is standard. The characterization of the monopolist's

[6] The only essentially novel feature in the definition is the pair of measurability constraints imposed on the firm's problem. The precise formulation of this problem, as well as that of the household's problem, can be found in the online appendix.

problem is slightly more exotic because of the heterogeneity in the signal ω_i^t upon which the input choices are based. To conserve on notation, we henceforth let, for any $z \in \{\ell, h, k\}$,

$$\mathrm{MP}_z(\omega_i^t, s^t) \equiv \left(\frac{y(\omega_i^t, s^t)}{Y(s^t)}\right)^{-1/\rho} A(s^t)\frac{\partial}{\partial z}F(k(\omega_i^t), h(\omega_i^t), \ell(\omega_i^t, s^t)).$$

In the eyes of the planner, MP_z represents the marginal product of input z in firm i, expressed in terms of the final good; in the eyes of the firm, it captures the corresponding marginal revenue product once it is multiplied by $\chi^* \equiv (\rho - 1)/\rho$, the reciprocal of one plus the monopoly markup. We may express the first-order conditions of the firm as follows:

$$(1 - \tau^r(s^t))\chi^*\mathrm{MP}_\ell(\omega_i^t, s^t) - w(s^t) = 0 \quad \forall\, t, \omega_i^t, s^t, \tag{3}$$

$$\mathbb{E}[\mathcal{M}(s^t)[(1 - \tau^r(s^t))\chi^*\mathrm{MP}_h(\omega_i^t, s^t) - 1]|\omega_i^t] = 0 \quad \forall\, t, \omega_i^t, \tag{4}$$

$$\mathbb{E}[\mathcal{M}(s^t)[(1 - \tau^r(s^t))\chi^*\mathrm{MP}_k(\omega_i^t, s^t) - r(s^t)]|\omega_i^t] = 0 \quad \forall\, t, \omega_i^t, \tag{5}$$

where $\mathcal{M}(s^t) \equiv U_c(s^t)/(1 + \tau^c(s^t))$ and $U_c(s^t)$ is a shortcut for the marginal utility of consumption.

These conditions have a simple interpretation. The firm seeks to equate the cost of each input with its after-tax marginal revenue product. The only difference among the three conditions is the extent to which this goal is achieved. Because labor is contingent on the realized state s^t, its marginal revenue product is equated with the real wage state by state. By contrast, the other two conditions hold only "on average," that is, in expectation conditional on the firm's signal.

Combining the optimality conditions of the firm with those of the household, imposing market clearing, and solving out for the prices and the policy instruments, we reach the following result.

Proposition 1. A feasible allocation, $\xi \in \mathcal{X}$, is part of a flexible-price equilibrium if and only if the following two properties hold: (i) the allocation satisfies

$$\sum_{t,s^t}\beta^t\mu(s^t)(U_c(s^t)C(s^t) + U_\ell(s^t)L(s^t)) = 0, \tag{6}$$

and (ii) for every t, there exist functions $\psi^r, \psi^\ell, \psi^c, \psi^k : S^t \to \mathbb{R}_+$ such that

$$\psi^r(s^t)\chi^*\mathrm{MP}_\ell(\omega_i^t, s^t) - \psi^\ell(s^t) = 0 \quad \forall\, \omega_i^t, s^t, \tag{7}$$

$$\mathbb{E}[\psi^r(s^t)\chi^*\mathrm{MP}_h(\omega_i^t, s^t) - \psi^c(s^t)|\omega_i^t] = 0 \quad \forall\, \omega_i^t, \tag{8}$$

$$\mathbb{E}[\psi^r(s^t)\chi^*\mathrm{MP}_k(\omega_i^t, s^t) - \psi^k(s^t)|\omega_i^t] = 0 \quad \forall\, \omega_i^t. \tag{9}$$

Condition (6) is familiar from the Ramsey literature. It encapsulates the absence of lump-sum taxation and follows directly from the intertemporal budget constraint of the government, after replacing the equilibrium prices and the policy instruments in terms of the allocation.

Consider next conditions (7)–(9). Were the informational friction absent, each firm would know s^t and these conditions would reduce to, respectively,

$$\mathrm{MP}_\ell(\omega_i^t, s^t) = \frac{\psi^\ell(s^t)}{\psi^r(s^t)},$$

$$\mathrm{MP}_h(\omega_i^t, s^t) = \frac{\psi^c(s^t)}{\psi^r(s^t)}, \quad \text{and}$$

$$\mathrm{MP}_k(\omega_i^t, s^t) = \frac{\psi^k(s^t)}{\psi^r(s^t)}$$

$\forall t, \omega_i^t, s^t$. Since the ψs are free variables, these conditions would require that the marginal product of each input is equated across all firms for all t and s^t. This defines what we call "perfect coordination" in production. It also means that the sole role of the tax instruments in that benchmark is to control the wedges between the common marginal rates of transformation of the firms and the corresponding marginal rates of substitution of the household.

When instead the informational friction is present, each firm conditions her choices on an idiosyncratic signal of s^t. As a result, marginal products are typically not equated across firms. This manifests as an aggregate TFP loss like that quantified in David, Hopenhayn, and Venkateswaran (2016). It also means that the available tax instruments may play a new role: their contingency on s^t influences how firms utilize their private information. This enables the planner to control not only the response of aggregate output to aggregate TFP and other shocks but also the cross-sectional dispersion in produced quantities and marginal products. It is this new role of the taxes that is encoded into conditions (7)–(9). We illustrate this point with an example in section VII.

B. Sticky-Price Allocations

We now add back the nominal rigidity (property 2). As in the New Keynesian model, this allows the realized monopoly markup to fluctuate around the ideal one. Formally, there now exists a random variable $\chi(\omega_i^t, s^t)$, representing the reciprocal of the realized markup, such that the following properties are true. First, the optimality conditions (3)–(5) are modified by replacing χ^* with $\chi(\omega_i^t, s^t)$. And second, the following optimality condition is added:

$$\mathbb{E}\left[\mathcal{M}(s^t)Y(s^t)^{1/\rho}y(\omega_i^t, s^t)^{1-1/\rho}(1-\tau^r(s^t))(\chi(\omega_i^t, s^t)-\chi^*)|\omega_i^t\right] = 0 \quad \forall\,\omega_i^t. \tag{10}$$

This condition captures the optimal price-setting behavior of the firm. It requires, in essence, that the risk-adjusted expectation of the realized markup coincides with the ideal one.

Adapting proposition 1 to these modifications, we reach the following result.

Proposition 2. A feasible allocation, $\xi \in \mathcal{X}$, is part of a sticky-price equilibrium if and only if the following three properties hold.

i. The allocation satisfies condition (6).

ii. For every t, there exist functions $\psi^r, \psi^\ell, \psi^k, \psi^c : \mathcal{S}^t \to \mathbb{R}_+$ and $\chi : \Omega^t \times \mathcal{S}^t \to \mathbb{R}_+$ such that the following conditions hold:

$$\chi(\omega_i^t, s^t)\psi^r(s^t)\mathrm{MP}_\ell(\omega_i^t, s^t) - \psi^\ell(s^t) = 0 \quad \forall\,\omega_i^t, s^t, \tag{11}$$

$$\mathbb{E}[\chi(\omega_i^t, s^t)\psi^r(s^t)\mathrm{MP}_h(\omega_i^t, s^t) - \psi^c(s^t)|\omega_i^t] = 0 \quad \forall\,\omega_i^t, \tag{12}$$

$$\mathbb{E}[\chi(\omega_i^t, s^t)\psi^r(s^t)\mathrm{MP}_k(\omega_i^t, s^t) - \psi^k(s^t)|\omega_i^t] = 0 \quad \forall\,\omega_i^t, \tag{13}$$

$$\mathbb{E}\left[Y(s^t)^{1/\rho}y(\omega_i^t, s^t)^{1-1/\rho}\psi^r(s^t)(\chi(\omega_i^t, s^t)-\chi^*)|\omega_i^t\right] = 0. \tag{14}$$

iii. The function $\chi : \Omega^t \times \mathcal{S}^t \to \mathbb{R}_+$ is log-separable in the sense that there exist positive-valued functions χ^ω and χ^s such that

$$\log\chi(\omega_i^t, s^t) = \log\chi^\omega(\omega_i^t) + \log\chi^s(s^t) \quad \forall\,\omega_i^t, s^t. \tag{15}$$

Clearly, the only differences from proposition 1 are the emergence of the wedge $\chi(\omega_i^t, s^t)$ in conditions (11)–(13) and the addition of conditions (14) and (15). As explained above, condition (14) follows from the optimal price-setting behavior of the firm. Condition (15), on the other hand, follows from the isoelastic demand structure; see the online appendix for details.

C. *Replication*

Through the lens of proposition 2, $\chi(\omega_i^t, s^t)$ represents an additional control variable for the planner, one that encapsulates the power of monetary policy over real allocations. This power is nontrivial, but it is also restrained by conditions (14) and (15). Since both conditions are automatically satisfied by letting $\chi(\omega_i^t, s^t) = \chi^*$, the following is immediate.

Corollary 1. Every flexible-price allocation can be replicated as a sticky-price allocation: $\mathcal{X}^{\mathrm{f}} \subset \mathcal{X}^{\mathrm{s}}$.

This proves that an appropriate monetary policy can undo the nominal rigidity but tells us neither whether such a policy is optimal nor how it looks. We address these questions next.

V. The Ramsey Optimum

In this section we define and characterize the efficiency benchmark that is relevant for our purposes. This leads to our main results regarding the optimal monetary policy.

A. An Appropriate Efficiency Benchmark

Our ultimate goal is to solve the problem of a Ramsey planner who maximizes welfare over $\mathcal{X}^s$, the set of sticky-price allocations. To this goal, we first characterize the allocation ξ^* that maximizes welfare over an enlarged and relaxed set, denoted by $\mathcal{X}^R$ and consisting of all technologically and informationally feasible allocations that satisfy only condition (6). That is, from the six implementability constraints seen in proposition 2, we maintain only the first one, which encapsulates the absence of lump-sum taxation, but drop the remaining ones. This is akin to allowing the planner to impose a completely flexible set of input- and signal-specific taxes.

PROPOSITION 3. There exists a constant $\Gamma \geq 0$ capturing the shadow value of government revenue, such that ξ^*, the optimal allocation over the enlarged set $\mathcal{X}^R$, is given by the feasible allocation that satisfies the following conditions:

$$\tilde{U}_c(s^t)\mathrm{MP}_\ell(\omega_i^t, s^t) + \tilde{U}_\ell(s^t) = 0 \quad \forall \omega_i^t, s^t, \tag{16}$$

$$\mathbb{E}\left[\tilde{U}_c(s^t)(\mathrm{MP}_h(\omega_i^t, s^t) - 1)|\omega_i^t\right] = 0 \quad \forall \omega_i^t, \tag{17}$$

$$\mathbb{E}\left[\tilde{U}_c(s^t)(\mathrm{MP}_k(\omega_i^t, s^t) - \kappa(s^t))|\omega_i^t\right] = 0 \quad \forall \omega_i^t, \tag{18}$$

for some function $\kappa : \mathcal{S}^t \to \mathbb{R}_+$ that captures the net-of-tax rental rate of capital and satisfies

$$\tilde{U}_c(s^t) = \beta\mathbb{E}\left(\tilde{U}_c(s^{t+1})\left(1 + \kappa\left(s^{t+1}\right) - \delta\right)|s^t\right] \quad \forall s^t, \tag{19}$$

where $\tilde{U}_c(s^t)$ and $\tilde{U}_\ell(s^t)$ are shortcuts for $(\partial/\partial C)\tilde{U}(C(s^t), L(s^t), s^t; \Gamma)$ and $(\partial/\partial L)\tilde{U}(C(s^t), L(s^t), s^t; \Gamma)$, respectively, and where

$$\tilde{U}(C, L, s; \Gamma) \equiv U(C, L, s) + \Gamma\left(C\frac{\partial}{\partial C}U(C, L, s) + L\frac{\partial}{\partial L}U(C, L, s)\right). \tag{20}$$

To understand this result, momentarily shut down the informational friction. In this case, conditions (16)–(18) reduce to the following:

$$\mathrm{MP}_{\ell}(s^t) = \frac{\tilde{U}_{\ell}(s^t)}{\tilde{U}_{c}(s^t)},$$

$$\mathrm{MP}_{h}(s^t) = 1, \quad \text{and}$$

$$\tilde{U}_{c}(s^t) = \beta\mathbb{E}\left[\tilde{U}_{c}\left(s^{t+1}\right)\left(1 - \delta + \mathrm{MP}_{k}\left(s^{t+1}\right)\right)|s^t\right],$$

respectively, where $\mathrm{MP}_z(s^t)$ now denotes the common marginal product of input z in all firms. The first condition is identical to the one found in Lucas and Stokey (1983) and identifies the optimal tax on labor. The second condition implies that the tax on the intermediate input is zero, an example of the result in Diamond and Mirrlees (1971): taxes should not interfere with productive efficiency. The last condition is identical to that found in Chari, Christiano, and Kehoe (1994) and relates to the celebrated Chamley-Judd result about the optimality of zero taxes on capital income.[7]

Now add back in the informational friction. In general, optimality requires that each firm condition her choices on her private information about the underlying state. Because such information contains idiosyncratic noise, the marginal products are no more equated across the firms. In comparison to the previous literature, this property may be misinterpreted as a symptom of productive inefficiency and relative-price distortions, but through the lens of proposition 3, it is understood as the by-product of the socially optimal decentralized use of information. This explains how our analysis revisits the concept of relative-price distortions.

Proposition 3 also revises the concept of the output gap. Because the CES structure implies that the social value of producing an extra unit of any given good increases with the quantities of other goods, the planner finds it optimal to let the firms coordinate their input choices.[8] This means that the optimal allocation characterized here allows a firm's production to vary, not only with her information about the underlying fundamentals but also with her beliefs about the beliefs of other firms. The business cycle can thus be driven by fluctuations in the level of "confidence," or by random shifts in sentiment, of the kind formulated in Angeletos and La'O (2013) and Benhabib, Wang, and Wen (2015) and quantified in Angeletos, Collard, and Dellas (2018) and Huo and Takayama (2015a). Under a traditional policy perspective, such fluctuations can be misinterpreted

[7] In addition, we bypass the issue studied in Straub and Werning (2020) and guarantee the validity of the optimality of a zero tax on capital income by allowing the government to tax fully (confiscate) the initial capital stock.

[8] Formally, the optimal allocation can be understood as the perfect Bayesian equilibrium of a game of strategic complementarity, in line with the more abstract analysis in Angeletos and Pavan (2007).

as fluctuations in the output gap, but through our analysis, they are recast as constrained efficient fluctuations in potential output.

To sum up, not only do the observable properties of the optimum have to be modified but also the familiar goals of "minimizing relative-price distortions" and "stabilizing the output gap" must be revised before we may understand the role of monetary policy.

B. Implementation

We now show how the optimum characterized in proposition 3 can be implemented with the available policy instruments.

Recall that $\mathcal{X}^{\mathrm{R}}$ is a superset of both $\mathcal{X}^{\mathrm{f}}$ and $\mathcal{X}^{\mathrm{s}}$ because it allows the planner to make the production choices of each firm an arbitrary function of her private information, whereas $\mathcal{X}^{\mathrm{f}}$ and $\mathcal{X}^{\mathrm{s}}$ restrain that control in the manner described in part ii of, respectively, propositions 1 and 2. Yet the additional control afforded by $\mathcal{X}^{\mathrm{R}}$ is immaterial for optimality.

PROPOSITION 4. The allocation ξ^* can be implemented as a flexible-price equilibrium: $\xi^* \in \mathcal{X}^{\mathrm{f}}$.

By corollary 1, we have $\mathcal{X}^{\mathrm{f}} \subset \mathcal{X}^{\mathrm{s}}$. It follows that ξ^* can be implemented as a sticky-price allocation with a monetary policy that replicates flexible prices. And because $\mathcal{X}^{\mathrm{s}} \subset \mathcal{X}^{\mathrm{R}}$, we have that ξ^* maximizes welfare over all sticky-price allocations. Combining these findings and identifying the taxes that support ξ^* as an equilibrium, we reach the following result.

THEOREM 1. The allocation ξ^* obtained in proposition 3 identifies the optimal allocation and is implemented with (i) a monetary policy that replicates flexible prices and (ii) the following set of tax rates:

$$\begin{aligned}
\frac{1-\tau^{\ell}(s^t)}{1+\tau^{c}(s^t)} &= \frac{U_{\ell}(s^t)/U_c(s^t)}{\tilde{U}_{\ell}(s^t)/\tilde{U}_c(s^t)},\\
1-\tau^{k}(s^t) &= 1,\\
1-\tau^{r}(s^t) &= \frac{\rho}{\rho-1},\\
1+\tau^{c}(s^t) &= \delta\frac{U_c(s^t)}{\tilde{U}_c(s^t)},
\end{aligned} \tag{21}$$

where U_c, U_ℓ, $\tilde{U}_c$, and $\tilde{U}_\ell$, are evaluated at ξ^* and $\delta > 0$ is any state-invariant scalar.

Part i extends the related result of Correia, Nicolini, and Teles (2008) to the class of economies under consideration. Part ii generalizes the optimal taxation results of Lucas and Stokey (1983) and Chari, Christiano, and Kehoe (1994). There are, however, three subtle differences.

First and foremost, replicating flexible prices is no more synonymous to targeting price stability. We expand on this point in the next section.

Second, the relevant wedges are evaluated at an allocation whose observable properties may differ from those characterized in the aforementioned works for the reasons explained above. This opens the door to the possibility that the cyclical properties of the optimal taxes are different, even though the tax formulas obtained are essentially the same.

Third, the consumption tax plays a novel role. In the absence of the informational friction, τ^c can be set to zero, insofar as public debt is state contingent and the zero lower bound on the nominal interest rate is nonbinding. Here, instead, it is generally necessary to let τ^c vary with the state of nature so as to make sure that the firms face the right price of risk when making their choices.

These last two subtleties can be sidestepped by imposing homotheticity of preferences.

LEMMA 1. Suppose preferences are homothetic as follows:

$$U(C, L) = \frac{C^{1-\gamma}}{1-\gamma} - \eta\frac{L^{1+\epsilon}}{1+\epsilon}, \tag{22}$$

for $\gamma, \epsilon, \eta > 0$. Then, the optimal allocation is implemented with a zero tax on capital, a zero tax on consumption, and a time- and state-invariant tax on labor.

Therefore, from an applied perspective, the most important lesson appears to be the incompatibility of replicating flexible prices with targeting price stability, to which we turn next.

VI. On the Optimal Cyclicality of the Price Level

Within the New Keynesian framework, the logic in favor of price stability is that it minimizes relative-price distortions (or, equivalently, maximizes productive efficiency). We now explain why this logic is upset once the informational friction is taken into consideration and the efficiency benchmark is revised along the lines we described in the previous section.

We start by noting that, along the optimal allocation, the output of each firm can be expressed as the logarithmic sum of two components, one measurable in the firm's private information and the other measurable in the realized state.

LEMMA 2. There exist positive-valued functions Ψ^ω and Ψ^s such that, along the optimal allocation, the output of a firm can be expressed as

$$\log y(\omega_i^t, s^t) = \log \Psi^\omega(\omega_i^t) + \log \Psi^s(s^t) \quad \forall \omega_i^t, s^t. \tag{23}$$

The precise values of these components follow from the solution to the optimality conditions in proposition 3. In the appendix (see, in particular, the proof of proposition 5), we show how Ψ^ω may be expressed as a function of the input choices that firms make on the basis of their imperfect observation of the state of the economy, whereas Ψ^s captures the adjustment in the labor input that takes place in order for supply to meet the realized demand, and markets to clear, at the set prices.

In the example studied in the next section, all these objects can be solved in closed form as simple functions of the available signals. It then becomes evident how the optimal input choices and the aforementioned output components covary with the state of the economy. For the present purposes, however, it suffices to note the following general points.

Whereas Ψ^s captures the component of output that is common across all firms, Ψ^ω captures the component that is driven by each firm's private information. The latter component can be thought of as a proxy of the firm's idiosyncratic belief about the state of the economy. Along the optimal allocation, this typically means that an optimistic firm is associated with a higher Ψ^ω, and produces more, than a pessimistic one.

Furthermore, Ψ^ω is the only source of variation in relative quantities and, thereby, in relative prices. Indeed, by the relative demand for the goods produced by firms i and j, we have

$$\log p(\omega_i^t) - \log p(\omega_j^t) = -\frac{1}{\rho}\left(\log y(s^t, \omega_i^t) - \log y(s^t, \omega_j^t)\right).$$

Using condition (23), we then get

$$\log p(\omega_i^t) - \log p(\omega_j^t) = -\frac{1}{\rho}\left(\log \Psi^\omega(\omega_i^t) - \log \Psi^\omega(\omega_j^t)\right),$$

which verifies that the relative price of any two firms is inversely related to their relative belief, as measured by the log difference between $\Psi^\omega(\omega_i^t)$ and $\Psi^\omega(\omega_j^t)$. Intuitively, if optimistic firms are to produce more than pessimistic ones, they must also charge lower relative prices.

This elementary insight underlies our result regarding the suboptimality of price stability. As long as firm i does not know ω_j^t and, symmetrically, firm j does not know ω_i^t, their relative price can be inversely related with their relative quantity only if the nominal price of firm i is itself negatively related to her belief, as captured by $\Psi^\omega(\omega_i^t)$, and similarly for j. Formally, it has to be that

$$\log p(\omega_i^t) = z_t - \frac{1}{\rho}\log \Psi^\omega(\omega_i^t), \tag{24}$$

for some variable z_t that is commonly known to the firms (meaning that the prices of all the firms can be contingent on z_t). Aggregating the above, we get that the aggregate price level must satisfy

$$\log P(s^t) = z_t - \frac{1}{\rho}\log \mathcal{B}(s^t), \tag{25}$$

where

$$\mathcal{B}(s^t) \equiv \left(\int \Psi^\omega(\omega_i^t)^{(\rho-1)/\rho}\, d\mu(\omega_i^t | s^t) \right)^{\rho/(\rho-1)}.$$

We thus reach the following result.

THEOREM 2. Along any sticky-price equilibrium that implements the optimal allocation, the price level is negatively correlated with the average belief and real economic activity, as proxied by $\mathcal{B}(s)$.

This is our main result regarding the suboptimality of price stability. Its applicability hinges on relating the object $\mathcal{B}(s^t)$ to a more concrete measure of economic activity. This is done in section VII within an example that allows for an explicit solution of the optimal allocation and the optimal price level. That example relies on assuming away capital and imposing a Gaussian information structure. But even without these restrictions, the following result can be shown.

PROPOSITION 5. Along any sticky-price equilibrium that implements the optimal allocation, $\mathcal{B}(s^t)$ is, to a first-order log-linear approximation, a log-linear combination of the aggregate quantities of firm inputs; $\mathcal{B}(s^t)$ is therefore procyclical if inputs are also procyclical.

This corroborates the interpretation of $\mathcal{B}(s^t)$ as proxy for the aggregate level of economic activity and the interpretation of theorem 2 as a case for "leaning against the wind."

The logic for our result follows directly from our earlier discussion about the relation between relative prices and relative beliefs. Because optimality requires that the output of each firm varies with its belief about the state of the economy, and because relative prices are inversely related to relative quantities, the nominal price of a firm has to move in the direction opposite its belief. At the aggregate level, this translates to negative comovement between the price level and real output—a property that resembles nominal GDP targeting.

It is worth noting, however, two subtleties. First, theorem 2 allows for a certain degree of nominal indeterminacy: as evident in condition (25), the price level is indeterminate vis-à-vis any variable z_t that is common knowledge to the firms. This is because firms can perfectly coordinate their price responses to any such shock, which in turn guarantees that varying the response of monetary policy to z_t affects the variation in the price level without affecting the real allocations.[9]

[9] The source of this indeterminacy is similar to that in the older literature on nominal confusion (Lucas 1972; Barro 1976); it is clearly welfare irrelevant in our setting and can be refined away by imposing that no shock is common knowledge. We suspect that this indeterminacy also disappears if we add a Calvo friction, even a tiny one, for this helps anchor the optimal price level at all $t \geq 0$ to P_{-1}, the historical price level.

Second, theorem 2 also contains a case for price stability: if the optimal allocation is invariant with a shock, then it is optimal to stabilize the price level vis-à-vis that shock. Consider, for example, a pure sunspot, namely, a shock that is orthogonal not only to the underlying fundamentals but also to the entire hierarchy of beliefs about them. Alternatively, abstract from capital accumulation and consider a shock to beliefs of future TFP. In either case, the optimal allocation remains stable. If the monetary authority fails to stabilize the price level with respect to the shock under consideration, then the production of a positive mass of firms will vary with it, contradicting optimality.

We close this section by emphasizing that our result hinges on allowing the informational friction to be a real friction in the sense of property 1. We formalize this point below.

Proposition 6. Suppose that we maintain property 2 but drop property 1; that is, we maintain the nominal role of the informational friction but drop the real one. Then, the optimal allocation is implemented by targeting price stability.

This is essentially the main result of Correia, Nicolini, and Teles (2008). Recall that the setting in that paper may be nested in our framework when the real rigidity is assumed away and the nominal rigidity is such that a fraction λ of the firms set their prices one period in advance (in which case $\omega_i^t = s^{t-1}$) while the remaining are free to adjust their prices (in which case $\omega_i^t = s^t$). Proposition 6 therefore replicates the main result of that paper and also extends it to the alternative, information-based foundations of the nominal rigidity proposed by Mankiw and Reis (2002), Woodford (2003), Mackowiak and Wiederholt (2009), and others.

To sum up, what drives the particular kind of "leaning against the wind" documented in our paper is precisely the real bite of the informational friction, captured here by property 1.[10]

VII. An Illustration

In this section we use a tractable Gaussian example to illustrate the main lessons of our paper. In particular, we first demonstrate how the policy instruments can manipulate the decentralized use of information and can possibly insulate aggregate output from the effects of noise, sentiments, and the like. We next characterize the optimal allocation, contrast it to its

[10] This also explains why Adam (2007) and Paciello and Wiederholt (2014), who abstract from the real rigidity that has been the focus of our paper, let monetary policy substitute for missing tax instruments. Ball, Mankiw, and Reis (2005) also abstract from the real rigidity, but they focus on a different issue, the transition from a suboptimal to an optimal policy.

complete-information counterpart, and show how the price level moves in the direction opposite that of aggregate output.[11]

A. Setup

We let preferences be homothetic, as in condition (22). We also abstract from capital, let government spending be constant, and add idiosyncratic TFP shocks. The production function is thus given by

$$y_{it} = A_{it}(h_{it}^{\eta})^{1-\alpha}\ell_{it}^{\alpha}, \tag{26}$$

where $\alpha \in (0, 1)$ and $\eta \in (0, 1)$ and where A_{it}, the productivity of firm i in period t, consists of an aggregate and a firm-specific component. In particular,

$$a_{it} \equiv \log A_{it} = a_t + v_{it},$$

where $a_t \equiv \log A_t$ is the aggregate component and v_{it} is the idiosyncratic one. The processes of a_t and v_{it} are Gaussian, stationary, and orthogonal to one another. The idiosyncratic component v_{it} is i.i.d. across firms but can be correlated over time within a firm. The aggregate component a_t can also be correlated over time. We finally let each firm know its own productivity, a_{it}, but not the underlying aggregate component, a_t.

The results presented below impose no further restrictions on the process for a_t and the available signals about it. This permits us to accommodate rich learning dynamics as well as rich higher-order uncertainty. For instance, by letting a_t follow an AR(1) (first-order autoregressive) process and each firm observe a noisy private signal of a_t in each period, we can accommodate the kind of inertial belief dynamics studied in Woodford (2003), Nimark (2008), Angeletos and Huo (2018), and elsewhere.

To fix ideas, however, the reader may restrict attention to the special case in which a_t is i.i.d. over time and firm i's information in period t is given by the pair (a_{it}, z_{it}), where

$$z_{it} = a_t + \sigma_v v_t + \sigma_\epsilon \epsilon_{it} \tag{27}$$

is a noisy signal of a_t and ϵ_{it} and v_t are, respectively, idiosyncratic and aggregate noises, independent of one another and of a_t. We let scalars $\sigma_\epsilon > 0$ and $\sigma_v > 0$, respectively, parameterize the level of these two noises. In this

[11] The example used in this section can be thought of as a hybrid of Woodford (2003) and Angeletos and La'O (2010). Woodford (2003) assumes away the real rigidity and lets monetary policy induce an exogenous Gaussian process for nominal GDP. Angeletos and La'O (2010) shuts down the nominal rigidity and abstracts from both fiscal and monetary policy. Relative to these earlier works, we not only combine the two forms of rigidity in the same example but also work out the optimal policy.

example, the shock v_t is a source of correlated noise in firms' first- and higher-order beliefs. Also note that the case of a noisy public signal is nested by letting $\sigma_\epsilon \to 0$, whereas the case with purely private information and no aggregate noise is nested by letting $\sigma_v \to 0$.

B. *Manipulating the Decentralized Use of Information*

Before characterizing the optimal policy, we find it useful to illustrate how the state contingency of the policy instruments can influence the decentralized use of information and thereby the stochastic process of aggregate output. To this end, we specify the tax system such that the relevant wedges are log-linear functions of aggregate productivity and aggregate output only. In particular, we impose

$$-\log(1 - \tau^r(A_t, Y_t)) = \hat{\tau}_0 + \hat{\tau}_A \log A_t + \hat{\tau}_Y \log Y_t$$

for some scalars $\hat{\tau}_0, \hat{\tau}_A, \hat{\tau}_Y \in \mathbb{R}$. We then let the remaining tax rates satisfy $\tau^k(s^t) = \tau^c(s^t) = 0$ and $1 + \tau^\ell(s^t) = 1/(1 - \tau^r(s^t))$. The scalars $(\hat{\tau}_0, \hat{\tau}_A, \hat{\tau}_Y)$ can then be thought of as the policy coefficients. Finally, here and for the rest of this section, we consider the log-linearized approximation of the equilibrium allocations around the steady state in which A_t takes its unconditional mean value.

PROPOSITION 7. Consider the economy and the taxes described above. In any flexible-price equilibrium, the variable GDP satisfies, up to a log-linear approximation,

$$\log \mathrm{GDP}(s^t) = \gamma_0 + \gamma_A \log A_t + \gamma_u u_t, \tag{28}$$

where the scalars $(\gamma_0, \gamma_A, \gamma_u)$ are pinned down by the policy coefficients $(\hat{\tau}_0, \hat{\tau}_A, \hat{\tau}_Y)$ and where u_t is a normally distributed random variable, orthogonal to $\log A_t$, with mean 0 and variance 1.

Furthermore, by appropriately choosing the policy coefficients $(\hat{\tau}_A, \hat{\tau}_Y)$, the planner can implement any pair (γ_A, γ_u) inside the set Υ, where

$$\Upsilon \equiv \{(\gamma_A, \gamma_u) \in \mathbb{R}^2 : \text{either } \gamma_u > 0 \text{ and } \gamma_A > \hat{\gamma} + \gamma_u, \text{ or } \gamma_u < 0 \text{ and } \gamma_A < \hat{\gamma} + \gamma_u\} \tag{29}$$

and where $\hat{\gamma}$ is a constant that depends on the underlying preference, technology, and information parameters but is invariant to policy and the implemented allocation.

To understand this result, note that u_t is the (standardized) residual of regressing aggregate output on the current aggregate productivity. This residual is zero in the absence of the informational friction but not when it is present. For instance, in the aforementioned special case in which a_t is i.i.d. over time and the signals are as in condition (27), u_t coincides with v_t, the aggregate noise in the available signals. More generally, u_t encapsulates all aggregate variation in the firms' first- and higher-order beliefs that is orthogonal to the current fundamentals (TFP).

With these points in mind, proposition 7 can be read as follows: by appropriately designing the coefficients $\hat{\tau}_A$ and $\hat{\tau}_Y$, the planner can affect both the covariation of aggregate output with the current fundamental and its residual variation as a result of noise or higher-order uncertainty. This is because these tax coefficients control how sensitive a firm's net-of-taxes revenue is to, respectively, TFP and the actions of other firms. As a result, these coefficients indirectly control the incentives each firm has in reacting to different pieces of information about these objects. In sum, policy coefficients may be used to control the decentralized use of information.

It can be shown that a similar result applies to monetary policy, with the analogues of $\hat{\tau}_A$ and $\hat{\tau}_Y$ being the responsiveness of the nominal interest rate to aggregate productivity and aggregate output, respectively. This illustrates our point that familiar policy instruments, whether fiscal or monetary, play novel roles once the informational friction is accommodated.

C. *The Ramsey Optimum*

Consider, as a reference point, the optimal allocation in the absence of the informational friction; this corresponds, in effect, to the Lucas-Stokey benchmark. In this case, it can be shown that aggregate output is given by

$$\log Y_t = \gamma_0^{\mathrm{LS}} + \gamma_A^{\mathrm{LS}} \log A_t,$$

for some scalars γ_0^{LS} and $\gamma_A^{\mathrm{LS}} > 0$ that depend on the preferences, technology, and level of government spending (or the tax distortion).

Consider now the case in which the informational friction is present. By proposition 7, there exist policies such that aggregate output is given by condition (28) with $\gamma_A = \gamma_A^{\mathrm{LS}}$ and $\gamma_u = 0$. That is, it is feasible for the planner to both induce the same covariation between aggregate output and aggregate productivity as in the frictionless benchmark and insulate aggregate output from noise, sentiments, and so on.

This is made possible by combining a $\hat{\tau}_Y$ high enough that the net-of-taxes returns are invariant to aggregate output and a $\hat{\tau}_A$ low enough that the net-of-taxes returns are sufficiently sensitive to aggregate productivity. The former property guarantees that the firms disregard information that is useful in predicting the choice of other firms but is not useful in predicting aggregate productivity; the latter ensures that the firms respond with enough strength to variation in aggregate productivity.

This may sound like a win-win situation. But it is not. When the planner induces the firms to disregard information about one another's choices over information about the fundamentals, she exacerbates the miscoordination of production and implements an inefficiently high level of cross-sectional dispersion in quantities. To economize on this margin, the optimal allocation allows the firms to utilize that kind of information, thus also allowing aggregate output to move with noise, sentiments, and so on. That is, optimality calls for $\gamma_u > 0$.

For essentially the same reason, the optimal allocation also induces a lower covariation between aggregate output and aggregate productivity than in the frictionless benchmark: the alternative requires that the firms respond too strongly to their private information and induces too much cross-sectional dispersion in quantities. That is, optimality calls for $\gamma_A < \gamma_A^{LS}$.

These points are established formally in the next proposition, which characterizes the process of aggregate output along the optimal allocation.

PROPOSITION 8. In any equilibrium that implements the optimal allocation, GDP is given by

$$\log \mathrm{GDP}_t = \gamma_0^* + \gamma_A^* \log A_t + \gamma_u^* u_t, \tag{30}$$

where u_t is a normally distributed random variable, orthogonal to $\log A_t$, with mean 0 and variance 1, and where the scalars γ_A^* and γ_u^* are uniquely determined by the underlying preference, technology, and information parameters. Furthermore,

$$0 < \gamma_A^* < \gamma_A^{LS} \quad \text{and} \quad \gamma_u^* > 0. \tag{31}$$

This result illustrates how the efficiency benchmark identified in our paper differs from that found in the literature. First, GDP features a lower sensitivity to the underlying fundamental than in the Lucas-Stokey benchmark. And second, GDP varies with noise, sentiments, beliefs, and so on.

D. *Monetary Policy*

We now turn attention to the optimal monetary policy and the associated price level. Theorems 1 and 2, of course, apply. The goal is to illustrate the particular form of "leaning against the wind" that obtains in the example under consideration.

PROPOSITION 9. In any sticky-price equilibrium that implements the optimal allocation, the aggregate price level satisfies

$$\log P(s^t) = \delta_0^* - \delta_A^* \log A_t - \delta_u^* u_t, \tag{32}$$

for some scalars δ_0^*, δ_A^*, δ_u^* that are determined by the underlying preference, technology, and information parameters and satisfy $\delta_A^* > 0$ and $\delta_u^* > 0$.

Corollary 2. The optimal monetary policy targets a negative correlation between the price level and GDP, both unconditionally and conditionally on the realized TFP.

This epitomizes our take-home policy lesson: the optimal policy leans against the wind both in response to innovations in the underlying fundamentals and in response to noise, sentiments, and so on.

VIII. Conclusion

This paper studies the question of how informational frictions affect the nature of optimal monetary policy. To this goal, we analyze a setting in which firms make both their pricing and their production choices on the basis of an imperfect and idiosyncratic understanding of the state of the economy. This amounts to introducing not only noisy information about the underlying fundamentals but also frictional coordination in the form of higher-order uncertainty.

In our setting, the optimal monetary policy is shown to replicate flexible-price allocations (properly defined). As in the New Keynesian paradigm, this holds as long as monetary policy does not have to substitute for missing tax instruments. Unlike that paradigm, however, the goal of replicating flexible-price allocations and minimizing relative-price distortions does not equate to a price-stability target. Instead, it implies a particular form of "leaning against the wind," namely, a negative correlation between the price level and aggregate output along the optimal path. This property is necessary in order to ensure that firms do not discard valuable private knowledge about the underlying shocks and coordinate their production choices in the best possible, albeit imperfect, manner.

To establish these lessons, we adapt the primal approach found in the Ramsey literature to the aforementioned kind of frictions. We show that this leads to a revision not only of the concept of flexible-price allocations but also of the efficiency benchmark relative to which the notions of the output gap and of relative-price distortions are to be defined. This benchmark differs from those studied in the literature because, and only because, the informational friction is a source of real rigidity. In particular, this benchmark may feature exotic business-cycle properties, which through the lens of conventional policy analysis could be misinterpreted as a call for stabilization policy but through the lens of our analysis are recast as symptoms of the efficient use of information.

Although real-world monetary policy surely reflects many concerns left outside our framework, our analysis emphasizes an aspect that has received relatively little attention but could be important: the role of monetary policy in affecting the incentives agents face when deciding how to react to their decentralized private information or when deciding what information to collect in the first place. Extending this insight, in ongoing work we show how monetary policy can also influence, indirectly, the quality of the information contained in prices or macroeconomic statistics.

Our analysis also has implications for the debate regarding the social value of information and the desirability of central bank transparency that was spurred by Morris and Shin (2002). These implications are worked out in Angeletos, Iovino, and La'O (2016). The bottom line is that, unless there are missing tax instruments, the optimal monetary policy guarantees that more information is unambiguously welfare improving in the class of business-cycle economies under consideration.

Notwithstanding these points, the most intriguing lesson of our analysis remains the recommendation that monetary policy ought to lean against the wind even in response to efficient business cycles. The quantitative evaluation of this lesson is an open question for future research.

Appendix

Proofs for Selected Results

This appendix provides the proofs for the propositions and theorems presented in sections V and VI. These are the main results of the paper. All other proofs are in online appendix B.

Proof of proposition 3—.The relaxed Ramsey optimal allocation solves the problem

$$\max_{\xi_t}\sum_{t=0}^{\infty}\sum_{s^t}\beta^t\mu(s^t)(U(C(s^t), L(s^t), s^t)),$$

subject to the following constraints:

$$0 \leq \sum_{t=0}^{\infty}\sum_{s^t}\beta^t\mu(s^t)(U_c(s^t)C(s^t) + U_\ell(s^t)L(s^t)), \tag{33}$$

$$\begin{aligned} C(s^t) + K(s^{t+1}) - (1-\delta)K(s^t) + G(s^t) + \sum_{\omega\in\Omega^t} h(\omega)\varphi(\omega|s^t) \\ = \left[\sum_{\omega\in\Omega^t}(A(s^t)F(k(\omega_i^t), h(\omega_i^t), \ell(\omega_i^t, s^t)))^{(\rho-1)/\rho}\varphi(\omega|s^t)\right]^{\rho/(\rho-1)} \quad \forall\, t, s^t, \end{aligned} \tag{34}$$

$$\sum_{\omega\in\Omega^t}\ell(\omega)\varphi(\omega|s^t) = L(s^t) \quad \forall\, t, s^t, \tag{35}$$

$$\sum_{\omega\in\Omega^t}k(\omega)\varphi(\omega|s^t) = K(s^t) \quad \forall\, t, s^t. \tag{36}$$

Let Γ be the Lagrange multiplier on the implementability constraint (33). Let $\beta^t\mu(s^t)\zeta(s^t)$, $\beta^t\mu(s^t)\zeta(s^t)\gamma(s^t)$, and $\beta^t\mu(s^t)\zeta(s^t)\kappa(s^t)$ be the multipliers on the constraints (34), (35), and (36), respectively. The relaxed Ramsey problem in Lagrangian form is then given by the following:

$$\begin{aligned}\mathcal{L} = &\sum_{t,s^t}\beta^t\mu(s^t)\tilde{U}(C(s^t), L(s^t), s^t)\\ &- \sum_{t,s^t}\beta^t\mu(s^t)\zeta(s^t)\left[C(s^t) + K(s^{t+1}) - (1-\delta)K(s^t) + G(s^t) + \sum_{\omega\in\Omega^t}h(\omega)\varphi(\omega|s^t)\right]\\ &+ \sum_{t,s^t}\beta^t\mu(s^t)\zeta(s^t)\left[\sum_{\omega\in\Omega^t}(A(s^t)F(k(\omega_i^t), h(\omega_i^t), \ell(\omega_i^t, s^t)))^{(\rho-1)/\rho}\varphi(\omega|s^t)\right]^{\rho/(\rho-1)}\\ &- \sum_{t,s^t}\beta^t\mu(s^t)\zeta(s^t)\gamma(s^t)\left(\sum_{\omega\in\Omega^t}\ell(\omega)\varphi(\omega|s^t) - L(s^t)\right)\\ &- \sum_{t,s^t}\beta^t\mu(s^t)\zeta(s^t)\kappa(s^t)\left(\sum_{\omega\in\Omega^t}k(\omega)\varphi(\omega|s^t) - K(s^t)\right),\end{aligned}$$

where $\tilde{U}$ is defined in condition (20). The first-order conditions (FOCs) with respect to $C(s^t)$, $L(s^t)$, and $K(s^{t+1})$ are given by

$$\begin{aligned}\tilde{U}_c(s^t) - \zeta(s^t) &= 0,\\ \tilde{U}_\ell(s^t) + \zeta(s^t)\gamma(s^t) &= 0,\\ -\beta^t\mu(s^t)\zeta(s^t) + \sum_{t,s^t}\beta^{t+1}\mu(s^{t+1})\left[\zeta(s^{t+1})\kappa(s^{t+1}) + \zeta(s^{t+1})(1-\delta)\right] &= 0.\end{aligned}$$

The last of these conditions may be written as

$$\zeta(s^t) = \sum_{s^{t+1}}\beta\mu(s^{t+1}|s^t)\zeta(s^{t+1})\left(1 + \kappa(s^{t+1}) - \delta\right).$$

Combining this with the FOCs for $C(s^t)$ and $C(s^{t+1})$, we get

$$\tilde{U}_c(s^t) = \beta\mathbb{E}\left[\tilde{U}_c(s^{t+1})\left(1 + \kappa(s^{t+1}) - \delta\right)|s^t\right],$$

thereby obtaining condition (19) of the proposition.

Second, the FOCs with respect to $\ell(\omega_i^t, s^t)$ are given by

$$\beta^t\mu(s^t)\varphi(\omega|s^t)\zeta(s^t)\left[\left(\sum_{\omega\in\Omega^t}y(\omega_i^t, s^t)^{(\rho-1)/\rho}\varphi(\omega|s^t)\right)^{[\rho/(\rho-1)]-1} y(\omega_i^t, s^t)^{[(\rho-1)/\rho]-1}A(s^t)f_\ell(\omega_i^t, s^t) - \gamma(s^t)\right] = 0$$

for all ω_i^t, s^t, which reduces to

$$\zeta(s^t)\left(\frac{y(\omega_i^t, s^t)}{Y(s^t)}\right)^{-(1/\rho)}A(s^t)f_\ell(\omega_i^t, s^t) - \zeta(s^t)\gamma(s^t) = 0.$$

Combining these with the FOCs for $C(s^t)$ and $L(s^t)$, we get

$$\tilde{U}_c(s^t)\left(\frac{y(\omega_i^t, s^t)}{Y(s^t)}\right)^{-(1/\rho)}A(s^t)f_\ell(\omega_i^t, s^t) - \left(-\tilde{U}_\ell(s^t)\right) = 0,$$

thereby obtaining condition (16) of the proposition.

Third, the FOCs with respect to $h(\omega_i^t)$ are given by

$$\sum_{s^t}\zeta(s^t)\mu(s^t)\varphi(\omega|s^t)\left[\left(\sum_{\omega\in\Omega^t}y(\omega_i^t, s^t)^{(\rho-1)/\rho}\varphi(\omega|s^t)\right)^{[\rho/(\rho-1)]-1} y(\omega_i^t, s^t)^{[(\rho-1)/\rho]-1}A(s^t)f_h(\omega_i^t, s^t)-1\right]=0$$

for all ω_i^t, s^t. By using $\mu(s^t)\varphi(\omega|s^t) = \varphi(s^t|\omega_i^t)\varphi(\omega_i^t)$, we rewrite this as

$$\sum_{s^t}\zeta(s^t)\varphi(s^t|\omega_i^t)\varphi(\omega_i^t)\left[\left(\frac{y(\omega_i^t, s^t)}{Y(s^t)}\right)^{-(1/\rho)}A(s^t)f_h(\omega_i^t, s^t) - 1\right] = 0$$

or, equivalently, as

$$\mathbb{E}\left[\tilde{U}_c(s^t)\left[\left(\frac{y(\omega_i^t, s^t)}{Y(s^t)}\right)^{-(1/\rho)}A(s^t)f_h(\omega_i^t, s^t) - 1\right]\middle|\,\omega_i^t\right] = 0.$$

We thereby obtain condition (17) of the proposition.

Fourth, the FOCs with respect to $k(\omega_i^t)$ are given by

$$\sum_{s^t}\zeta(s^t)\mu(s^t)\varphi(\omega|s^t)\left[\left(\sum_{\omega\in\Omega^t}y(\omega_i^t, s^t)^{(\rho-1)/\rho}\varphi(\omega|s^t)\right)^{[\rho/(\rho-1)]-1} y(\omega_i^t, s^t)^{[(\rho-1)/\rho]-1}A(s^t)f_k(\omega_i^t, s^t)-\kappa(s^t)\right]=0$$

for all ω_i^t, s^t. Again, by using $\mu(s^t)\varphi(\omega|s^t) = \varphi(s^t|\omega_i^t)\varphi(\omega_i^t)$, we rewrite this as

$$\sum_{s^t}\zeta(s^t)\varphi(s^t|\omega_i^t)\varphi(\omega_i^t)\left[\left(\frac{y(\omega_i^t, s^t)}{Y(s^t)}\right)^{-(1/\rho)}A(s^t)f_k(\omega_i^t, s^t) - \kappa(s^t)\right] = 0$$

or, equivalently, as

$$\mathbb{E}\left[\tilde{U}_c(s^t)\left[\left(\frac{y(\omega_i^t, s^t)}{Y(s^t)}\right)^{-(1-\rho)}A(s^t)f_k(\omega_i^t, s^t) - \kappa(s^t)\right]\middle|\,\omega_i^t\right] = 0.$$

We thereby obtain condition (18) of the proposition. QED

Proof of proposition 4.—First, note that aside from the implementability condition for government solvency (eq. [6]), which holds by construction of the relaxed set $\mathcal{X}^R$, three additional conditions, conditions (7)–(9), must be satisfied in order for an allocation to be implementable under flexible prices. We hereby show that there exist functions $\psi^c, \psi^\ell, \psi^k\psi^r : \mathcal{S}^t \to \mathbb{R}_+$ such that the relaxed Ramsey optimal allocation ξ^* satisfies conditions (7)–(9).

First, consider condition (16) in the relaxed Ramsey optimal allocation. Let us choose $\psi^r(s^t)$ and $\psi^\ell(s^t)$ such that

$$\psi^\ell(s^t) = -\tilde{U}_\ell(s^t) \quad \text{and} \quad \chi^*\psi^r(s^t) = \tilde{U}_c(s^t). \tag{37}$$

Then condition (16), along with our chosen functions $\psi^r(s^t)$ and $\psi^\ell(s^t)$ in condition (37), ensures that the flexible-price implementability condition (7) holds.

Second, consider condition (17) in the relaxed Ramsey optimal allocation. Let us choose $\psi^c(s^t)$ such that

$$\psi^c(s^t) = \tilde{U}_c(s^t). \tag{38}$$

Then condition (17), along with our chosen functions $\psi^r(s^t)$ and $\psi^c(s^t)$ in conditions (37) and (38), ensures that the flexible-price implementability condition (8) holds.

Third, consider condition (18) in the relaxed Ramsey optimal allocation. Let us choose $\psi^k(s^t)$ such that

$$\psi^k(s^t) = \tilde{U}_c(s^t)\kappa(s^t), \tag{39}$$

where the function $\kappa(s^t)$ satisfies condition (19). Then condition (18), along with our chosen functions $\psi^r(s^t)$ and $\psi^k(s^t)$ in conditions (37) and (39), ensures that the flexible-price implementability condition (9) holds.

Therefore, there exist functions $\psi^c, \psi^\ell, \psi^k\psi^r : \mathcal{S}^t \rightarrow \mathbb{R}_+$, given specifically by

$$\begin{aligned} \psi^c(s^t) &= \tilde{U}_c(s^t), \\ \psi^\ell(s^t) &= -\tilde{U}_\ell(s^t), \\ \psi^r(s^t) &= \tilde{U}_c(s^t)/\chi^*, \quad \text{and} \\ \psi^k(s^t) &= \tilde{U}_c(s^t)\kappa(s^t), \end{aligned} \tag{40}$$

such that the flexible price implementability conditions (7)–(9) are all satisfied at the relaxed Ramsey optimal allocation, along with condition (6) by construction. The relaxed Ramsey optimal allocation may therefore be implemented as an equilibrium under flexible prices. QED

Proof of theorem 1.—We have established that $\xi^* \in \mathcal{X}^{\mathrm{f}}$. From corollary 1 we furthermore have that $\mathcal{X}^{\mathrm{f}} \subseteq \mathcal{X}^{\mathrm{s}}$. Together, these imply $\xi^* \in \mathcal{X}^{\mathrm{s}}$.[12] What remains to be shown is that the set of tax rates proposed in condition (21) implements the Ramsey optimum as a flexible-price equilibrium. For this we state the following auxiliary lemma, which offers a complete characterization of the set flexible-price equilibria.

Lemma 3. An allocation ξ, a policy θ, and a price system ϱ are part of a flexible-price equilibrium if and only if the following four properties hold. (i) The following household optimality conditions are satisfied:

$$-U_\ell(s^t) = U_c(s^t)\frac{1-\tau^\ell(s^t)}{1+\tau^c(s^t)}w(s^t), \tag{41}$$

$$\frac{U_c(s^t)}{1+\tau^c(s^t)} = \beta\left[\frac{U_c(s^{t+1})}{1+\tau^c(s^{t+1})}\left(1+\tilde{r}(s^{t+1})-\delta\right)\,\middle|\, s^t\right], \tag{42}$$

$$\frac{U_c(s^t)}{(1+\tau^c(s^t))P(s^t)} = \beta\left[\frac{U_c(s^{t+1})}{(1+\tau^c(s^{t+1}))P(s^{t+1})}(1+R(s^t))\,\middle|\, s^t\right], \tag{43}$$

[12] In particular, the optimal allocation ξ^* is implemented as an equilibrium under sticky prices with functions $\psi^c, \psi^\ell, \psi^k, \psi^r : \mathcal{S}^t \rightarrow \mathbb{R}_+$ given by eq. (40), and a function $\chi : \Omega^t \times \mathcal{S}^t \rightarrow \mathbb{R}_+$ that satisfies $\chi(\omega_i^t, s^t) = \chi^* \quad \forall \omega_i^t, s^t$.

where $\tilde{r}(s^t) = (1 - \tau^k(s^t))r(s^t)$ is the net-of-taxes return on savings. (ii) The following firm optimality conditions are satisfied:

$$(1 - \tau^r(s^t))\frac{\rho - 1}{\rho}\frac{p(\omega_i^t, s^t)}{P(s^t)}A(s^t)f_\ell(\omega_i^t, s^t) - w(s^t) = 0, \quad (44)$$

$$\mathbb{E}\left[\frac{U_c(s^t)}{1 + \tau^c(s^t)}\left[(1 - \tau^r(s^t))\frac{\rho - 1}{\rho}\frac{p(\omega_i^t, s^t)}{P(s^t)}A(s^t)f_h(\omega_i^t, s^t) - 1\right] \middle| \omega_i^t\right] = 0, \quad (45)$$

$$\mathbb{E}\left[\frac{U_c(s^t)}{1 + \tau^c(s^t)}\left[(1 - \tau^r(s^t))\frac{\rho - 1}{\rho}\frac{p(\omega_i^t, s^t)}{P(s^t)}A(s^t)f_k(\omega_i^t, s^t) - r(s^t)\right] \middle| \omega_i^t\right] = 0, \quad (46)$$

along with the intermediate-good demand condition,

$$y(\omega_i^t, s^t) = \left(\frac{p(\omega_i^t, s^t)}{P(s^t)}\right)^{-\rho} Y(s^t). \quad (47)$$

(iii) The household's and government's budget constraints are satisfied. (iv) Markets clear.

We relegate the proof of lemma 3 to the online appendix, as it is relatively straightforward. Condition (41) is the household's intratemporal condition for labor supply, condition (42) is the household's Euler condition for capital accumulation, and condition (43) is the household's Euler condition for the nominal bond. Conditions (44)–(46) are the firm's optimality conditions for labor, materials, and capital, respectively. Note that the last two conditions hold under expectation conditional on ω_i^t, reflecting the manager's informational constraint.

We first construct equilibrium prices that are consistent with the allocation. From the intermediate-good demand condition (47), relative prices must satisfy

$$\frac{p(\omega_i^t, s^t)}{P(s^t)} = \left(\frac{y(\omega_i^t, s^t)}{Y(s^t)}\right)^{-(1/\rho)}. \quad (48)$$

Next consider the real wage. Substituting the proposed tax ratio $(1 - \tau^\ell(s^t))/(1 + \tau^c(s^t))$ from condition (21) into the household's necessary optimality condition for labor (eq. [41]), we obtain the following real wage:

$$w(s^t) = -\tilde{U}_\ell(s^t)/\tilde{U}_c(s^t). \quad (49)$$

Consider condition (16) of the Ramsey optimum. Combining this with the equilibrium real wage in equation (49), we obtain

$$\left(\frac{y(\omega_i^t, s^t)}{Y(s^t)}\right)^{-(1/\rho)} A(s^t)f_\ell(\omega_i^t, s^t) - w(s^t) = 0 \quad \forall \omega_i^t, s^t.$$

Next, substituting in the equilibrium relative prices from equation (48) results in

$$\frac{p(\omega_i^t, s^t)}{P(s^t)}A(s^t)f_\ell(\omega_i^t, s^t) - w(s^t) = 0 \quad \forall \omega_i^t, s^t.$$

This satisfies the firm's labor optimality condition (eq. [44]) with the revenue tax proposed in condition (21).

Next, take condition (17) of the Ramsey optimum. Again, substituting in the equilibrium relative prices from equation (48) as well as the consumption tax proposed in condition (21) results in

$$\mathbb{E}\left[\frac{U_c(s^t)}{1+\tau^c(s^t)}\left(\frac{p(\omega_i^t, s^t)}{P(s^t)}A(s^t)f_h(\omega_i^t, s^t) - 1\right) \middle| \omega_i^t\right] = 0 \quad \forall\, \omega_i^t. \tag{50}$$

This satisfies the firm's optimality condition for materials (eq. [45]) with the revenue tax proposed in condition (21).

Finally, take condition (18) of the Ramsey optimum. Again, substituting in the equilibrium relative prices from equation (48) as well as the consumption tax proposed in condition (21) results in

$$\mathbb{E}\left[\frac{U_c(s^t)}{1+\tau^c(s^t))}\left(\frac{p(\omega_i^t, s^t)}{P(s^t)}A(s^t)f_k(\omega_i^t, s^t) - \kappa(s^t)\right) \middle| \omega_i^t\right] = 0 \quad \forall\, \omega_i^t. \tag{51}$$

This satisfies the firm's optimality condition for capital (eq. [46]) with the revenue tax proposed in condition (21), as long as the real rental rate on capital is $r(s^t) = \kappa(s^t)$.

Note that if it were not for the informational friction, the expectation operator could be dropped from conditions (50) and (51); conditions (50) and (51) would then be satisfied for any consumption tax. This is why in the standard Ramsey framework τ^c may be set to zero without loss of generality. Here, instead, $\tau^c(s^t)$ must be set according to condition (21) so that the firm's risk appetite coincides with that of the Ramsey planner.

At the Ramsey optimum the function $\kappa(s^t)$ satisfies condition (19). On the other hand, the equilibrium rental rate $r(s^t)$ must satisfy the household's Euler condition for capital accumulation, given by condition (42). Therefore, in order for these two conditions to coincide, it must be the case that $r(s^t) = \tilde{r}(s^t)$, which implies that $\tau^k(s^t) = 0$, as in condition (21).

What remains to be shown is that there exists a nominal interest rate that replicates the flexible-price allocation and hence implements ξ^*. The equilibrium nominal interest rate is pinned down by the household's Euler condition for nominal bonds, given by condition (43). Substituting the consumption tax proposed in condition (21) into condition (43) results in the following expression:

$$\frac{\tilde{U}_c(s^t)}{P(s^t)} = \beta\mathbb{E}\left[\frac{\tilde{U}_c(s^{t+1})}{P(s^{t+1})}(1 + R(s^t)) \middle| s^t\right].$$

By theorem 2, the price level that implements flexible price allocations is given by $P(s^t) = e^{z_t}\mathcal{B}(s^t)^{-(1/\rho)}$ where z_t is commonly known. It follows that the nominal interest rate that implements the optimal allocation is given by

$$1 + R(s^t) = \frac{\tilde{U}_c(s^t)}{\exp(z_t - z_{t-1})\mathcal{B}(s^t)^{-(1/\rho)}}\left(\beta\mathbb{E}\left[\frac{\tilde{U}_c(s^{t+1})}{\mathcal{B}(s^{t+1})^{-(1/\rho)}} \middle| s^t\right]\right)^{-1}.$$

Finally, the nominal debt holdings $B(s^t)$ that support this allocation as an equilibrium can be directly read off the budget constraint of the household, as is done in the proof of proposition 1 in the online appendix. QED

Proof of theorem 2.—In any sticky-price equilibrium, for any arbitrary common-knowledge process z_t, nominal prices are given by $p(\omega_i^t) = e^{z_t}\Psi^\omega(\omega_i^t)^{-(1/\rho)}$, as in condition (24). (See the online appendix for a more detailed argument.) It follows that the aggregate price level satisfies

$$P(s^t) = \left(\sum_{\omega\in\Omega^t} p(\omega_i^t)^{1-\rho}\varphi(\omega|s^t)\right)^{1/(1-\rho)} = e^{z_t}\left(\sum_{\omega\in\Omega^t}\Psi^\omega(\omega_i^t)^{(\rho-1)/\rho}\varphi(\omega|s^t)\right)^{1/(1-\rho)},$$

We may thus express the aggregate price level in terms of $\mathcal{B}(s^t)$ as follows:

$$P(s^t) = e^{z_t}\mathcal{B}(s^t)^{-(1/\rho)},$$

thereby obtaining condition (25). QED

Proof of proposition 5.—First, we write the Cobb-Douglas production function more generally as isoelastic in labor:

$$F(k, h, \ell) = \ell^\alpha F(k, h, 1) = \ell^\alpha g(k, h) \tag{52}$$

for all (k, h, ℓ) and some $\alpha \in (0, 1)$. Output may thereby be written as

$$y_i(\omega_i^t, s^t) = A(s^t)\ell(\omega_i^t, s^t)^\alpha g(k(\omega_i^t), h(\omega_i^t)) = A(s^t)\ell(\omega_i^t, s^t)^\alpha g(\omega_i^t), \tag{53}$$

where, with some abuse of notation, $g(\omega_i^t) = g(k(\omega_i^t), h(\omega_i^t))$.

Take any flexible-price equilibrium. For any realization of (ω_i^t, s^t), output and labor must jointly satisfy the production function (eq. [53]) and the optimality condition (eq. [7]). Given technology (53), condition (7) may be expressed as

$$\chi^*\frac{\psi^r(s^t)}{\psi^\ell(s^t)}\left(\frac{y(\omega_i^t, s^t)}{Y(s^t)}\right)^{-(1/\rho)}\alpha\frac{y(\omega_i^t, s^t)}{\ell(\omega_i^t, s^t)} = 1. \tag{54}$$

We may solve equations (53) and (54) simultaneously for $y(\omega_i^t, s^t)$ and $\ell(\omega_i^t, s^t)$; this yields the following expression for equilibrium output:

$$y(\omega_i^t, s^t) = \left[\alpha\chi^*\frac{\psi^r(s^t)}{\psi^\ell(s^t)}Y(s^t)^{1/\rho}A(s^t)^{1/\alpha}g(k(\omega_i^t), h(\omega_i^t))^{1/\alpha}\right]^{\alpha/\{1-\alpha[(\rho-1)/\rho]\}}.$$

Therefore, output $y(\omega_i^t, s^t)$ and labor $\ell(\omega_i^t, s^t)$ are log-separable in ω_i^t and s^t:

$$\begin{aligned} y(\omega_i^t, s^t) &= \Psi^\omega(\omega_i^t)\Psi^s(s^t), \quad \text{and} \\ \ell(\omega_i^t, s^t) &= \Psi^\omega(\omega_i^t)^{(\rho-1)/\rho}\left(\frac{\Psi^s(s^t)}{A(s^t)}\right)^{1/\alpha}, \quad \text{with} \\ \Psi^\omega(\omega_i^t) &= g(k(\omega_i^t), h(\omega_i^t))^{1/\{1-\alpha[(\rho-1)/\rho]\}}, \quad \text{and} \\ \Psi^s(s^t) &= \left(Y(s^t)^{1/\rho}A(s^t)^{1/\alpha}\frac{\psi^r(s^t)}{\psi^\ell(s^t)}\right)^{\alpha/\{1-\alpha[(\rho-1)/\rho]\}}, \end{aligned} \tag{55}$$

where we abstract from the constant scalar $(\alpha\chi^*)^{\alpha/\{1-\alpha[(\rho-1)/\rho]\}}$. This confirms that along any flexible-price equilibrium, $y(\omega_{it}, s^t)$ is log-separable, with components

$\Psi^\omega(\omega_i^t)$ and $\Psi^s(s^t)$ given by equation (55). If technology is, furthermore, Cobb-Douglas, then we may write $\Psi^\omega(\omega_i^t)$ as

$$\Psi^\omega(\omega_i^t) = \left(k(\omega_i^t)^{1-\eta} h(\omega_i^t)^\eta\right)^{(1-\alpha)/\{1-\alpha[(\rho-1)/\rho]\}}.$$

In this case, $\mathcal{B}(s^t)$ is given by

$$\mathcal{B}(s^t) = \left[\sum_{\omega\in\Omega^t} \left(k(\omega_i^t)^{1-\eta} h(\omega_i^t)^\eta\right)^{((1-\alpha)/\{1-\alpha[(\rho-1)/\rho]\})[(\rho-1)/\rho]} \varphi(\omega|s^t)\right]^{\rho/(\rho-1)}. \quad (56)$$

Next, let $K(s^t)$ denote the aggregate capital stock and let $H(s^t)$ denote aggregate intermediate-good purchases. Then equation (56) implies that along any flexible-price equilibrium, up to a first-order log-linear approximation,

$$\log \mathcal{B}(s^t) = \zeta_K \log K(s^{t-1}) + \zeta_H \log H(s^t), \quad (57)$$

for some scalars ζ_K, ζ_H given by

$$\zeta_K \equiv (1-\eta)\frac{1-\alpha}{1-\alpha[(\rho-1)/\rho]} > 0 \quad \text{and}$$

$$\zeta_H \equiv \eta\frac{1-\alpha}{1-\alpha[(\rho-1)/\rho]} > 0.$$

Therefore, if the aggregate quantities of capital and intermediate goods are procyclical along the equilibrium path, then $\mathcal{B}(s^t)$ is also procyclical. QED

Proof of proposition 6.—Suppose that k and h may be conditioned on s^t. Then by symmetry, firm optimality conditions imply $y(\omega_i^t, s^t) = Y(s^t)$ for all ω_i^t. Therefore, along any equilibrium $y(\omega_{it}, s^t)$ is log-separable, with $\Psi^\omega(\omega_i^t) = 1$. This implies that along any equilibrium (including the optimal one), $\mathcal{B}(s^t) = 1$ is a constant, and as a result the equilibrium allocation is implemented by targeting price stability. QED

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