

# Optimal Monetary Policy with Informational Frictions \*

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## Abstract

This paper studies optimal policy in a business-cycle setting in which firms hold dispersed private information about the state of the economy, or have a blurry understanding about it due to rational inattention. The informational friction is not only the source of nominal rigidity but also an impediment to the coordination of production. The main lesson is that the optimal monetary policy does not target price stability; instead, it leans against the wind in the sense of targeting a negative relation between the nominal price level and real economic activity. This policy serves the goal of inducing the firms to utilize their information and to coordinate their decisions in the best possible manner. An additional contribution is the adaptation of the primal approach of the Ramsey literature to a setting with a rich form of informational friction.

JEL codes: E32, E52, D61, D83.

Keywords: business cycles, incomplete information, rational inattention, bounded rationality, optimal policy, price stability.

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# 1 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, 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-a-vis the future, and nearly self-fulfilling waves of optimism and pessimism.<sup>1</sup> 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 micro-founded, 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.

**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

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<sup>1</sup>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.

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.

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.

**Nominal vs Real Rigidity.** The informational constraint on a firm’s pricing-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 which is responsible for the novel lessons delivered in our paper.

**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, 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. Due to this rigidity, solution 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—which explains the revision of the efficiency benchmark relative to which the concept of the output gap and that of relative-price distortions should be defined.

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.

**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 the opposite direction, which explains the result.

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

**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.

**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 is the source not only of nominal rigidity but also of real rigidity (in the sense defined earlier). As already explained, 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 due to the complexity in the dynamics of higher-order beliefs.<sup>2</sup> 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, 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 \(2007, 2009\)](#), which studies efficiency in a class of abstract incomplete-information games. Close, although not as flexible, variants of such

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<sup>2</sup>See the discussions in [Townsend \(1983\)](#), [Huo and Takayama \(2015b\)](#) and [Nimark \(2017\)](#).

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 \(2018\)](#), which proves a version of the welfare theorems for a class of economies with a generalized form of rational inattention. Related is also [Paciello and Wiederholt \(2014\)](#), which 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.

**Layout.** Section 2 sets up our framework. Section 3 defines the appropriate concepts of sticky-price and flexible-price allocations. Section 4 characterizes the set of allocations that can be implemented as decentralized equilibria in each of these two scenarios. Section 5 defines and characterizes the optimal allocation. Section 6 presents our key results on optimal monetary policy. Section 7 contains a simple, tractable example that helps illustrate the lessons of our paper more sharply. Section 8 concludes. The in-print Appendix contains the proofs for our main results (those regarding optimality). The Online Appendices contain the remaining proofs and the extension with endogenous information acquisition.

## 2 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).

**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 non-contingent debt.

**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

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  $t$  is comprised by the history of draws of  $s_\tau$  for all  $\tau \in \{0, \dots, t\}$ . The state is therefore an element of  $S^t \equiv S_0 \times \dots \times S_t$  and is henceforth denoted by  $s^t \equiv (s_0, \dots, s_t)$ . Its unconditional probability is denoted by  $\mu(s^t)$ .

**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  $\tau_t^c$ ; a proportional tax on labor income at rate  $\tau_t^\ell$ ; a proportional tax on capital income, net of depreciation, at rate  $\tau_t^k$ ; and a 100% tax on distributed profits. In addition, the government can issue two kinds of debt instruments. The first is a one-period, non-contingent, debt instrument that costs 1 dollar in period  $t$  and pays out  $1 + R_t$  in period  $t+1$ , 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 non-contingent debt, on the other hand, is denoted by  $B_t$ .

**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 pre-tax 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:

$$(1 + \tau_t^c)P_t C_t + P_t X_t + B_t + \sum_{s \in S(s^t)} Q_{t,s} D_{t,s} = (1 - \tau_t^\ell)P_t w_t L_t + (1 - \tau_t^k)P_t r_t K_{t-1} + (1 + R_{t-1})B_{t-1} + D_{t-1, s^t}$$

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  $(C_t, -L_t)$ .

**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”),  $\ell_{it}$  is the labor input, and  $F$  is a Cobb-Douglas production function.<sup>3</sup> The firm faces a proportional revenue tax, at rate  $\tau_t^r$ . Its nominal profit net of taxes is therefore given by

$$\Pi_{it} = (1 - \tau_t^r)p_{it}y_{it} - P_t r_t k_{it-1} - P_t h_{it} - P_t w_t \ell_{it},$$

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 aggregator of all the intermediate varieties:

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

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

**The government.** The government’s period- $t$  budget constraint, in nominal terms, is given by

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

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  $\Pi_t$  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.

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<sup>3</sup>The Cobb-Douglas restriction is with some, but not serious, loss of generality. For details, see Section 4 in the September 2017 version of this paper (<https://economics.mit.edu/files/7025>).



**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  $\int_I \ell_{it} di = L_t$ .

**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 an 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  $\omega_i^t$  from a finite set  $\Omega^t$  according to a probability distribution  $\varphi$ . 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  $(\omega^t, s^t)$ , with  $\varphi(\omega^t | s^t)$  the probability of  $\omega^t$  conditional on  $s^t$ , and with  $\varphi(s^t | \omega^t)$  the probability of  $s^t$  conditional on  $\omega^t$ . Conditional on  $s^t$ , the draws are i.i.d. 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  $\omega^t$ .<sup>4</sup> Finally, we impose the following two measurability restrictions.

**Property 1.** *There exists 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  $\omega_i^t$  rather than  $s^t$ , introduces the same kind of *nominal rigidity*

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<sup>4</sup>See Uhlig (1996) for an applicable law of large numbers with a continuum of draws.

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  $\omega_i^t$ . Finally, letting  $\ell_{it}$  (and thereby also  $y_{it}$ ) adjust to  $s^t$  guarantees that supply can meet demand and markets clear for all realizations of uncertainty.<sup>5</sup>

**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,  $\omega_i^t$  may contain an arbitrary information, not only about the 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 about it, one private and one public; see Section 7 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  $\varphi$  assign probability  $\mu$  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 (i) allowing each firm to choose its own  $\varphi$ , the joint distribution of its signal and of the underlying state, and (ii) making different assumptions on set of feasible  $\varphi$  and the associated cognitive costs.

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<sup>5</sup>Although we make a specific modeling choice regarding which input choices are restricted to be contingent on  $\omega_i^t$ , 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.

These possibilities are nested in the extension studied in Online Appendix A.

**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  $\lambda$  and  $\omega_i^t = s^t$  with probability  $1 - \lambda$ , which means that a fraction  $\lambda$  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.

### 3 Sticky vs Flexible Prices: Definitions

The dual role of the informational friction as both a source of 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  $\xi_t$ ) 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:

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

We can then define our notion of sticky-price equilibria as follows.<sup>6</sup>

**Definition 1.** A *sticky-price equilibrium* is a triplet  $(\xi, \varrho, \theta)$  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 (1);
- (iii) the government's budget constraint is satisfied;
- (iv) 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:

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<sup>6</sup>The only essentially novelty 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.

**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:

$$P(s^t) = \left[ \sum_{\omega_i^t} (p(\omega_i^t, s^t))^{\rho-1} \varphi(\omega_i^t | s^t) \right]^{\frac{1}{\rho-1}} \quad (2)$$

We can then state the relevant definition as follows.

**Definition 2.** *A **flexible-price equilibrium** is a triplet  $(\xi, \varrho, \theta)$  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  $\mathcal{X}^f$  and  $\mathcal{X}^s$  denote the sets of the allocations that are part of a flexible-price 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.

## 4 Sticky vs 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.

**Flexible-Price Allocations.** Consider any flexible-price equilibrium. The characterization of the household's problem is standard. The characterization of the monopolist's problem is slightly more exotic due to the heterogeneity in the signal  $\omega_i^t$  upon which the input choices are based. To conserve on notation, we henceforth let, for any  $z \in \{\ell, h, k\}$ ,

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

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  $\chi^* \equiv \frac{\rho-1}{\rho}$ , the reciprocal of one plus the monopoly markup. We

may express the first-order conditions of the firm as follows:

$$(1 - \tau^r(s^t)) \chi^* MP_\ell(\omega_i^t, s^t) - w(s^t) = 0 \quad \forall t, \omega_i^t, s^t \quad (3)$$

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

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

where  $\mathcal{M}(s^t) \equiv \frac{U_c(s^t)}{1 + \tau^c(s^t)}$  and  $U_c(s^t)$  is a short-cut 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*

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

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

$$\psi^r(s^t) \chi^* MP_\ell(\omega_i^t, s^t) - \psi^\ell(s^t) = 0 \quad \forall \omega_i^t, s^t \quad (7)$$

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

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

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), (8) and (9). Were the informational friction absent, each firm would know  $s^t$  and these conditions would reduce to, respectively,

$$MP_\ell(\omega_i^t, s^t) = \frac{\psi^\ell(s^t)}{\psi^r(s^t)}, \quad MP_h(\omega_i^t, s^t) = \frac{\psi^c(s^t)}{\psi^r(s^t)}, \quad \text{and} \quad MP_k(\omega_i^t, s^t) = \frac{\psi^k(s^t)}{\psi^r(s^t)}, \quad \forall t, \omega_i^t, s^t.$$

Since the  $\psi$ 's 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* MRTs of the firms and the corresponding MRSs 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 7](#).

**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  $\chi^*$  with  $\chi(\omega_i^t, s^t)$ . And second, the following optimality condition is added:

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

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 (6).*
- (ii) *For every  $t$ , there exists functions  $\psi^r, \psi^\ell, \psi^k, \psi^c : \mathcal{S}^t \rightarrow \mathbb{R}_+$  and  $\chi : \Omega^t \times \mathcal{S}^t \rightarrow \mathbb{R}_+$  such*

that the following conditions hold:

$$\chi(\omega_i^t, s^t) \psi^r(s^t) MP_\ell(\omega_i^t, s^t) - \psi^\ell(s^t) = 0 \quad \forall \omega_i^t, s^t \quad (11)$$

$$\mathbb{E} [\chi(\omega_i^t, s^t) \psi^r(s^t) MP_h(\omega_i^t, s^t) - \psi^c(s^t) \mid \omega_i^t] = 0 \quad \forall \omega_i^t \quad (12)$$

$$\mathbb{E} [\chi(\omega_i^t, s^t) \psi^r(s^t) MP_k(\omega_i^t, s^t) - \psi^k(s^t) \mid \omega_i^t] = 0 \quad \forall \omega_i^t \quad (13)$$

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

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

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

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 already explained, condition (14) follows from the optimal price-setting behavior of the firm. Condition (15), on the other hand, follows from the iso-elastic demand structure; see the Online Appendix for details.

**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 non-trivial, 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:  $\mathcal{X}^f \subset \mathcal{X}^s$ .*

This proves that an appropriate monetary policy can undo the nominal rigidity, but does not tell us whether such a policy is optimal or how it looks like. We address these questions next.

## 5 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.

**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  $\xi^*$  that maximizes welfare over an *enlarged* 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 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  $\xi^*$ , the optimal allocation over the enlarged set  $\mathcal{X}^R$ , is given by the feasible allocation that satisfies the following conditions:*

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

$$\mathbb{E} \left[ \tilde{U}_c(s^t) \{MP_h(\omega_i^t, s^t) - 1\} \mid \omega_i^t \right] = 0 \quad \forall \omega_i^t \quad (17)$$

$$\mathbb{E} \left[ \tilde{U}_c(s^t) \{MP_k(\omega_i^t, s^t) - \kappa(s^t)\} \mid \omega_i^t \right] = 0 \quad \forall \omega_i^t \quad (18)$$

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

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

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

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

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

$$MP_\ell(s^t) = \frac{\tilde{U}_\ell(s^t)}{\tilde{U}_c(s^t)}, \quad MP_h(s^t) = 1, \quad \text{and} \quad \tilde{U}_c(s^t) = \beta \mathbb{E} \left[ \tilde{U}_c(s^{t+1}) (1 - \delta + MP_k(s^{t+1})) \mid s^t \right],$$

where  $MP_z(s^t)$  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.

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.<sup>7</sup> This means that the third best 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 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 as fluctuations in the output gap; but through our analysis, they are recast as 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.

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

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

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

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

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<sup>7</sup>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).

**Theorem 1.** *The allocation  $\xi^*$  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:*

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

where  $U_c$ ,  $U_\ell$ ,  $\tilde{U}_c$ , and  $\tilde{U}_\ell$  are evaluated at  $\xi^*$  and where  $\delta > 0$  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 already explained. 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,  $\tau^c$  can be set to zero insofar as public debt is state-contingent and the zero lower bound on the nominal interest rate is non-binding. Here, instead, it is generally necessary to let  $\tau^c$  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:*

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

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.

## 6 On the Optimal Cyclicity 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  $\Psi^\omega$  and  $\Psi^s$  such that, along the optimal allocation, the output of a firm can be expressed as*

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

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  $\Psi^\omega$  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  $\Psi^s$  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  $\Psi^s$  captures the component of the output that is common across all firms,  $\Psi^\omega$  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  $\Psi^\omega$ , and produces more, than a pessimistic one.

Furthermore,  $\Psi^\omega$  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

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

Using condition (23), we then get

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

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  $\omega_j^t$  and, symmetrically, firm  $j$  does not know  $\omega_i^t$ , 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

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

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

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

where

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

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 sub-optimality 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 7 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 opposite direction that its belief and its output. At the aggregate level, this translates to negative co-movement between the price level and real output—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-a-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.<sup>8</sup>

Second, Theorem 2 contains also a case *for* price stability: if the optimal allocation is invariant with a shock, then it is optimal to stabilize the price level vis-a-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, 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 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

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<sup>8</sup>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 this indeterminacy disappears also 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.

nominal rigidity is such that a fraction  $\lambda$  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 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 herein by Property 1.<sup>9</sup>

## 7 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 complete-information counterpart, and show how the price level moves in the opposite direction than aggregate output.<sup>10</sup>

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

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

where  $\alpha \in (0, 1)$  and  $\eta \in (0, 1)$  and where  $A_{it}$ , the productivity of firm  $i$  in period  $t$ , is comprised of both 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  $v_{it}$

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<sup>9</sup>This also explains why [Adam \(2007\)](#) and [Paciello and Wiederholt \(2014\)](#), which 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 focus on a different issue, the transition from a suboptimal to an optimal policy.

<sup>10</sup>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.

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) 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

$$z_{it} = a_t + \sigma_v v_t + \sigma_\epsilon \epsilon_{it} \quad (27)$$

is a noisy signal of  $a_t$  and where  $\epsilon_{it}$  and  $v_t$  are, respectively, idiosyncratic and aggregate noises, independent of one another and of  $a_t$ . We let scalars  $\sigma_\epsilon > 0$  and  $\sigma_v > 0$  parameterize the level of the two noises, respectively. In this 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  $\sigma_\epsilon \rightarrow 0$ , whereas the case with purely private information and no aggregate noise is nested by letting  $\sigma_v \rightarrow 0$ .

**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, GDP satisfies, up to a log-linear approximation,*

$$\log GDP(s^t) = \gamma_0 + \gamma_A \log A_t + \gamma_u u_t, \quad (28)$$

*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  $(\gamma_A, \gamma_u)$  inside the set  $\Upsilon$ , where*

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

*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 due to 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.

**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

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

for some scalars  $\gamma_0^{LS}$  and  $\gamma_A^{LS} > 0$  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 (28) with  $\gamma_A = \gamma_A^{LS}$  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* to insulate aggregate output from noise, sentiments, etc.

This is made possible by combining a  $\hat{\tau}_Y$  high enough so that the net-of-taxes returns are invariant to aggregate output and a  $\hat{\tau}_A$  low enough so 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 mis-coordination 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, etc. 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*

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

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

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

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, etc.

**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*

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

for some scalars  $\delta_0^*, \delta_A^*, \delta_u^*$  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, etc.

## 8 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 had to 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 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 oughts 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 5 and 6. 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 following 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:

$$0 \leq \sum_{t=0}^{\infty} \sum_{s^t} \beta^t \mu(s^t) [U_c(s^t) C(s^t) + U_\ell(s^t) L(s^t)]; \quad (33)$$

$$C(s^t) + K(s^{t+1}) - (1 - \delta)K(s^t) + G(s^t) + \sum_{\omega \in \Omega^t} h(\omega) \varphi(\omega|s^t) \quad (34)$$

$$= \left\{ \sum_{\omega \in \Omega^t} (A(s^t) F(k(\omega_i^t), h(\omega_i^t), \ell(\omega_i^t, s^t)))^{\rho-1/\rho} \varphi(\omega|s^t) \right\}^{\rho/\rho-1} \quad \forall t, s^t;$$

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

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

Let  $\Gamma$  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:

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

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

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

The last of these conditions may be written as

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

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

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

thereby obtaining condition (19) of the proposition.

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

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

for all  $\omega_i^t, s^t$ , which reduces to

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

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

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

thereby obtaining condition (16) of the proposition.

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

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

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

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

or, equivalently, as

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

We thereby obtain condition (17) of the proposition.

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

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

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

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

or, equivalently, as

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

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

**Proof of Proposition 4.** First, note that aside from the implementability condition for government solvency (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 exists functions  $\psi^c, \psi^\ell, \psi^k, \psi^r : \mathcal{S}^t \rightarrow \mathbb{R}_+$  such that the relaxed Ramsey optimal allocation  $\xi^*$  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

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

Then (16) along with our chosen functions  $\psi^r(s^t)$  and  $\psi^\ell(s^t)$  in (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

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

Then (17) along with our chosen functions  $\psi^r(s^t)$  and  $\psi^c(s^t)$  in (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

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

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

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

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

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  $\xi^* \in \mathcal{X}^f$ . From Corollary 1 we furthermore have that  $\mathcal{X}^f \subseteq \mathcal{X}^s$ . Together, these imply  $\xi^* \in \mathcal{X}^s$ .<sup>11</sup> What remains to be shown is that the set of tax rates proposed in (21) implement 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  $\xi$ , a policy  $\theta$ , and a price system  $\varrho$ , are part of a flexible-price equilibrium if and only if the following four properties hold.*

(i) *The following household optimality conditions are satisfied:*

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

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

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

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

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<sup>11</sup>In particular, the optimal allocation  $\xi^*$  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 (40), and a function  $\chi : \Omega^t \times \mathcal{S}^t \rightarrow \mathbb{R}_+$  that satisfies  $\chi(\omega_i^t, s^t) = \chi^*, \forall \omega_i^t, s^t$ .



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  $\omega_i^t$ , 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

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

Next consider the real wage. Substituting the proposed tax ratio  $\frac{1-\tau^\ell(s^t)}{1+\tau^c(s^t)}$  from (21) into the household's necessary optimality condition for labor (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 (49) we obtain

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

Next, substituting in the equilibrium relative prices from (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 (44) with the revenue tax proposed in (21).

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

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

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

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

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

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

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  $\tau^c$  may be set to zero without loss of generality. Here instead  $\tau^c(s^t)$  must be set according to (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 (19). On the other hand, the equilibrium rental rate  $r(s^t)$  must satisfy the household's Euler condition for capital accumulation given by (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 (21).

What remains to be shown is that there exists a nominal interest rate that replicates the flexible-price allocation and hence implements  $\xi^*$ . The equilibrium nominal interest rate is pinned down by the household's Euler condition for nominal bonds given by (43). Substituting the consumption tax proposed in (21) into (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  $P(s^t) = e^{z_t} \mathcal{B}(s^t)^{-\frac{1}{\rho}}$  where  $z_t$  is commonly known. It follows that the nominal interest rate that implements the optimal allocation is given by

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

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  $p(\omega_i^t) = e^{z_t} \Psi^\omega(\omega_i^t)^{-\frac{1}{\rho}}$  as in (24). (See the online appendix for a more detailed argument.) It follows that the aggregate price level satisfies

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

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

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

thereby obtaining condition (25). **QED.**

**Proof of Proposition 5.** First, we write the Cobb-Douglas production function more generally as iso-elastic in labor:

$$F(k, h, \ell) = \ell^\alpha F(k, h, 1) = \ell^\alpha g(k, h) \quad (52)$$

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

$$y_i(\omega_i^t, s^t) = A(s^t) \ell(\omega_i^t, s^t)^\alpha g(k(\omega_i^t), h(\omega_i^t)) = A(s^t) \ell(\omega_i^t, s^t)^\alpha g(\omega_i^t). \quad (53)$$

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  $(\omega_i^t, s^t)$ , output and labor must jointly satisfy the production function (53) and the optimality condition (7). Given technology (53), condition (7) may be expressed as

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

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:

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

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

$$y(\omega_i^t, s^t) = \Psi^\omega(\omega_i^t) \Psi^s(s^t), \quad \text{and} \quad \ell(\omega_i^t, s^t) = \Psi^\omega(\omega_i^t)^{\frac{\rho-1}{\rho}} \left( \frac{\Psi^s(s^t)}{A(s^t)} \right)^{\frac{1}{\alpha}}, \quad \text{with}$$

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

where we abstract from the constant scalar  $(\alpha \chi^*)^{\frac{\alpha}{1-\alpha(\frac{\rho-1}{\rho})}}$ . This confirms that along any flexible-price equilibrium,  $y(\omega_i^t, s^t)$  is log-separable with components  $\Psi^\omega(\omega_i^t)$  and  $\Psi^s(s^t)$  given by (55). If technology is furthermore Cobb-Douglas, then we may write  $\Psi^\omega(\omega_i^t)$  as

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

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

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

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  $\zeta_K, \zeta_H$  given by

$$\zeta_K \equiv (1-\eta) \frac{1-\alpha}{1-\alpha\left(\frac{\rho-1}{\rho}\right)} > 0 \quad \text{and} \quad \zeta_H \equiv \eta \frac{1-\alpha}{1-\alpha\left(\frac{\rho-1}{\rho}\right)} > 0.$$

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  $\omega_i^t$ . 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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