Inflation, Innovation and Growth: A Survey

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Abstract

In this survey, we provide a selective review of the literature on inflation, innovation and economic growth. The relationship between economic growth and inflation is a fundamental question in economics. Most studies in this literature explore this relationship in capital-based growth models. This survey reviews a recent branch of this literature on inflation and innovation-driven growth. Specifically, we use a canonical monetary Schumpeterian growth model to demonstrate the effects of inflation on innovation and the macroeconomy via different channels. We find that the cash-in-advance constraints on consumption and R&D investment have drastically different implications on the macroeconomic effects of inflation.

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1 Introduction

The relationship between economic growth and inflation has been a fundamental question in economics since the seminal study by Tobin (1965). There is now a well established literature that explores this question in capital-based growth models; see Gillman and Kejak (2005) for an excellent survey of this literature. However, the seminal study by Solow (1956) provides an important insight that in the long run, economic growth is driven by technological progress. Therefore, to fully capture the long-run relationship between inflation and economic growth, we need to also explore the effects of inflation on economic growth via innovation.

This survey provides a selective review of the literature on inflation and innovation-driven growth. This literature is based on the literature on innovation and economic growth. In this literature, the seminal study is Romer (1990), who develops the first R&D-based growth model in which innovation is due to new products. Aghion and Howitt (1992) develop the Schumpeterian growth model in which innovation is due to quality improvement; see also Grossman and Helpman (1991) and Segerstrom *et al.* (1990) for other early studies. In this survey, we use a canonical monetary Schumpeterian growth model to demonstrate the effects of inflation on innovation and economic growth.

The seminal study in this literature is Marquis and Reffett (1994), who introduce a transaction-service sector and a cash-in-advance (CIA) constraint on consumption to the Romer model. They find that an increase in the inflation rate gives rise to a reallocation of factor input from R&D and production to transaction services. The decrease in factor input in R&D in turn reduces economic growth. Furthermore, the Friedman rule (i.e., a zero nominal interest rate) is optimal in Marquis and Reffett (1994) because the Romer model with only positive R&D externalities always features R&D underinvestment. As a result, a nominal interest rate that is above zero is suboptimal by depressing R&D investment in the economy.

Surprisingly, it wasn't until the early 2010's, the relationship between inflation and innovation-driven growth started to receive attention again. Funk and Kromen (2010) introduce sticky prices to a Schumpeterian growth model to examine the effects of inflation on economic growth. They find that under flexible prices, money is superneutral (i.e., changes in the inflation rate have no effect on economic growth). Therefore, they require sticky prices in order for inflation to affect economic growth in the short run. However, Chu and Lai (2013) show that the Schumpeterian growth model with flexible prices can feature a non-neutral relationship between inflation and economic growth even in the long run. Both Funk and Kromen (2010) and Chu and Lai (2013) consider a Schumpeterian growth model with elastic labor supply and a money-in-utility specification. The crucial difference is that Chu and Lai (2013) allow for a non-unitary elasticity of substitution between the real money balance and consumption, whereas Funk and Kromen (2010) focus on a unitary elasticity of substitution. Chu and Lai

(2013) find that if the elasticity of substitution between the real money balance and consumption is less than unity, then an increase in inflation decreases R&D, economic growth and social welfare. They also provide empirical evidence for a negative relationship between inflation and R&D; see also the empirical evidence in Chu, Cozzi, Lai and Liao (2015).

Chu and Lai (2013) explore the effects of inflation via a general-equilibrium channel, namely the consumption-leisure tradeoff. However, there is empirical evidence from the corporate finance literature that R&D investment is subject to liquidity constraints. Early studies by Hall (1992), Himmelberg and Petersen (1994), Opler *et al.* (1999) and Brown and Petersen (2009) identify a positive and significant relationship between R&D and cash flows in US firms. Bates *et al.* (2009) find that the substantial increase in the average cash-to-assets ratio in US firms from 1980 to 2006 is partly driven by their increased R&D expenditures. More recent studies by Brown and Petersen (2011) and Brown *et al.* (2012) provide evidence that firms maintain a buffer stock of liquidity in the form of cash reserves to smooth R&D expenditures. Therefore, Chu and Cozzi (2014) develop a monetary Schumpeterian growth model by formulating a CIA constraint on R&D investment and explore the effects of monetary policy through this direct channel. Interestingly, they find that the Friedman rule can be suboptimal depending on the underinvestment versus overinvestment of R&D in the Schumpeterian economy. If the economy exhibits R&D overinvestment (underinvestment), then the Friedman rule is suboptimal (optimal) because a positive nominal interest rate depresses R&D and mitigates (worsens) its overinvestment (underinvestment). This result differs from Marquis and Reffett (1994). In the rest of this survey, we use a canonical monetary Schumpeterian growth model to demonstrate the effects of inflation on innovation and the macroeconomy via different channels and review recent studies.

The rest of this survey is organized as follows. Section 2 explores the effects of inflation on innovation and economic growth. Section 3 considers monetary policy in an open economy. Section 4 discusses the effects of inflation on other macroeconomic variables. Section 5 concludes.

2 Inflation and innovation-driven growth

In this section, we present a canonical monetary Schumpeterian growth model. The Schumpeterian growth model originates from Aghion and Howitt (1992). We introduce money to the model via CIA constraints on consumption and R&D investment as in Chu and Cozzi (2014).

2.1 Household

The economy features a representative household, which has a lifetime utility function:

$$\overline{U} = \int_0^\infty e^{-\rho t} \ln U_t dt = \int_0^\infty e^{-\rho t} \left[\ln c_t + \theta \ln(L - l_t)\right] dt. \tag{1}$$

The parameter $\rho > 0$ is the subjective discount rate of the household and the parameter $\theta > 0$ determines the importance of leisure $L - l_t$ (relative to consumption c_t), where L is labor endowment and l_t is employment at time t.

The household maximizes utility subject to the accumulation of assets:

$$\dot{a}_t + \dot{m}_t = r_t a_t + i_t b_t - \pi_t m_t + w_t l_t - c_t + \tau_t. \tag{2}$$

a_t is the value of real assets (i.e., shares of monopolistic firms), and r_t is the real interest rate. b_t is the real value of money borrowed by R&D entrepreneurs, and i_t is the nominal interest rate. m_t is the household's real money holding, and π_t is the inflation rate. w_t is the real wage rate, and τ_t is a lump-sum transfer of the seigniorage revenue from the government. The household also faces the following CIA constraint: $b_t + \alpha c_t \leq m_t$, in which $\alpha \in [0, 1]$ is the share of consumption expenditure that is subject to the CIA constraint and requires the use of money for transaction.

Let η_t denote the Hamiltonian co-state variable on (2). Then, dynamic optimization yields the intertemporal optimality condition as

$$-\frac{\dot{\eta}_t}{\eta_t} = r_t - \rho, \tag{3}$$

where η_t is determined in the optimality condition for consumption given by $1/\eta_t = (1 + \alpha i_t)c_t$. The household's supply of labor is given by

$$l_t = L - \frac{\theta(1 + \alpha i_t)c_t}{w_t}. \tag{4}$$

Furthermore, the Fisher equation $i_t = \pi_t + r_t$ holds as a no-arbitrage condition.

2.2 Final good

Final good y_t is produced by competitive firms. They use a Cobb-Douglas aggregator given by

$$y_t = N \exp\left(\frac{1}{N}\int_0^N \ln x_t(j) dj\right). \tag{5}$$

There are N differentiated intermediate goods $x_t(j)$ for $j \in [0, N]$.[1] Let $p_t(j)$ denote the price of $x_t(j)$. The profit-maximizing condition for $x_t(j)$ is given by

$$p_t(j)x_t(j) = \frac{y_t}{N}, \tag{6}$$

which is also the conditional demand function for $x_t(j)$.

2.3 Intermediate goods

Each of the N monopolistic industries is dominated by a temporary industry leader (who owns the highest-quality product in the industry) until the arrival of the next innovation. The industry leader's production function for $x_t(j)$ in industry j is

$$x_t(j) = z^{q_t(j)} l_{x,t}(j), \tag{7}$$

where $z > 1$ is the exogenous step size of quality improvements, $q_t(j)$ is the number of quality improvements that have occurred in industry j as of time t, and $l_{x,t}(j)$ is production labor employed in industry j.

Given the quality level $z^{q_t(j)}$, the marginal cost of the leader in industry j is $w_t/z^{q_t(j)}$. From the Bertrand competition between the current industry leader and the previous industry leader, the profit-maximizing price for the current industry leader is

$$p_t(j) = z\frac{w_t}{z^{q_t(j)}}, \tag{8}$$

where the quality step size z determines the markup as in Aghion and Howitt (1992) and Grossman and Helpman (1991).[2] The wage payment in industry j is

$$w_t l_{x,t}(j) = \frac{1}{z} p_t(j)x_t(j) = \frac{1}{z}\frac{y_t}{N}, \tag{9}$$

and the monopolistic profit in industry j is

$$\Pi_t(j) = p_t(j)x_t(j) - w_t l_{x,t}(j) = \frac{z-1}{z}\frac{y_t}{N}, \tag{10}$$

where the profit margin is $(z-1)/z$.

[1] We include N as a parameter to demonstrate some recent results in the literature.

[2] One can generalize the model to introduce a markup parameter that differs from the quality step size z; see for example, Li (2001) who interprets such a parameter as a patent policy instrument.

2.4 R&D

Given $\Pi_t(j) = \Pi_t$ for all j in (10), we focus on a symmetric equilibrium in which the value of inventions is symmetric across industries (i.e., $v_t(j) = v_t$ for all j); see Cozzi *et al.* (2007) for a proof that the symmetric equilibrium is the unique rational-expectation equilibrium in the Schumpeterian growth model. No arbitrage implies that the value of an invention v_t is determined by

$$r_t = \frac{\Pi_t + \dot{v}_t - \lambda_t v_t}{v_t}, \tag{11}$$

which equates the real interest rate r_t to the rate of return on v_t. The return on v_t is the sum of monopolistic profit Π_t, capital gain $\dot{v}_t$ and expected capital loss $\lambda_t v_t$, where λ_t is the arrival rate of innovation. When the next quality improvement arrives, the previous quality improvement becomes obsolete; see Cozzi (2007) for a discussion on the Arrow replacement effect.

Competitive entrepreneurs perform innovation. They devote $l_{r,t}$ units of labor to innovation in each industry. The arrival rate of innovation is specified as

$$\lambda_t = \varphi l_{r,t}, \tag{12}$$

where the parameter $\varphi > 0$ determines R&D productivity. Free entry into the R&D sector implies that

$$\lambda_t v_t = w_t l_{r,t} + i_t \beta w_t l_{r,t} \Leftrightarrow \varphi v_t = (1 + \beta i_t) w_t, \tag{13}$$

where $\beta \in [0, 1]$ is the share of R&D expenditure that is subject to the CIA constraint and requires money lending from the household.

2.5 Monetary authority

Let M_t denote the nominal money supply. Then, the real money balance is $m_t = M_t/P_t$, where P_t denotes the price level of final good y_t. We consider the nominal interest rate i_t as the monetary policy instrument set by the monetary authority. Given an exogenous i, the inflation rate π_t is endogenous and determined by the Fisher equation:

$$\pi_t = i - r_t = i - g_t - \rho, \tag{14}$$

where the second equality uses the consumption growth rate $g_t \equiv \dot{c}_t/c_t = -\dot{\eta}_t/\eta_t$ in (3). Differentiating π_t with respect to i yields

$$\frac{\partial \pi_t}{\partial i} = 1 - \frac{\partial g_t}{\partial i}, \tag{15}$$

which implies $\partial \pi_t/\partial i > 0$ if and only if $\partial g_t/\partial i < 1$. A negative effect of the nominal interest rate on the growth rate would be sufficient for a positive *long-run* relationship between the nominal interest rate i_t and the inflation rate π_t (i.e., the Fisher effect).

2.6 Innovation and economic growth

The aggregate level of technology is defined as

$$Z_t \equiv \exp\left(\frac{1}{N}\int_0^N q_t(j)dj \ln z\right) = \exp\left(\int_0^t \lambda_s ds \ln z\right), \tag{16}$$

which uses the law of large numbers and equates the average number of quality improvements $\frac{1}{N}\int_0^N q_t(j)dj$ that have occurred as of time t to the average number of innovation arrivals $\int_0^t \lambda_s ds$ up to time t. We differentiate the log of Z_t with respect to time to derive the growth rate of technology as

$$\frac{\dot{Z}_t}{Z_t} = \lambda_t \ln z. \tag{17}$$

Substituting (7) into (5) yields the aggregate production function given by

$$y_t = N\exp\left(\frac{1}{N}\int_0^N q_t(j)dj \ln z + \frac{1}{N}\int_0^N \ln l_{x,t}(j)dj\right) = NZ_t l_{x,t}, \tag{18}$$

which uses the symmetry condition $l_{x,t}(j) = l_{x,t}$. Therefore, given a steady-state level of production labor $l_{x,t} = l_x$ per industry, the growth rate of output y_t is equal to the growth rate of technology Z_t.[3] We denote this steady-state equilibrium growth rate as g, which is also the steady-state growth rate of consumption c_t. The equilibrium growth rate g is determined by the arrival rate λ of innovation as $g = \lambda \ln z$ in (17).

Using (3) in (11), we derive the invention value on the balanced growth path as

$$v_t = \frac{\Pi_t}{\rho+\lambda} = \frac{1}{\rho+\lambda}\frac{z-1}{z}\frac{y_t}{N}, \tag{19}$$

which uses (10). Substituting (9) and (19) into (13) yields an equilibrium condition:

$$l_r = \frac{z-1}{1+\beta i}l_x - \frac{\rho}{\varphi}. \tag{20}$$

Substituting the resource constraint on labor $(l_r + l_x)N = l$ into (20) yields the arrival rate of innovation as

$$\lambda = \varphi l_r = \frac{1}{z+\beta i}\left[\varphi(z-1)\frac{l}{N} - (1+\beta i)\rho\right], \tag{21}$$

which is decreasing in the nominal interest rate i via the CIA constraint on R&D (i.e., $\beta > 0$) for a given l. However, the equilibrium level of labor l is still an endogenous

[3] It can be shown that the economy in this model always jumps to the balanced growth path.

variable (unless $\theta = 0$ in which case $l = L$). To determine l, we use $y_t = c_t$, (4), (9) and (21) to derive

$$\frac{l}{N} = \frac{\frac{L}{N} - z\theta(1+\alpha i)\left(\frac{1+\beta i}{z+\beta i}\right)\frac{\rho}{\varphi}}{1 + z\theta(1+\alpha i)\left(\frac{1+\beta i}{z+\beta i}\right)}, \tag{22}$$

which is decreasing in the nominal interest rate i via both the CIA constraint on consumption (i.e., $\alpha > 0$) and the CIA constraint on R&D (i.e., $\beta > 0$).[4]

2.7 Discussion

In summary, the CIA constraint β on R&D investment gives rise to a negative effect of the nominal interest rate i on innovation λ via a direct effect on the borrowing cost of R&D as shown in (21) and an indirect effect through endogenous labor supply l as shown in (22). In contrast, the CIA constraint α on consumption gives rise to a negative effect of the nominal interest rate i on innovation λ via only the indirect channel through endogenous labor supply l as shown in (22). In all cases, an increase in the nominal interest rate i reduces the equilibrium growth rate $g = \lambda \ln z$ and raises the inflation rate π (i.e., the Fisher effect) according to (15). Therefore, the monetary Schumpeterian growth model features a negative relationship between inflation and economic growth. Proposition 1 summarizes this result.

Proposition 1 *An increase in the nominal interest rate reduces innovation and economic growth in the monetary Schumpeterian growth model, which features a negative relationship between inflation and economic growth.*

This result originates from Chu and Cozzi (2014), who use CIA constraints on consumption and R&D investment to introduce money demand to the Schumpeterian growth model.[5] An earlier study by Chu and Lai (2013) instead uses the following money-in-utility specification to model money demand:

$$U_t = \left[(1-\phi)c_t^{\varepsilon} + \phi m_t^{\varepsilon}\right]^{1/\varepsilon}(L - l_t)^{\theta}, \tag{23}$$

which nests (1) as a special case with $\phi = 0$. Here the parameter $\varepsilon \in (-\infty, 1)$ determines the elasticity of substitution between consumption c_t and the real money balance m_t as $1/(1-\varepsilon) \in (0, \infty)$. They find that if the elasticity of substitution is less (greater) than unity, then an increase in the nominal interest rate stifles (stimulates) innovation

[4] Recall that $z > 1$.

[5] They also consider a CIA constraint on manufacturing expenses.

and economic growth by reducing (raising) labor supply l. Given an empirically relevant elasticity of substitution being less than unity, a higher nominal interest rate reduces innovation and economic growth via endogenous labor supply as in the CIA constraint on consumption.[6]

Unlike the CIA constraint on R&D investment, both the money-in-utility specification and the CIA constraint on consumption give rise to a negative relationship between inflation and innovation-driven growth via the consumption-leisure tradeoff. Therefore, it is important to examine whether this channel is robust to different modelling assumptions. Chu and Ji (2016) explore the importance of endogenous market structure by introducing money demand via a CIA constraint on consumption to the second-generation Schumpeterian growth model (which features both quality improvement and new product development) in Peretto (2007). They obtain a novel result that a higher nominal interest rate decreases economic growth only in the short run but changes the market structure by decreasing the number of products in the long run. As a result, the nominal interest rate does not affect the steady-state equilibrium growth rate when money affects the economy via the CIA constraint on consumption.

To see the intuition of this result, (21) shows that the nominal interest rate affects innovation via the term l/N. In the second-generation Schumpeterian growth model, the number of products N is endogenous and becomes proportional to labor in equilibrium such that

$$N = \delta l, \tag{24}$$

where δ is a composite parameter that is independent of the nominal interest rate. Substituting (24) into (21) yields

$$\lambda = \frac{1}{z + \beta i} \left[\frac{\varphi (z-1)}{\delta} - (1 + \beta i) \rho \right], \tag{25}$$

which is now decreasing in the nominal interest rate i only via the CIA constraint on R&D investment (i.e., $\beta > 0$).

Huang *et al.* (2021) and Zheng *et al.* (2021) also consider the second-generation Schumpeterian growth model and confirm that an increase in the nominal interest rate has a negative effect on economic growth via the CIA constraint on quality-improving R&D. Interestingly, they find that an increase in the nominal interest rate has a positive effect on economic growth via a CIA constraint on variety-expanding R&D. The intuition of this result can be seen from (21), which shows that a smaller number of products N gives rise to a higher growth rate $g = \lambda \ln z$ by increasing the amount of resources for the innovation of each product.[7]

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[6] In the extreme case that consumption c_t and the real money balance m_t are perfect complements (i.e., the substitution elasticity $1/(1-\varepsilon) \to 0$), the model yields an equilibrium condition $m_t = [(1-\phi)/\phi]c_t$, which leads to the same results as our CIA constraint on consumption $m_t = \alpha c_t$.

[7] One can also think of the composite parameter δ in (25) being decreasing in the nominal interest rate via the CIA constraint on variety-expanding R&D.

2.8 Innovation and different monetary policy variables

In this section, we clarify an often neglected issue in the literature: the relationship between different monetary policy variables. The monetary Schumpeterian growth model features the following monetary policy variables: the nominal interest rate i_t, the inflation rate π_t, and the growth rate of real money supply denoted as $\mu_t \equiv \dot{m}_t/m_t$. At any point in time, only one of these monetary policy variables can be exogenous, whereas the other two must be endogenous. Our above analysis treats the nominal interest rate i_t as the exogenous policy parameter.

Using (14) and $\dot{m}_t/m_t = \dot{c}_t/c_t$, we can derive the following relationship between the growth rate of real money supply μ_t and the nominal interest rate i_t:

$$\mu_t = i_t - \rho,$$

which shows an one-to-one relationship between μ_t and i_t. In other words, an one-unit increase in i_t gives rise to an one-unit increase in μ_t. If we treat the nominal interest rate as an exogenous policy parameter i, then the growth rate of real money supply must be endogenously determined as $\mu_t = i - \rho$. In this case, the negative effect of the nominal interest rate on innovation implies a negative relationship between the growth rate of real money supply and innovation.

Conversely, if we treat the growth rate of real money supply as an exogenous policy parameter μ, then the nominal interest rate must be endogenously determined as $i_t = \mu + \rho$. In this case, a higher growth rate of real money supply stifles innovation by raising the nominal interest rate. Then, (14) implies that the inflation rate would also be endogenously determined as $\pi_t = i_t - r_t = \mu - g_t$, which implies that

$$\frac{\partial \pi_t}{\partial \mu} = 1 - \frac{\partial g_t}{\partial \mu} > 0.$$

Therefore, the negative effect of the real money growth rate on innovation also implies a negative relationship between inflation and innovation.

In summary, our analysis does not assume that all monetary policy variables are exogenous. Instead, we can only treat one of the monetary policy variables as an exogenous policy instrument (e.g., the nominal interest rate i), and then, the other monetary policy variables (e.g., the inflation rate π_t and the growth rate μ_t of real money supply) would be endogenously determined along with innovation and economic growth.

2.9 Heterogeneous firms

The negative relationship between inflation and innovation in Chu and Cozzi (2014) is consistent with the empirical findings in Chu and Lai (2013) and Chu, Cozzi, Lai and Liao (2015). Specifically, Chu, Cozzi, Lai and Liao (2015) use cross-country panel regressions to document a negative relationship between inflation and R&D. In a canonical monetary Schumpeterian growth model, this negative relationship between inflation and R&D translates to a negative relationship between inflation and economic growth. However, there is an important stylized fact in the empirical literature that the relationship between inflation and economic growth is sometimes inverted-U; see for example, Bick (2010), Lopez-Villavicencio and Mignon (2011) and Chu, Cozzi, Fan, Furukawa and Liao (2019) for evidence.

To reconcile a negative effect of inflation on R&D and an inverted-U effect of inflation on economic growth, Chu, Cozzi, Furukawa and Liao (2017) generalize the model in Chu and Cozzi (2014) to allow for firm heterogeneity arising from a random step size of quality improvements, which is based on the Schumpeterian model in Minniti *et al.* (2013). Specifically, when a higher-quality product is invented, the R&D entrepreneur draws its quality-improvement step size $z > 1$ from a Pareto distribution with the following probability density function:

$$f(z) = \frac{z^{-(1+\kappa)/\kappa}}{\kappa}, \tag{26}$$

where $\kappa \in (0, 1)$ is a parameter that determines the shape of the Pareto distribution. Due to the presence of an entry cost, firms with a very small quality improvement z do not enter the market because the profit margin $(z-1)/z$ is too low to justify incurring the entry cost. As a result, the distribution of innovations that are implemented becomes endogenous. In this case, an increase in the nominal interest rate reduces the entry threshold of the quality step size z by reducing the arrival rate of innovation and raising the value of inventions.[8] Consequently, more innovations are implemented and give rise to a positive effect of inflation on economic growth. Together with its negative effect on the arrival rate of innovation, the overall relationship between inflation and economic growth becomes inverted-U.

Arawatari *et al.* (2018) and Hori (2020) also consider firm heterogeneity, and they focus on heterogeneity in the productivity of R&D entrepreneurs. Arawatari *et al.* (2018) show that heterogeneity in R&D productivity gives rise to an interesting nonlinear negative effect of inflation on economic growth. Intuitively, at a high inflation rate, a further increase in inflation triggers an occupational change (i.e., some R&D entrepreneurs become workers) in their model, which gives rise to a sudden and sharp decrease in the growth rate. Hori (2020) finds that when R&D entrepreneurs face financial constraints, heterogeneity in R&D productivity also affects optimal monetary policy and makes the Friedman rule more likely to be suboptimal. Intuitively, although a positive nominal interest rate reduces the total amount of R&D, it may improve social welfare by concentrating R&D activities among the more productive entrepreneurs.

[8] For example, $v_t = \Pi_t/(\rho + \lambda)$ in (19) is decreasing in the arrival rate λ of innovation.

2.10 Other general-equilibrium channels

In the literature, recent studies have explored various general-equilibrium channels that influence the macroeconomic effects of inflation. For example, Chu, Ning and Zhu (2019) introduce endogenous human capital accumulation to a monetary Schumpeterian growth model and find that endogenous human capital accumulation amplifies the welfare cost of inflation. Chu, Lai and Liao (2019) consider a CIA constraint on consumption in a hybrid growth model in which innovation and physical capital accumulation are both engines of *long-run* economic growth. They find that the market power of firms can amplify or mitigate the welfare cost of inflation depending on the relative importance of innovation and physical capital accumulation on economic growth. Gil and Iglesias (2020) also develop a monetary growth model with both innovation and capital accumulation, and they explore the effects of inflation through CIA constraints on R&D and manufacturing.

He (2018) considers a monetary Schumpeterian growth model with endogenous fertility, which features a novel channel through which inflation reduces economic growth via endogenous fertility. He provides empirical evidence that supports this theoretical result. He *et al.* (2020) introduce status-seeking preferences to a monetary Schumpeterian growth model and show that status-seeking preferences give rise to ambiguous effects of inflation on economic growth. Specifically, when the preference for status seeking is sufficiently strong, the effect of inflation on economic growth becomes positive. He and Zou (2016) find a positive seigniorage effect of monetary expansion on R&D in a monetary Schumpeterian growth model and provide supportive evidence based on time-series data in China.

Lin *et al.* (2020) introduce credit constraints to a monetary Schumpeterian growth model and derive interesting implications of financial development on economic growth and convergence. Mao *et al.* (2019) model a banking sector, which allows them to analyze additional monetary policy instruments, such as the required reserve ratio and the leverage ratio. They explore the effects of these policy instruments on economic growth and social welfare and find that banking inefficiency can amplify the welfare cost of inflation.

Oikawa and Ueda (2018) introduce sticky prices to a canonical Schumpeterian growth model via menu costs and model the resulting state-dependent pricing in a tractable way. They compute the welfare-maximizing and grow-maximizing inflation rates and find that their difference is determined by the extent of R&D overinvestment in the economy. Miyakawa, Oikawa and Ueda (2020) introduce sticky prices and menu costs to the Schumpeterian growth model with heterogeneous multi-product firms developed by Klette and Kortum (2004) and extended by Lentz and Mortensen (2008) and find that the optimal inflation rate can be positive by causing quality-superior firms (i.e., firms with a larger number of products) to grow and quality-inferior firms to exit. Benigno and Fornaro (2018) consider a Schumpeterian growth model with sticky wages and show an important result that the economy features a stagnation trap, in which monetary policy is ineffective in stimulating the economy.

3 Monetary policy in an open economy

All the abovementioned studies focus on a closed economy. Chu, Cozzi, Lai and Liao (2015) extend the closed-economy model in Chu and Cozzi (2014) into an open-economy model with two innovating economies to analyze the cross-country effects of inflation on economic growth and social welfare. They find that by affecting innovation and technologies, inflation has international spillover effects through trade. Their two-country model captures these effects as international technology spillovers and international business stealing. Specifically, they use the following Armington aggregator for the production of a global consumption good C_t that is distributed to households in the two countries $\{H, F\}$:[9]

$$C_t = \left[(y_t^H)^{(\sigma-1)/\sigma} + (y_t^F)^{(\sigma-1)/\sigma} \right]^{\sigma/(\sigma-1)}, \tag{27}$$

where y_t^H and y_t^F denote final goods produced by country H and country F, respectively. The parameter $\sigma > 0$ is the elasticity of substitution between y_t^H and y_t^F. International technology spillovers arise because innovation in one country benefits households in both countries. International business stealing arises because innovation in one country allows the country to capture a larger share of the global consumption market when y_t^H and y_t^F are gross substitutes (i.e., $\sigma > 1$).

Chu, Cozzi, Lai and Liao (2015) find that these international spillover effects influence the outcome of monetary policy competition across countries. Specifically, the Nash-equilibrium inflation rates between the two countries are higher than their globally optimal inflation rates, and the degree of this inflationary bias is increasing (decreasing) in the market power of firms under the CIA constraint on R&D (consumption). They use cross-country panel data to estimate the effects of inflation on R&D. Then, they calibrate moments from their theoretical model to this empirical estimate and other data in the Euro Area and the US. In summary, they find a significant welfare gain from monetary coordination between the two regions.

Chu, Cozzi, Furukawa and Liao (2019) also consider monetary policy across countries. However, they explore the cross-country effects of inflation in an open economy with North-South product cycles and international technology transfer via foreign direct investment (FDI). Their theoretical framework is based on the North-South Schumpeterian growth model in Dinopoulos and Segerstrom (2010). In this case, the

[9] They allow for a weight parameter in the aggregator. Here we simply assume symmetric weight.

aggregator for the production of the global consumption good C_t is modified as

$$C_t = \left\{ \int_0^1 [x_t(j)]^{(\sigma-1)/\sigma} \, dj \right\}^{\sigma/(\sigma-1)} = \left\{ \int_0^{\vartheta_t} [x_t(j)]^{(\sigma-1)/\sigma} \, dj + \int_{\vartheta_t}^1 [x_t(j)]^{(\sigma-1)/\sigma} \, dj \right\}^{\sigma/(\sigma-1)}, \tag{28}$$

where intermediate goods $x_t(j)$ for $j \in [0, \vartheta_t]$ are produced in the North and intermediate goods $x_t(j)$ for $j \in [\vartheta_t, 1]$ are produced in the South. The variable ϑ_t changes over time. Specifically, multinational firms invest in R&D in the North to improve the quality of products to be manufactured in the North. Then, they invest in FDI in the South to transfer production there in order to reduce the production cost. Chu, Cozzi, Furukawa and Liao (2019) introduce money via CIA constraints on R&D and FDI into this North-South model to explore the cross-country effects of inflation. In summary, they find that Southern inflation reduces both technology transfer to the South and innovation in the North, whereas Northern inflation reduces innovation in the North but has ambiguous effects on technology transfer to the South. Calibrating the model to China-US data and quantifying the cross-country effects of inflation, they find an asymmetric implication that monetary policy in the US has a significant effect on the welfare of households in China, but not vice versa.

To remove the counterfactual scale effect,[10] the North-South Schumpeterian growth model in Dinopoulos and Segerstrom (2010) and Chu, Cozzi, Furukawa and Liao (2019) features semi-endogenous growth, under which monetary policy affects the level of output but not its growth rate in the long run. Chen (2018) converts the semi-endogenous growth process in Dinopoulos and Segerstrom (2010) to allow for fully endogenous growth and explores the effects of monetary policy on the long-run growth rate via the CIA constraints on R&D and FDI as in Chu, Cozzi, Furukawa and Liao (2019). Most results under semi-endogenous growth without the scale effect are robust to fully endogenous growth with the scale effect, except that the ambiguous effects of Northern inflation on technology transfer to the South become unambiguously negative.

4 Inflation and other macroeconomic variables

In this section, we review the relationship between inflation and other macroeconomic variables in the monetary Schumpeterian growth model. Section 4.1 considers inflation and income inequality. Section 4.2 considers inflation and unemployment.

[10] See Jones (1999) for a discussion on the scale effect in the R&D-based growth model.

4.1 Inflation and income inequality

All the above studies focus on models with a representative household. Therefore, they could not explore the implications of inflation on income inequality. Chu, Cozzi, Fan, Furukawa and Liao (2019) generalize the monetary Schumpeterian growth model with random quality improvements in Chu, Cozzi, Furukawa and Liao (2017) to allow for heterogeneous households in order to explore the effects of monetary policy on innovation and income inequality. Here household heterogeneity comes from an unequal distribution of wealth. Given that income inequality is driven by wealth inequality in this model, the degree of income inequality is increasing in the real interest rate, which determines asset income. To see this, the level of income received by household h is

$$I_t(h) \equiv r_t a_t(h) + i_t b_t(h) - \pi_t m_t(h) + w_t l_t(h) = r_t[a_t(h) + m_t(h)] + w_t L, \tag{29}$$

where we set $b_t(h) = m_t(h)$ (i.e., $\alpha = 0$) and $l_t(h) = L$ for simplicity.[11] Let $\omega_t(h) \equiv a_t(h)+m_t(h)$ denote the amount of wealth owned by household h. Suppose we consider two households $\{h, k\}$. Then, their income difference is given by

$$I_t(h) - I_t(k) = r_t[\omega_t(h) - \omega_t(k)], \tag{30}$$

which shows that an increase in the real interest rate r_t enlarges the income difference between the two households.[12]

Recall that inflation has an inverted-U effect on the equilibrium growth rate g in Chu, Cozzi, Furukawa and Liao (2017) due to firm heterogeneity that arises from random quality improvements. This inverted-U effect translates to an inverted-U effect of inflation on the interest rate $r = \rho + g$ and also on the degree of income inequality. Chu, Cozzi, Fan, Furukawa and Liao (2019) use cross-country panel data to estimate the growth-maximizing inflation rate and the inequality-maximizing inflation rate. Then, they calibrate moments from the theoretical model to data in the US and show that their model can match these empirical estimates.

Zheng *et al.* (2020) also consider heterogeneous households as in Chu, Cozzi, Fan, Furukawa and Liao (2019) but in an innovation-driven growth model with sticky prices and menu costs as in Oikawa and Ueda (2018). In general, their model yields ambiguous effects of inflation on income inequality. According to their preferred set of parameter values, their simulation yields a negative relationship between inflation and inequality.

[11] Chu, Cozzi, Fan, Furukawa and Liao (2019) allow for elastic labor supply in their analysis.

[12] Chu, Cozzi, Fan, Furukawa and Liao (2019) consider the coefficient of variation of income as their measure of income inequality. They derive the coefficient of variation of income as a function of the coefficient of variation of wealth. Chu, Furukawa, Mallick, Peretto and Wang (2021) show that the Gini coefficient of income has the same expression but as a function of the Gini coefficient of wealth.

4.2 Inflation and unemployment

All the above studies exhibit full employment. Therefore, they could not explore the implications of inflation on unemployment. Chu, Cozzi, Fan and Furukawa (2021) incorporate equilibrium unemployment driven by matching frictions in the labor market as in Mortensen (2005) into the monetary Schumpeterian growth model. Then, they use the theoretical framework to explore the long-run relationship between inflation and unemployment. Once again, the CIA constraints on consumption and R&D investment have very different implications. They find that in the presence of a CIA constraint on R&D investment, an increase in inflation reduces innovation, which in turn decreases labor-market tightness and increases unemployment by depressing labor demand. In contrast, under the CIA constraint on consumption, an increase in inflation decreases unemployment by depressing labor supply and also stifles innovation. To see the difference between the two CIA constraints, we rewrite the resource constraint on labor as $l_t = l_{x,t} + l_{r,t} + u_t$,[13] where u_t denotes unemployment which is positive due to search frictions. Suppose we denote $l_t^s \equiv l_t$ as labor supply and $l_t^d \equiv l_{x,t} + l_{r,t}$ as labor demand. Then, we have

$$u_t = l_t^s - l_t^d > 0, \tag{31}$$

where l_t^s is decreasing in the inflation rate via the CIA constraint on consumption and l_t^d is decreasing in the inflation rate via the CIA constraint on R&D.

In summary, the CIA constraint on R&D implies a positive relationship between inflation and unemployment, whereas the CIA constraint on consumption implies a negative relationship between inflation and unemployment. Using US data, Chu, Cozzi, Fan and Furukawa (2021) consider a variable that captures financial constraints on firms (a proxy for the CIA constraint on R&D) and another variable that captures financial constraints on consumers (a proxy for the CIA constraint on consumption). They find that inflation has a positive effect on unemployment via the financial constraint on firms and a negative effect on unemployment via the financial constraint on consumers. This empirical finding is consistent with the above theoretical result.

5 Conclusion

In this survey, we have provided a selective review of the small but growing literature on inflation and innovation-driven growth. In particular, we have used a monetary Schumpeterian growth model to explore its fruitful implications on how inflation affects innovation and economic growth. Recent studies in the literature have extended the model in different ways to consider different general-equilibrium channels which influence the macroeconomic effects of inflation. Some recent studies have also extended

[13] Here we simply normalize N to unity.

the monetary Schumpeterian growth model to analyze monetary policy in an open economy and the effects of inflation on other macroeconomic variables, such as income inequality and unemployment. In several cases, the CIA constraints on consumption and R&D investment have very different implications on the effects of inflation.

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