

Vertical International Trade as a Monetary Transmission Mechanism in an Open Economy*

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Abstract

This paper analyzes a two-country general equilibrium model with multiple stages of production and sticky prices. Working through the cross-country input-output relations and endogenous price stickiness, the model generates the observed patterns in international aggregate comovements following monetary shocks. In particular, both output and consumption comove across countries, and output correlation is larger than consumption correlation, as in the data. The model also generates persistent fluctuations of real exchange rates. Thus, vertical international trade plays an important role in propagating monetary shocks in an open economy.

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1 Introduction

A long-standing puzzle in the international business cycle literature is the inability of standard models in explaining the observed international comovements among aggregate variables. A related challenge is to identify mechanisms that can propagate monetary shocks to generate persistent real exchange rate movements. In this paper, we propose a mechanism that helps explain these puzzles.

Our model builds on a standard general equilibrium monetary model (e.g. Chari, et al. 1998) and incorporates a new ingredient: the input-output connections across countries. In the recent decades, countries have become increasingly interconnected in a vertical trading chain, and there is a growing tendency to trade in goods produced at different processing stages (e.g., Feenstra, 1998; Hummels et al. 1999). Working through the input-output connections, the model is able to generate the observed patterns in international aggregate comovements following monetary shocks. In particular, both output and consumption comove across countries, and output correlation is larger than consumption correlation, as in the data. The model also generates persistent fluctuations of real exchange rates.

In the model, countries trade both across different production stages (i.e., vertical international trade) and between industries at the same stage (i.e., intra-industry trade). Specifically, production of final consumption goods in each country requires multiple stages of processing, from raw materials to intermediate goods, then to semi-finished goods and finished goods. Intermediate goods production requires both domestically produced raw materials and those imported; semi-finished goods production requires both domestically made intermediate goods and those imported, and so on. To generate real effects of monetary shocks, we assume that prices are set in a staggered fashion (e.g., Taylor 1980 and 1999), and we derive optimal price setting rules within the standard monopolistic competition framework (e.g., Blanchard and Kiyotaki 1987). Under staggered price contracts, in each period a fraction of firms at each stage can set new prices while others cannot; once a price is set, it remains effective for several periods.¹ The input-output connection across countries along with the staggered price contracts generates both international comovements and real exchange rate persistence.

In the literature, it has been a challenge to identify mechanisms that generate the observed international correlations and persistence in real exchange rate. The standard one-good model encounters difficulties in explaining the cross-country comovements (e.g., Baxter (1995)). In such a model, capital tends to move to its most productive location, leading to a rise in the returns to labor in the country experiencing an

¹See Taylor (1999) for a survey of empirical evidence on staggered price contracts.

investment boom, while the returns to labor are relatively low in the other country. In general, as pointed out by Backus, et al. (1995), this class of models tends to generate low or even negative cross-country output correlation, which is at odds with the data. A more robust anomaly is that output correlation is lower than consumption correlation in such a model.

More recently, there emerges a new line of research that emphasizes the importance of multi-sector models in explaining the international comovements. For example, Kouparitsas (1998) constructs a model with a primary goods sector and a manufacturing sector (which uses primary goods as inputs) and studies the transmission of technology shocks between Northern countries and Southern countries. Ambler, et al. (1998) find that adding multiple sectors on top of the baseline economy of Backus, et al. (1992) can help explain the observed international correlations in aggregate investment and employment. These multi-sector models are similar in spirit to our chain-of-production model with three exceptions. First, the driving forces of aggregate fluctuations in these models are technology shocks, while those in ours are monetary shocks. Second, and more importantly, these models predict that the anomalous order between output correlation and consumption correlation remains robust, while in our model, the order is in accordance with the data. Third, these authors focus on explaining international correlations in quantity variables, while we study both the quantity comovements and the real exchange rate persistence.

To explain the real exchange rate behavior following monetary shocks, several mechanisms are proposed in the literature. Beaudry and Devereux (1995) emphasize the role of increasing returns to scale in a sticky price model; Bergin and Feenstra (1999) study the interactions between translog preferences and staggered price contracts in explaining the real exchange rate behavior; and Chari, et al. (1998) analyze a model similar to ours except for the absence of the vertical input-output structure. Our model suggests that the empirically relevant cross-country input-output connections can be a promising monetary transmission mechanism in generating the observed international comovements and the persistent deviations of real exchange rate from PPP.

The paper is organized as follows. Section 2 presents a two-country general equilibrium business cycle model with a vertical input-output structure across countries. Section 3 describes the calibration strategies. Section 4 reports our main findings. Section 5 concludes the paper. The Appendix describes the computation methods.

2 The model

In the model, there are two countries, a home country and a foreign country. Each country is populated by a large number of identical and infinitely-lived households. In each period t , the economy experiences a realization of shocks s_t , and the history of events up to date t is denoted by $s^t \equiv (s_0, \dots, s_t)$ with probability $\pi(s^t)$. The initial realization s_0 is given.

Production of consumption goods in each country requires N stages of processing, from raw materials to intermediate goods, then to more advanced intermediate goods, and so on. At each stage, there is a continuum of firms producing differentiated goods indexed in the interval $[0, 1]$, with an elasticity of substitution $\theta > 1$. Production of intermediate goods at stage $n \in \{2, \dots, N\}$ uses all intermediate goods of stage $n - 1$, either domestically produced or imported from the other country. Production of goods at the first stage ($n = 1$) requires homogeneous labor and capital provided by domestic households. The households in both countries have access to a complete-contingent bond market (see Figure 1 for an illustration of the model's structure).

The utility function of the representative household in the home country is given by

$$\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi(s^t) \left[\ln(\hat{C}(s^t)) + \eta \ln(1 - L(s^t)) \right],$$

where $\beta \in (0, 1)$ is a subjective discount factor, $\hat{C}(s^t) = [bC(s^t)^\nu + (1 - b)(M(s^t)/\bar{P}(s^t))^\nu]^{1/\nu}$ a CES composite of consumption and real money balances, $L(s^t)$ labor hours, and $\bar{P}(s^t)$ a price level. For each s^t , the household's budget constraint is given by

$$\begin{aligned} \bar{P}(s^t)[C(s^t) + K(s^t) - (1 - \delta)K(s^{t-1})] + \sum_{s^{t+1}} D(s^{t+1}|s^t)B(s^{t+1}) + M(s^t) \\ \leq W(s^t)L(s^t) + R^k(s^t)K(s^{t-1}) + \Pi(s^t) + B(s^t) + M(s^{t-1}) + T(s^t), \end{aligned} \quad (1)$$

where $K(s^t)$ is a capital stock, $\delta \in (0, 1)$ a depreciation rate, $B(s^{t+1})$ a one-period nominal bond that costs $D(s^{t+1}|s^t)$ dollars at s^t and pays off one dollar in the next period if s^{t+1} is realized, $W(s^t)$ and $R^k(s^t)$ nominal wage and rental rate, $\Pi(s^t)$ the household's claim to all firms' profits, and $T(s^t)$ a nominal lump-sum transfer from the government.

The consumption (investment) good is a composite of stage- N goods, either domestically produced or imported. Let $Y(s^t)$ denote this composite, then

$$C(s^t) + K(s^t) - (1 - \delta)K(s^{t-1}) = Y(s^t), \quad (2)$$

and

$$Y(s^t) = \left[\omega_1 \left(\int_0^1 Y_{NH}(i, s^t)^{\frac{\theta-1}{\theta}} di \right)^{\frac{\rho\theta}{\theta-1}} + \omega_2 \left(\int_0^1 Y_{NF}(i, s^t)^{\frac{\theta-1}{\theta}} di \right)^{\frac{\rho\theta}{\theta-1}} \right]^{\frac{1}{\rho}}. \quad (3)$$

where $Y_{NH}(i, s^t)$ and $Y_{NF}(i, s^t)$ are goods produced at stage N in the home country and in the foreign country, respectively. In (3), the parameter θ determines the steady state markup of price over marginal cost; the parameter $\rho (> 0)$ determines the elasticity of substitution between the composites of domestically produced goods and of imported goods; and given ρ and θ , the parameters $\omega_1 (> 0)$ and $\omega_2 (> 0)$ determine the steady state ratio of imports to GNP.

The household maximizes utility subject to (1)-(3) and a borrowing constraint $B(s^t) \geq -\bar{B}$ for some large positive number \bar{B} , for each s^t and each $t \geq 0$, with initial conditions $K(s^{-1})$, $M(s^{-1})$, and $B(s^0)$ given. From the first order conditions, we obtain demand functions for a type i good produced at stage N in the home country ($Y_{NH}^d(i, s^t)$) and in the foreign country ($Y_{NF}^d(i, s^t)$):

$$Y_{NH}^d(i, s^t) = \left[\frac{\bar{P}_H(s^t)}{\omega_1 \bar{P}(s^t)} \right]^{-\frac{1}{1-\rho}} \left[\frac{P_{NH}(i, s^t)}{\bar{P}_H(s^t)} \right]^{-\theta} Y(s^t), \quad (4)$$

$$Y_{NF}^d(i, s^t) = \left[\frac{\bar{P}_F(s^t)}{\omega_1 \bar{P}(s^t)} \right]^{-\frac{1}{1-\rho}} \left[\frac{P_{NF}(i, s^t)}{\bar{P}_F(s^t)} \right]^{-\theta} Y(s^t), \quad (5)$$

where $\bar{P}_H(s^t) = \left(\int_0^1 P_{NH}(i, s^t)^{1-\theta} di \right)^{\frac{1}{1-\theta}}$ is a price index of stage- N goods produced and used in the home country, and $\bar{P}_F(s^t) = \left(\int_0^1 P_{NF}(i, s^t)^{1-\theta} di \right)^{\frac{1}{1-\theta}}$ a price index of stage- N goods made in the foreign country and exported to the home country. The overall price level in the home country is an average of the two, that is,

$$\bar{P}(s^t) = \left(\omega_1^{\frac{1}{1-\rho}} \bar{P}_H(s^t)^{\frac{\rho}{\rho-1}} + \omega_2^{\frac{1}{1-\rho}} \bar{P}_F(s^t)^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}}. \quad (6)$$

Given that θ is the elasticity of substitution among differentiated goods produced at the same stage and $1/(1-\rho)$ is the elasticity of substitution between the composites of domestically produced goods and of imported goods, the interpretation of (4) and (5) seems to be straightforward. For example, (4) says that, holding other things equal, a one percent rise in the price of a type i good produced and used in the home country relative to the price index of all such goods results in a θ percent fall in the relative demand; while a one percent change in the price index of all goods produced and used in the home country relative to the overall home price level results in a $1/(1-\rho)$ percent decline in the relative quantity demanded.

The technology for producing a type i good at the first stage (i.e. the raw material sector) is a standard Cobb-Douglas function given by $Y_{1H}(i, s^t) + Y_{1H}^*(i, s^t) = K(i, s^t)^\alpha L(i, s^t)^{1-\alpha}$, where $K(i, s^t)$ and

$L(i, s^t)$ are capital and labor inputs. The technology at stage $n \in \{2, \dots, N\}$ is given by

$$Y_{nH}(i, s^t) + Y_{nH}^*(i, s^t) = \left[\omega_1 \left(\int_0^1 Y_{n-1,H}(i, j, s^t)^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\rho\theta}{\theta-1}} + \omega_2 \left(\int_0^1 Y_{n-1,F}(i, j, s^t)^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\rho\theta}{\theta-1}} \right]^{\frac{1}{\rho}}, \quad (7)$$

where $Y_{n-1,H}(i, j, s^t)$ is the input of a type j good produced at stage $n - 1$ in the home country, and $Y_{n-1,F}(i, j, s^t)$ is the input imported from the foreign country. In the production functions, $Y_{nH}(i, s^t)$ and $Y_{nH}^*(i, s^t)$ denote goods produced at stage n and used by firms at stage $n + 1$ in the home country and in the foreign country, respectively.

To generate real effects of monetary shocks, we introduce nominal rigidities through staggered price contracts (e.g., Taylor 1980 and 1999) and derive optimal price setting rules within the standard monopolistic competition framework (e.g., Blanchard and Kiyotaki 1987). Under staggered price contracts, in each period, a fraction $1/J$ of home producers at a given stage $n \in \{1, \dots, N\}$ can choose new prices $P_{nH}(i, s^t)$ in home currency units for the home market and $P_{nH}^*(i, s^t)$ in foreign currency units for the foreign market. Once these prices are set, they remain fixed for J periods. We sort the indices of firms at each stage so that those indexed by $i \in [0, 1/J]$ set prices in periods $t, t + J, t + 2J, \dots$; those indexed by $i \in (1/J, 2/J]$ set prices in periods $t + 1, t + J + 1, t + 2J + 1, \dots$; and so on. Formally, upon the realization of s^t , a home firm $i \in [0, 1]$ at stage $n \in \{1, \dots, N\}$ that can set new prices maximizes expected profits in the next J periods, choosing $P_{nH}(i, s^t)$ and $P_{nH}^*(i, s^t)$ to solve

$$\text{Max} \quad \sum_{\tau=t}^{t+J-1} \sum_{s^\tau} D(s^\tau | s^t) \{ [P_{nH}(i, s^t) - V_n(i, s^\tau)] Y_{nH}^d(i, s^\tau) + [e(s^\tau) P_{nH}^*(i, s^t) - V_n(i, s^\tau)] Y_{nH}^{*d}(i, s^\tau) \},$$

where $V_n(i, s^\tau)$ is a unit cost function, $Y_{nH}^d(i, s^\tau)$ and $Y_{nH}^{*d}(i, s^\tau)$ output demand functions, and $e(s^t)$ a nominal exchange rate.

The unit cost functions and output demand functions are derived from cost-minimization. The resulting output demand functions are given by

$$Y_{nH}^d(i, s^t) = \left[\frac{\bar{P}_{nH}(s^t)}{\omega_1 \bar{P}_n(s^t)} \right]^{-\frac{1}{1-\rho}} \left[\frac{P_{nH}(i, s^t)}{\bar{P}_{nH}(s^t)} \right]^{-\theta} Y_{n+1}(s^t), \quad (8)$$

$$Y_{nF}^d(i, s^t) = \left[\frac{\bar{P}_{nF}(s^t)}{\omega_1 \bar{P}_n(s^t)} \right]^{-\frac{1}{1-\rho}} \left[\frac{P_{nF}(i, s^t)}{\bar{P}_{nF}(s^t)} \right]^{-\theta} Y_{n+1}(s^t), \quad (9)$$

where $n \in \{1, \dots, N-1\}$, $Y_{n+1}(s^t) \equiv \int_0^1 [Y_{n+1,H}(j, s^t) + Y_{n+1,H}^*(j, s^t)] dj$ is a linear aggregator of all goods produced at stage $n+1$ in the home country, $\bar{P}_{nH}(s^t) = \left(\int_0^1 P_{nH}(i, s^t)^{1-\theta} di \right)^{\frac{1}{1-\theta}}$ and $\bar{P}_{nF}(s^t) = \left(\int_0^1 P_{nF}(i, s^t)^{1-\theta} di \right)^{\frac{1}{1-\theta}}$ are price indices of home goods and of imported goods, respectively, and

$$\bar{P}_n(s^t) = \left(\omega_1^{\frac{1}{1-\rho}} \bar{P}_{nH}(s^t)^{\frac{\rho}{\rho-1}} + \omega_2^{\frac{1}{1-\rho}} \bar{P}_{nF}(s^t)^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}} \quad (10)$$

is a home price index of all stage- n goods, both domestically produced and imported. Equation (8) says that the demand for a type i good produced at stage n will be higher if its price relative to the price index of all such goods is lower and if the price index of these goods relative to the overall price of stage- n goods, either domestically produced or imported, falls. The demand function in (9) can be similarly interpreted.

The unit cost functions derived from cost-minimization are

$$V_1(s^\tau) = \tilde{\alpha} R^k(s^\tau)^\alpha W(s^\tau)^{1-\alpha}, \quad V_n(s^\tau) \equiv V_n(i, s^\tau) = \bar{P}_{n-1}(s^\tau), \quad (11)$$

where $n \in \{2, \dots, N\}$, and $\tilde{\alpha} = \alpha^{-\alpha}(1-\alpha)^{\alpha-1}$. Given constant returns to scale, they are also the marginal cost functions. As shown in (11), the marginal cost for a firm at the first stage is a weighted average of wage rate and rental rate, since labor and capital are the only inputs at that stage. The marginal cost for a stage- n firm equals the price index of all stage- $(n-1)$ goods, since the production of each stage- n good requires all stage- $(n-1)$ goods, either domestically made or imported. Note that V_n is firm-independent for all n .

The solution to firm i 's profit maximization problem gives the optimal price setting rules

$$P_{nH}(i, s^t) = \frac{\theta}{\theta-1} \frac{\sum_{\tau=t}^{t+J-1} \sum_{s^\tau} D(s^\tau|s^t) V_n(s^\tau) Y_{nH}^d(i, s^\tau)}{\sum_{\tau=t}^{t+J-1} \sum_{s^\tau} D(s^\tau|s^t) Y_{nH}^d(i, s^\tau)}, \quad (12)$$

$$P_{nH}^*(i, s^t) = \frac{\theta}{\theta-1} \frac{\sum_{\tau=t}^{t+J-1} \sum_{s^\tau} D(s^\tau|s^t) V_n(s^\tau) Y_{nH}^{d*}(i, s^\tau)}{\sum_{\tau=t}^{t+J-1} \sum_{s^\tau} D(s^\tau|s^t) e(s^\tau) Y_{nH}^{d*}(i, s^\tau)}, \quad (13)$$

where $n \in \{1, \dots, N\}$. The pricing rule in (12) says that the optimal price set for the home market in home currency units is a constant markup over a weighted average of the firm's J -period marginal costs. The weights are normalized demand in the corresponding periods. Equation (13) can be similarly interpreted, with currency units appropriately converted by the nominal exchange rate.

In the foreign country, the problems of the representative household and of the firms at each production stage are analogous to the home country's problems. To help further exposition, we display the budget constraint facing the foreign household:

$$\bar{P}^*(s^t)[C^*(s^t) + K^*(s^t) - (1-\delta)K^*(s^{t-1})] + \frac{1}{e(s^t)} \sum_{s^{t+1}} D(s^{t+1}|s^t) B^*(s^{t+1}) + M^*(s^t)$$

$$\leq W^*(s^t)L^*(s^t) + R^{k*}(s^t)K^*(s^{t-1}) + \Pi^*(s^t) + \frac{B^*(s^t)}{e(s^t)} + M^*(s^{t-1}) + T^*(s^t), \quad (14)$$

where the variables with stars are the foreign counterparts of the home country's corresponding variables.

The money supply processes in the two countries are given by $M(s^t) = \mu(s^t)M(s^{t-1})$ and $M^*(s^t) = \mu^*(s^t)M^*(s^{t-1})$. The money growth rate $\mu(s^t)$ in the home country follows a stationary stochastic process given by

$$\ln \mu(s^t) = \rho_\mu \ln \mu(s^{t-1}) + \varepsilon_t, \quad (15)$$

where $0 < \rho_\mu < 1$ and ε_t is an i.i.d., normally distributed stochastic process with zero mean and variance σ_μ^2 . The μ^* -process is identical, with an innovation term ε_t^* independent of ε_t . Newly created money is injected into the economy via a lump-sum transfer in each country, thus $T(s^t) = M(s^t) - M(s^{t-1})$ and $T^*(s^t) = M^*(s^t) - M^*(s^{t-1})$.

Finally, the market clearing conditions for labor and capital in the home country are given by $\int_0^1 L^d(i, s^t) di = L(s^t)$ and $\int_0^1 K^d(i, s^t) di = K(s^{t-1})$, and those in the foreign country are analogous. The bond market clearing condition is $B(s^t) + B^*(s^t) = 0$. Note that, while firms choose capital and labor after the realization of s^t , the available capital stock for rent in period t is chosen by the household before the realization of s^t . It is also important to note that, while physical capital stocks are immobile across countries, financial assets (in the form of nominal bonds) can be freely traded (subject to the borrowing constraints).

An equilibrium for this economy is a collection of allocations $\{C(s^t), K(s^t), L(s^t), M(s^t), B(s^{t+1})\}$ for the household in the home country; allocations $\{C^*(s^t), K^*(s^t), L^*(s^t), M^*(s^t), B^*(s^{t+1})\}$ for the household in the foreign country; allocations $\{Y_{nH}(i, s^t), Y_{nH}^*(i, s^t)\}$ and prices $\{P_{nH}(i, s^t), P_{nH}^*(i, s^t)\}$ for home intermediate goods producers, where $i \in [0, 1]$ and $n \in \{1, \dots, N\}$; allocations $\{Y_{nF}(i, s^t), Y_{nF}^*(i, s^t)\}$ and prices $\{P_{nF}(i, s^t), P_{nF}^*(i, s^t)\}$ for foreign intermediate goods producers, where $i \in [0, 1]$ and $n \in \{1, \dots, N\}$; price indices $\{\bar{P}_n(s^t), \bar{P}_n^*(s^t)\}$ for $n \in \{1, \dots, N\}$; wages $\{W(s^t), W^*(s^t)\}$; rental rates $\{R^k(s^t), R^{k*}(s^t)\}$; and bond prices $D(s^{t+1}|s^t)$ that satisfy the following four conditions: (i) taking prices as given, households' allocations solve their utility maximization problems; (ii) the prices of each intermediate goods producer solve its profit-maximization problem; (iii) markets for labor, capital, money, and bonds all clear; (iv) monetary policy rules are as specified.

Given the Markov money supply process (15), a stationary equilibrium in this open economy consists of stationary decision rules which are functions of the state of the economy. In period t , in each country and at each production stage, there are $J - 1$ prevailing prices that were set in period $t - J + 1$ through period $t - 1$ due to staggered price contracts. Thus, the state of the economy in period t must record the prices

set in the previous $J - 1$ periods in addition to the beginning-of-period capital stocks and the exogenous money growth rates. To induce stationarity, we divide all prices by the appropriate money stocks. Thus, the state at s^t is given by

$$\left[K(s^{t-1}), K^*(s^{t-1}), \mu(s^t), \mu^*(s^t), \frac{P(s^{t-J+1})}{M(s^t)}, \dots, \frac{P(s^{t-1})}{M(s^t)}, \frac{P^*(s^{t-J+1})}{M^*(s^t)}, \dots, \frac{P^*(s^{t-1})}{M^*(s^t)} \right],$$

where $P(s^t) \equiv \{P_{nH}(s^t), P_{nF}(s^t)\}_{n \in \{1, \dots, N\}}$ and $P^*(s^t) \equiv \{P_{nH}^*(s^t), P_{nF}^*(s^t)\}_{n \in \{1, \dots, N\}}$. The stationary equilibrium decision rules are computed using standard log-linearization methods, as described in the Appendix.

3 The calibration and the measurement

In this section, we calibrate the model's parameters and describe how to relate the model's equilibrium variables to aggregate variables in the data.

3.1 The calibration

The parameters to be calibrated include the subjective discount factor β , the preference parameters b , ν and η , the capital income share α , the capital depreciation rate δ , the goods demand elasticity parameter θ , parameters in the aggregation technology ρ , ω_1 , and ω_2 , and the monetary policy parameters ρ_μ and σ_μ . The calibrated values are summarized in Table 1.

In our baseline model, we set $J = 4$ so that a period in the model corresponds to a quarter. Following the standard business cycle literature, we choose $\beta = 0.96^{1/4}$. To assign values for b and ν , we use the money demand equation (derived from the first order conditions of the household's problem):

$$\ln \left(\frac{M(s^t)}{\bar{P}(s^t)} \right) = -\frac{1}{1-\nu} \ln \left(\frac{b}{1-b} \right) + \ln(C(s^t)) - \frac{1}{1-\nu} \log \left(\frac{R(s^t) - 1}{R(s^t)} \right),$$

where $R(s^t) = (\sum_{s^{t+1}} D(s^{t+1}|s^t))^{-1}$ is the gross nominal interest rate. The regression of this equation as performed in Chari, et al. (1998) implies that $\nu = -1.56$ and $b = 0.98$ for quarterly U.S. data with a sample range from quarter one in 1960 to quarter four in 1995. The parameter η is selected to match an average share of time allocated to market activity of $1/3$, as in most business cycle studies.

We next choose $\alpha = 1/3$ and $\delta = 1 - 0.92^{1/4}$ so that the baseline model predicts an annualized capital-output ratio of 2.6 and an investment-output ratio of 0.21. We set $\theta = 10$, corresponding to a steady state markup of 11%. We choose $\rho = 1/3$ so that the elasticity of substitution between domestically produced

goods and imported goods is 1.5, which is the value obtained by Backus, et al. (1994). To assign values for ω_1 and ω_2 , we first choose a normalization $\omega_1^{\frac{1}{1-\rho}} + \omega_2^{\frac{1}{1-\rho}} = 1$ so that when $\bar{P}_{nH} = \bar{P}_{nF}$, we have $\bar{P}_n = \bar{P}_{nH}$. We then use the steady state relation that $Y_H/Y_F = [\omega_1/\omega_2]^{\frac{1}{1-\rho}}$. The share of imported goods in U.S. GNP is about 15% on average, implying that $Y_H/Y_F = 0.85/0.15$. The steady state condition along with the normalization yields values for ω_1 and ω_2 .

Finally, the serial correlation parameter ρ_μ for money growth is set to 0.57 and the standard deviation of ε_t to $\sigma_\mu = 0.0092$, based on quarterly U.S. data on M1 from quarter three in 1959 through quarter two in 1995, obtained from Citibase (see also Chari, et al. (1998)). We assume that the monetary shocks are independent across countries.

3.2 The measurement

The non-competitive environment in the model seems to pose difficulties in computing real gross national product (GNP), and the multiple-stage feature seems to compound such difficulties. Specifically, firms are monopolistic competitors at each stage, and thus profits are non-zero. Since real GNP equals to the sum of factor incomes (including labor income and capital income), profit income, and earnings on the country's net foreign assets, we need to integrate profits across all stages in order to calculate real GNP from the income side.

Yet there is an alternative (and easier) way of calculating real GNP, that is, from the expenditure side. In an equilibrium, the household's budget constraint (1) is binding since the utility function is strictly monotone. Imposing the money market clearing condition, we can cancel out the nominal transfer $T(s^t)$ with the two terms involving nominal money balances. Then moving the term containing $B(s^{t+1})$ to the right hand side, the resulting budget equation reveals that real GNP corresponds to the term $Y(s^t)$ in our model: the left hand side is the total expenditure on all goods (i.e., $\bar{P}(s^t)Y(s^t)$), and the right hand side is the sum of factor incomes, profit income, and earnings from net foreign assets, where the earnings are given by $B(s^t) - \sum_{s^{t+1}} D(s^{t+1}|s^t)B(s^{t+1})$. Other aggregate variables including consumption, investment, and employment in the model directly correspond to those in the data.

4 Main results

In Table 2, we report the cross-country correlation statistics computed both from the data and from two different models: our baseline model with four production stages (i.e., $N = 4$) and its counterpart with a single production stage.²

The table shows that there are significant cross-country aggregate comovements in the data: real GNP, consumption, investment, and employment are all significantly and positively correlated across countries. Yet, the model with a single production stage does not generate such comovements. The correlation statistics it generates are too low (or even negative). This is a key anomaly found in a standard international business cycle model (e.g., Backus, et al. 1995; Baxter 1995). In contrast, the baseline model with a chain of production produces statistics that are much closer to the data: the correlations are all significantly positive, and more importantly, the output correlation is larger than the consumption correlation, in accordance with the data.

To gain intuition, we compute the equilibrium impulse responses to a temporary monetary shock in the home country. In particular, we choose the magnitude of ε_0 in (15) so that the home country's money stock rises by 1% one year after the shock occurs (that is, at the end of the initial price contract duration) while we set $\varepsilon_t^* = 0$ for all t . The results are presented in Figures 2 through 5.

Figure 2 displays the impulse responses of aggregate variables in the baseline economy. In response to the shock, aggregate variables including real GNP, consumption, investment, and employment rise in both countries. There are two driving forces for this result. One works through the intersectoral and international input-output relations, the other through (endogenous) price stickiness embodied in the production chain, and the two interact with each other.

The input-output relations help generate international comovements. Following the shock, real income in the home country rises because staggered price contracts prevent price level from fully rising. With the higher real income, the household raises its demand for goods produced at the final stage in both countries. To meet this higher demand, firms that cannot adjust prices have to raise their demand for

²We choose $N = 4$ as our benchmark for the following reasons. In computing the producer price indices (PPI) based on stages of production, the Bureau of Labor Statistics classifies all manufacturing industries into three production stages: raw materials, intermediate goods, and finished goods. The service industry is not included. Thus, in a closed economy, there are at least four production stages. In an open economy, as noted by Feenstra (1998), it is likely to have more stages involved. Thus $N = 4$ is a lower bound for the number of stages. As we will show, having more stages will only strengthen the cross-country correlations and magnify the real exchange rate persistence.

intermediate goods, both domestically produced and imported. The intermediate goods producers that cannot adjust prices then have to raise their demand for raw materials produced in both countries. Finally, the raw material producers that cannot adjust prices have to increase their demand for labor and capital, pushing up real wages and thus households' real income in both countries. Additionally, the household in the foreign country receives higher wage income from its raw material producing sector because, in that sector, firms that cannot adjust prices have to employ more workers in order to meet the higher demand from intermediate goods producers in both countries. With this higher income, the foreign household demands more goods produced at the final stage in both countries, which in turn raises the demand for intermediate goods in both countries, and so on. This reinforces the initial effect of the home country's higher demand for the foreign's products at each stage, leading to a tendency of aggregate comovements across countries.

To induce *actual* aggregate comovements, however, sluggish price adjustments are also essential. Since the money supply in the foreign country is unchanged, a quick rise in price level will lower the real money balances held by the foreign residents and hence dampen their aggregate demand. The chain-of-production model helps resolve this problem since it generates endogenous price level inertia in both countries. The price level inertia arises from a cumulative dampening effect on marginal cost fluctuations across production stages. That is, firms at a more advanced stage face smaller fluctuations in marginal costs than those at a less-processed stage, and thus have less incentive to change prices. Following an expansionary monetary shock (in the home country), domestic firms at the first stage (i.e., the raw material sector) face quickly risen marginal costs, since their marginal costs consist of real wage and rental rate, and both the labor market and the capital market are frictionless. These firms thus do have incentive to raise prices if they have the chance to renew contracts. But firms at the second stage that use all goods produced at the first stage do not face fully risen marginal costs. Their marginal costs do not fully rise because they are the price index of the first stage goods, and the price index records both the newly adjusted prices and those fixed by previous contracts. Thus firms at the second stage have less incentive to fully adjust their prices, even if they have the chance to renew contracts. This makes the marginal costs facing firms at the third stage even smaller, and thus those firms have even less incentive to fully adjust their prices, and so on. The resulting pattern of price adjustment is known as the "snake effect" because it mimics a snake-like movement: prices adjust by smaller amounts and less rapidly at later stages than at earlier stages (e.g., Blanchard, 1983; Huang and Liu, 1999).

The snake effect restrains responses of price levels in both countries and helps induce aggregate comovements. In the home country, since prices do not fully rise following the shock, the nominal exchange rate depreciation translates into real depreciation at each production stage. The magnitude of real depreciation at more advanced stages is larger since price adjustments at those stages are smaller. The real depreciation of home currency lowers the effective prices of goods exported to the foreign country (in foreign currency units). Meanwhile, the snake effect dampens the price fluctuations across stages in the foreign country. Since the foreign price level is an average of prices of imported goods (which are now lower) and prices of domestically produced goods (which now rise slowly), it is more likely for the price level to fall the more are the production stages. In our baseline model with four stages, the foreign's price level indeed falls and thus real money balances rise, so does the aggregate demand. Comparing Figures 2 and 3 confirms this intuition. Figure 3 displays the impulse responses of the same set of variables when there is a single production stage (for a similar model, see Chari, et al. 1998). Although employment in both countries rises in response to the home monetary shock, the income effect generated from the rising demand for exported goods is dominated by the quick rise in the price level (and hence the fall in real money balances), leading to a fall in the foreign's aggregate consumption and virtually no changes in investment and output.

Figure 2 also helps understand the order between output correlation and consumption correlation. In accordance with the data, our baseline model predicts that consumption correlation is lower than output correlation (and both are significantly positive). This is so because consumption and real money balances are non-separable in the utility function, and the cross-country correlation between real balances is relatively low. In response to the home monetary shock, real balances in the home country rise since nominal money balances rise and price level does not fully adjust. Though the foreign's real balances also rise because of the price level inertia in both countries and the real depreciation in home's currency, they rise less quickly since the foreign's nominal money stock does not change. Thus the consumption comovement across countries is less pronounced than the output comovement (see the top two panels in Figure 2).³ We conclude from these experiments that the input-output connections across countries and the endogenous price stickiness embodied in the chain are important in accounting for the observed international comovements.

³This result does not depend on the assumption that real money balances enter the utility function. The model can be reinterpreted as a cash-in-advance model (e.g., Lucas and Stokey 1987) with $M(s^t)/\bar{P}(s^t)$ being the cash good and $C(s^t)$ the credit good.

Finally, Figures 4 and 5 display the impulse responses of real and nominal exchange rates. Figure 4 shows that the input-output connections help generate persistent movements in real exchange rate (which is defined with respect to finished goods). In the baseline economy, the response of real exchange rate at the end of the initial price contract duration is about 26% of the response in the impact period, whereas it dies out more quickly in the single-stage economy. The real exchange rate is determined by the cross-country marginal rates of substitution in consumption. Since the model with input-output connections generates price level inertia and thus consumption persistence, it also generates real exchange rate persistence. Figure 5 shows that the baseline model generates nominal exchange rate “over-shooting” (e.g., Dornbusch 1976): the initial response of the nominal exchange rate is larger than its long-run value. This is because of the persistent decrease in the nominal interest rate following the shock (i.e., there is a liquidity effect). Lower expected nominal interest rates magnify the depreciation of the home’s currency.

5 Conclusions

A long-standing puzzle in the international business cycle literature is the inability of a standard model, with either real or monetary shocks, in generating the observed cross-country comovements among aggregate economic variables including real GNP, consumption, investment, and employment. A related challenge is to identify mechanisms that can propagate monetary shocks to generate persistent real exchange rate movements. In this paper, we have proposed a mechanism that helps resolve both puzzles. The cross-country input-output connections along with endogenous price stickiness can generate both international comovements and real exchange rate persistence.

Our purpose in this paper has been to analyze the role of the cross-country input-output relations in transmitting monetary shocks. We focus on an environment with monetary shocks alone and thus do not attempt to match our model’s predictions with the unconditional correlations in the data. To assess the quantitative importance of monetary shocks in such an environment, it is necessary to calibrate the model using international input-output data. In particular, we need to calibrate the total number of stages, the share of labor and capital at each stage, and the import share at each stage. This task should be feasible given the renewed interest in studying the empirical importance of international trade at different stages of processing (e.g., Feenstra 1998; Hummels, et al. 1998). We leave this task for future research.

Appendix

In this appendix, we describe the model's equilibrium conditions and computation methods.

We begin with firms' cost-minimization problems. The unit cost function of firm i at stage $n = 1$ is derived from solving $V_1(i, s^t) = \min_{K, L} R^k(s^t)K + W(s^t)L$, subject to $K^\alpha L^{1-\alpha} \geq 1$; while for $n \in \{2, \dots, N\}$, it's obtained from solving

$$V_n(i, s^t) = \min_{Y_{n-1,H}(i,j), Y_{n-1,F}(i,j)} \int_0^1 P_{n-1,H}(j, s^t) Y_{n-1,H}(i, j) dj + \int_0^1 P_{n-1,F}(j, s^t) Y_{n-1,F}(i, j) dj,$$

subject to $[\omega_1 \left(\int_0^1 Y_{n-1,H}(i, j)^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\rho\theta}{\theta-1}} + \omega_2 \left(\int_0^1 Y_{n-1,F}(i, j)^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\rho\theta}{\theta-1}}]^{1/\rho} \geq 1$. The solutions yield the output demand functions in (8)-(9) and the cost functions in (11).

Now we characterize the optimal choices of the households. The first order conditions for the home country's representative household are given by

$$-\frac{U_l(s^t)}{U_c(s^t)} = \frac{W(s^t)}{\bar{P}(s^t)}, \quad (16)$$

$$\frac{U_m(s^t)}{U_c(s^t)} = 1 - \beta \sum_{s^{t+1}} \pi(s^{t+1}|s^t) \frac{U_c(s^{t+1})\bar{P}(s^t)}{U_c(s^t)\bar{P}(s^{t+1})}, \quad (17)$$

$$D(s^\tau|s^t) = \beta^{\tau-t} \pi(s^\tau|s^t) \frac{U_c(s^\tau)\bar{P}(s^t)}{U_c(s^t)\bar{P}(s^\tau)}, \quad \tau \geq t, \quad (18)$$

$$U_c(s^t) = \beta \sum_{s^{t+1}} \pi(s^{t+1}|s^t) U_c(s^{t+1}) \left[\frac{R^k(s^{t+1})}{\bar{P}(s^{t+1})} + 1 - \delta \right],$$

where $U_c(s^t)$, $U_l(s^t)$, and $U_m(s^t)$ denote the marginal utility of consumption, leisure, and real money balances, respectively, and $\pi(s^\tau|s^t) = \pi(s^\tau)/\pi(s^t)$ is the conditional probability of s^τ given s^t . Equations (16)-(19) are standard first order conditions with respect to the household's choice of labor, money, bond, and capital, respectively. The foreign household's first order conditions are analogous. Allocations and prices in the foreign country are denoted with star superscripts.

With appropriate substitutions, the equilibrium conditions can be reduced to $4N + 4$ equations, including two capital Euler equations, two money demand equations, and $4N$ price decision equations. The decision variables are aggregate consumption for both countries, aggregate capital stocks for both countries, and $4N$ current prices. The four prices at stage n are P_{nH} , P_{nH}^* , P_{nF}^* , and P_{nF} . We focus on a symmetric equilibrium in which firms in the same country and in the same cohort at each stage make

identical decisions so that the price decisions of a firm depends only on the stage at which it produces, the time at which it can set a new price, and the country in which it locates.

To reduce the equilibrium conditions to the $4N + 4$ equations, we first link capital and labor inputs to the final aggregate goods. This is accomplished by integrating the goods demand functions (4)-(5), (8)-(9), and the counterparts in the foreign country to obtain the following recursive relations:

$$\begin{aligned} Y_n(s^t) &= G_{nH}(s^t)Y_{n+1}(s^t) + G_{nH}^*(s^t)Y_{n+1}^*(s^t), \\ Y_n^*(s^t) &= G_{nF}^*(s^t)Y_{n+1}^*(s^t) + G_{nF}(s^t)Y_{n+1}(s^t), \end{aligned} \quad (19)$$

where the G terms are given by

$$\begin{aligned} G_{nH} &= [\omega_1 \bar{P}_n]^{1-\rho} \bar{P}_{nH}^{\theta - \frac{1}{1-\rho}} \int_0^1 P_{nH}(i)^{-\theta} di, \\ G_{nH}^* &= [\omega_2 \bar{P}_n^*]^{1-\rho} \bar{P}_{nH}^{*\theta - \frac{1}{1-\rho}} \int_0^1 P_{nH}^*(i)^{-\theta} di, \\ G_{nF}^* &= [\omega_1 \bar{P}_n^*]^{1-\rho} \bar{P}_{nF}^{*\theta - \frac{1}{1-\rho}} \int_0^1 P_{nF}^*(i)^{-\theta} di, \\ G_{nF} &= [\omega_2 \bar{P}_n]^{1-\rho} \bar{P}_{nF}^{\theta - \frac{1}{1-\rho}} \int_0^1 P_{nF}(i)^{-\theta} di. \end{aligned}$$

The implied relation between capital and labor inputs and aggregate final output is then given by

$$\begin{aligned} K(s^{t-1})^\alpha L(s^t)^{1-\alpha} &= H_1(s^t)Y(s^t) + H_1^*(s^t)Y^*(s^t), \\ K^*(s^{t-1})^\alpha L^*(s^t)^{1-\alpha} &= F_1^*(s^t)Y^*(s^t) + F_1(s^t)Y(s^t), \end{aligned} \quad (20)$$

where the terms H_1 , H_1^* , F_1^* , and F_1 are functions of the G terms above. In these equations, we have used the factor market clearing conditions. We then use (2) and (20) to express $Y(s^t)$ and $Y^*(s^t)$ in terms of the decision variables.

Next, we express all variables in the $4N$ price decision equations in terms of the aggregate decision variables. This involves the N unit cost functions and price indices in each country in addition to the stage-specific demand functions. Using (11), (16), the factor demand functions, and the factor market clearing conditions, we obtain

$$V_1(s^t) = \frac{1}{1-\alpha} \left(\frac{L(s^t)}{K(s^{t-1})} \right)^\alpha \left(\frac{-U_l(s^t)}{U_c(s^t)} \right) \bar{P}(s^t),$$

and a similar equation for the foreign country. The unit cost function at stage $n \geq 2$ is simply given by the price index at the previous stage, as shown in (11). In a symmetric equilibrium, firms in the same cohort at each stage and in each country make identical price decisions, and thus the price indices at stage

$n \in \{1, \dots, N\}$ are given by

$$\begin{aligned}\bar{P}_{nH}(s^t) &= \left[\frac{1}{J} P_{nH}(s^{t-J+1})^{1-\theta} + \frac{1}{J} P_{nH}(s^{t-J+2})^{1-\theta} + \dots + \frac{1}{J} P_{nH}(s^t)^{1-\theta} \right]^{\frac{1}{1-\theta}}, \\ \bar{P}_{nF}(s^t) &= \left[\frac{1}{J} P_{nF}(s^{t-J+1})^{1-\theta} + \frac{1}{J} P_{nF}(s^{t-J+2})^{1-\theta} + \dots + \frac{1}{J} P_{nF}(s^t)^{1-\theta} \right]^{\frac{1}{1-\theta}}, \\ \bar{P}_{nF}^*(s^t) &= \left[\frac{1}{J} P_{nF}^*(s^{t-J+1})^{1-\theta} + \frac{1}{J} P_{nF}^*(s^{t-J+2})^{1-\theta} + \dots + \frac{1}{J} P_{nF}^*(s^t)^{1-\theta} \right]^{\frac{1}{1-\theta}}, \\ \bar{P}_{nH}^*(s^t) &= \left[\frac{1}{J} P_{nH}^*(s^{t-J+1})^{1-\theta} + \frac{1}{J} P_{nH}^*(s^{t-J+2})^{1-\theta} + \dots + \frac{1}{J} P_{nH}^*(s^t)^{1-\theta} \right]^{\frac{1}{1-\theta}},\end{aligned}$$

and the price indices for the composite goods are

$$\bar{P}_n(s^t) = \left[\omega_1^{\frac{1}{1-\rho}} \bar{P}_{nH}(s^{t-1})^{\frac{\rho}{\rho-1}} + \omega_2^{\frac{1}{1-\rho}} \bar{P}_{nF}(s^{t-1})^{\frac{\rho}{\rho-1}} \right]^{\frac{\rho-1}{\rho}}, \quad (21)$$

$$\bar{P}_n^*(s^t) = \left[\omega_1^{\frac{1}{1-\rho}} \bar{P}_{nF}^*(s^{t-1})^{\frac{\rho}{\rho-1}} + \omega_2^{\frac{1}{1-\rho}} \bar{P}_{nH}^*(s^{t-1})^{\frac{\rho}{\rho-1}} \right]^{\frac{\rho-1}{\rho}}. \quad (22)$$

In addition, the G terms in (19) are given by

$$\begin{aligned}G_{nH}(s^t) &= [\omega_1 \bar{P}_n(s^t)]^{\frac{1}{1-\rho}} \bar{P}_{nH}(s^t)^{\theta - \frac{1}{1-\rho}} \left[\frac{1}{J} P_{nH}(s^{t-J+1})^{-\theta} + \dots + \frac{1}{J} P_{nH}(s^t)^{-\theta} \right], \\ G_{nH}^*(s^t) &= [\omega_2 \bar{P}_n^*(s^t)]^{\frac{1}{1-\rho}} \bar{P}_{nH}(s^t)^{\theta - \frac{1}{1-\rho}} \left[\frac{1}{J} P_{nH}^*(s^{t-J+1})^{-\theta} + \dots + \frac{1}{J} P_{nH}^*(s^t)^{-\theta} \right], \\ G_{nF}^*(s^t) &= [\omega_1 \bar{P}_n^*(s^t)]^{\frac{1}{1-\rho}} \bar{P}_{nF}^*(s^t)^{\theta - \frac{1}{1-\rho}} \left[\frac{1}{J} P_{nF}^*(s^{t-J+1})^{-\theta} + \dots + \frac{1}{J} P_{nF}^*(s^t)^{-\theta} \right], \\ G_{nF}(s^t) &= [\omega_2 \bar{P}_n(s^t)]^{\frac{1}{1-\rho}} \bar{P}_{nF}(s^t)^{\theta - \frac{1}{1-\rho}} \left[\frac{1}{J} P_{nF}(s^{t-J+1})^{-\theta} + \dots + \frac{1}{J} P_{nF}(s^t)^{-\theta} \right].\end{aligned}$$

Finally, we substitute for $R^k(s^t)$ in the capital Euler equation using the equilibrium condition $R^k(s^t)/\bar{P}(s^t) = [\alpha/(1-\alpha)][L(s^t)/K(s^{t-1})][-U_l(s^t)/U_c(s^t)]$ derived from the cost-minimization problems, and substitute for $\bar{P}(s^t)$ in the money demand equation using (21).

Given these $4N + 4$ equilibrium conditions, we proceed to compute the decision rules for the $4N + 4$ decision variables. This is accomplished by log-linearizing these equations around a deterministic steady state. Upon obtaining the linear decision rules, we use standard computation methods to generate the impulse response functions and obtain cross-country correlation statistics.

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Table 1
Calibrated parameters

Preferences:	$\beta = 0.96^{1/4}, b = 0.98, \nu = -1.56, \eta = 1.1$
Intermediate goods technologies:	$\alpha = 1/3, \theta = 10$
Aggregation technology:	$\rho = 1/3, [\omega_1/\omega_2]^{1/(1-\rho)} = 0.85/0.15$
Capital depreciation rate:	$\delta = 1 - 0.92^{1/4},$
Money growth process:	$\rho_\mu = 0.57, \sigma_\mu = 0.0092$

Table 2
Cross-country correlations

Statistics	Data	Single-stage model	Baseline model
Foreign and domestic GNP	0.52	-0.10	0.17
Foreign and domestic consumption	0.27	-0.09	0.14
Foreign and domestic investment	0.22	0.01	0.28
Foreign and domestic employment	0.51	0.27	0.67

Note: The statistics are based on logged and HP-filtered data. The correlations in the data are taken from Chari, et al. (1998b), and are between the U.S. time series and a trade-weighted average of the European time series. The model's statistics are averages over 300 simulations of 90 periods each (the first 20 observations in each simulated series are discarded to avoid dependence on initial conditions).

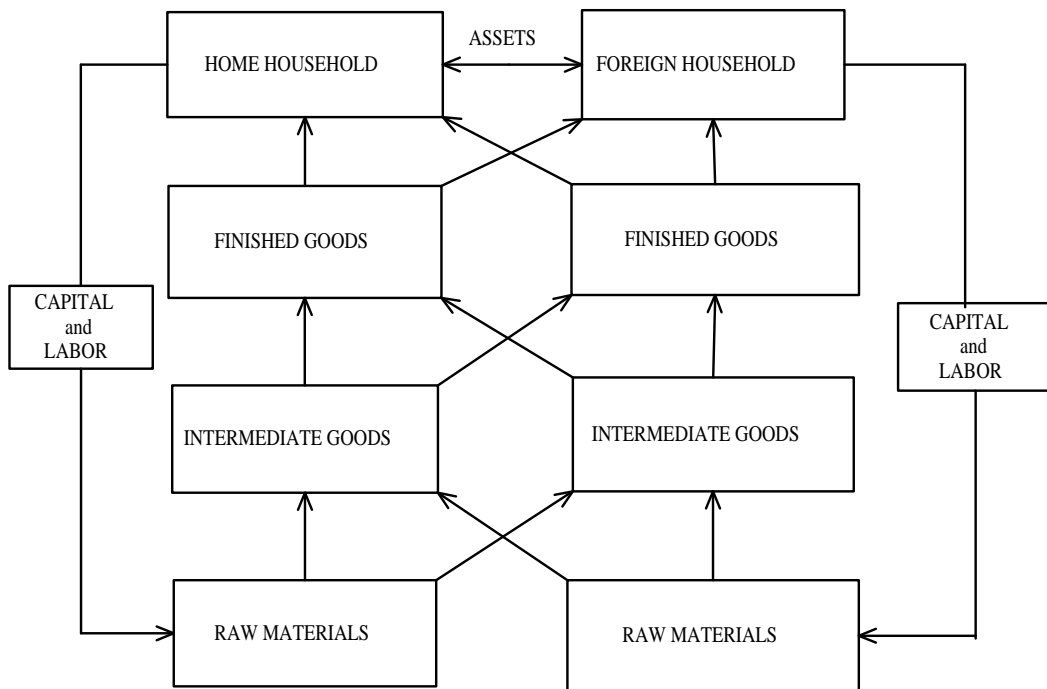


Figure 1.—Chain structure of the economy

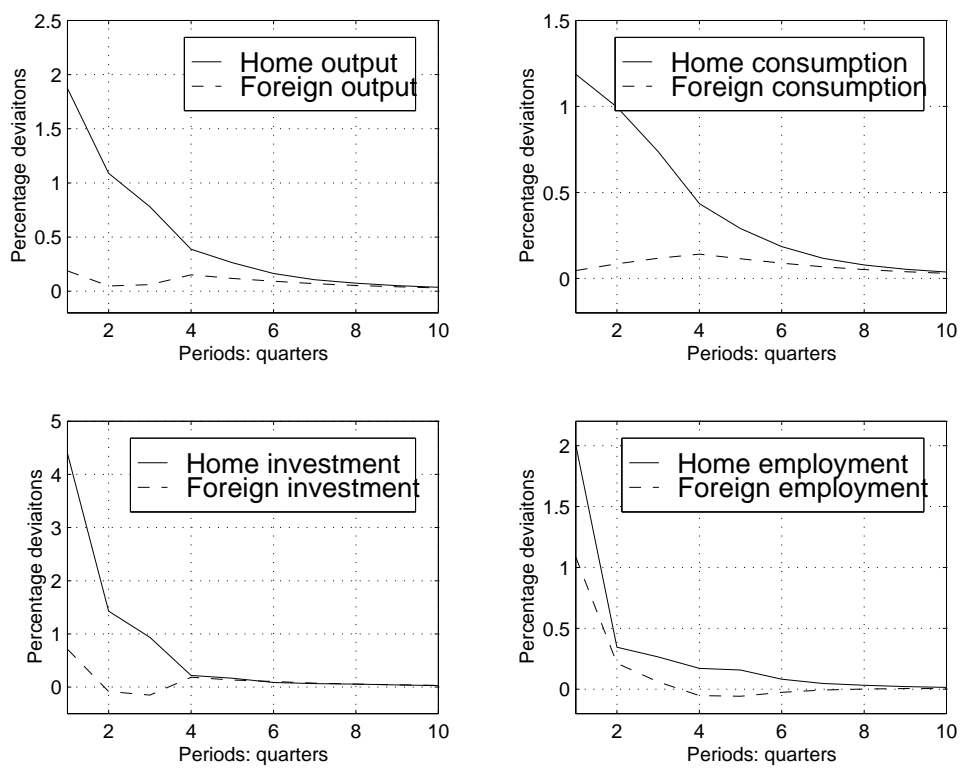


Figure 2.—International comovements: the baseline economy

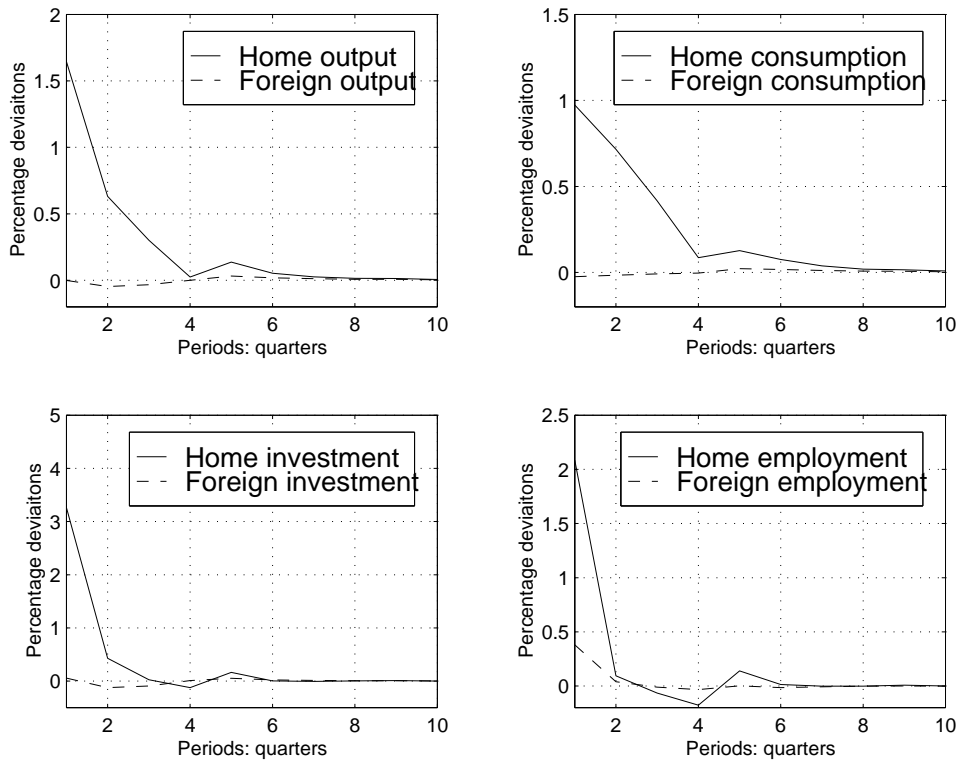


Figure 3.—International comovements: the single-stage economy

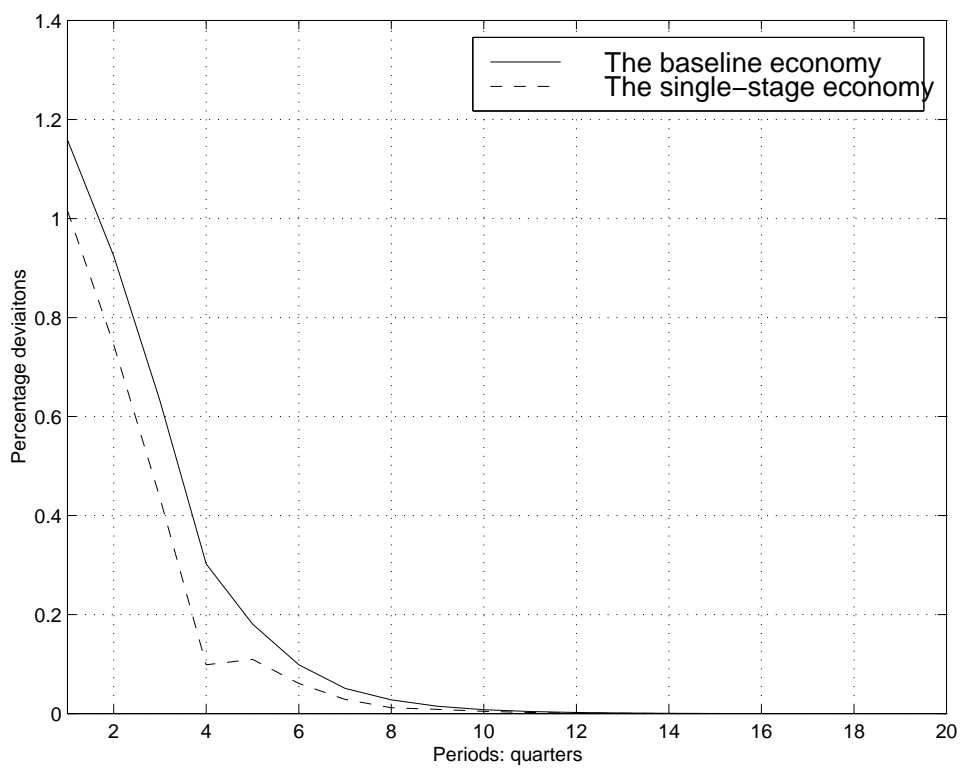


Figure 4.—Response of real exchange rates

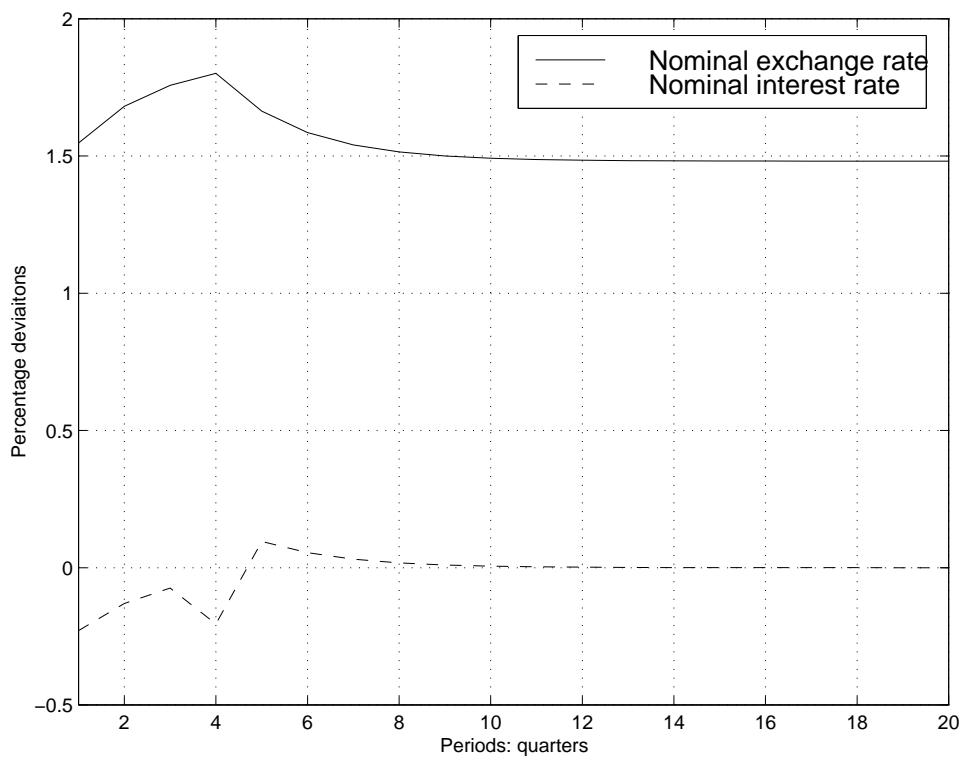


Figure 5.—Nominal exchange rate and nominal interest rate:
the baseline economy