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Mundell-Fleming Lecture

International Macroeconomics: Beyond the Mundell-Fleming Model

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This paper presents a broad overview of postwar analytical thinking on international macroeconomics, culminating in a more detailed discussion of very recent progress. Along the way, it reviews important empirical evidence that has inspired alternative modeling approaches, as well as theoretical and policy considerations behind developments in the field. The most recent advances in model building center on the "new open-economy macroeconomics," which synthesizes Keynesian nominal rigidities, intertemporal approaches to open-economy dynamics, and the effects of market structure on international trade. [JEL F41, F33]

Modern international macroeconomics progresses in two main ways. First, techniques or paradigms developed in mainstream micro or macro theory have been applied in an international setting. Second, researchers probe more deeply, using both theoretical and empirical methods, into the classic issues that define international economics as a distinct field—the implications of sovereign governments and national monies, of partial or complete cross-border factor immobility, of transport costs and cross-border information asymmetries that

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impede or even prevent trade. Frequently, prominent international policy problems, even crises, provide the inspiration for new explorations.

Enduring contributions typically reflect both modes of progress. For example, an application of new techniques developed elsewhere to an international monetary problem may consist merely of relabeling “households” as “countries.” But the most productive deployments of new techniques throw additional light on the specific problems of imperfect international economic integration at the heart of the field. In words that Robert A. Mundell (1968, p. 111) used to describe the rise of pure trade theory, advances in general economics, when applied with skill and sense in settings that capture salient empirical features of international economic data, have allowed “constant refinement and extension” in open-economy macroeconomics, “permitting analytical developments surpassing the possible achievements of unaided intuition.” The contributions of Mundell and of J. Marcus Fleming (1962) exemplify the most successful interactions of method and subject. No wonder this body of work has now been honored through the award to Mundell of the 1999 Nobel Prize in Economic Sciences. By merging Keynesian pricing assumptions and international market segmentation within a simple yet illuminating model, Mundell and Fleming provided the basic template for much subsequent research in both theory and policy.[1]

This paper presents a broad overview of postwar analytical thinking on international macroeconomics, culminating in a more detailed discussion of very recent progress. Along the way, I will review some important empirical evidence that has inspired alternative modeling approaches, as well as theoretical and policy considerations behind developments in the field. My general topic is, in fact, too large and diverse for comprehensive coverage, given my limited space and scholarship. The account that follows therefore should be interpreted as my own, somewhat impressionistic, view.

A testament to the lasting influence of their work is that much of the discussion can be framed with reference to what Fleming and especially Mundell accomplished in their work of the 1960s and 1970s—and left undone.[2]

The discussion is organized as follows. Section I focuses on postwar advances, discussing how, successively, the work of Mundell and Fleming, the monetary approach to the balance of payments, and the intertemporal approach to the current account placed international capital mobility and dynamics at center stage in open-economy macromodels. Section II is an overview of the behavior of international prices, and presents the strong evidence that prices are sticky in

[1]The most elaborate exposition-cum-interpretation of the Mundell-Fleming framework is offered by Frenkel and Razin (1987).

[2]The postwar period is coterminous with the history of the International Monetary Fund, and it is no accident that a number of important postwar intellectual developments—including contributions by Mundell and Fleming—originated in the research functions of the Fund. In this paper, however, I will not attempt systematically to review research done by the Fund or by any other institution. Retrospective evaluations of Fund research can be found in Bléjer, Khan, and Masson (1995) and Polak (1995). I will focus on nuts-and-bolts modeling of open-economy macrostructure and policy effects, to the exclusion of the very interesting work done in recent years on regime switches, policy credibility, and the like. Even my discussion of macrostructure will be partial, because I have space only to mention in passing research on international asset pricing and on the different functions of international capital flows.

nominal terms and that international markets for "tradable" goods remain highly segmented. Section III discusses newer modeling approaches that reconcile the breakthroughs in dynamic open-economy theory through the 1980s with the sticky-price setup pioneered by Mundell and Fleming. The section includes a rather detailed example of a stochastic "new open-economy macroeconomics" model in which the expenditure-switching effects of exchange rates central to the Mundell-Fleming model coexist with extreme market segmentation for tradable consumption goods and pricing to market. This class of models allows us to address rigorously, for the first time, a number of issues that have long been central to informal policy discussions in international macroeconomics. Section IV concludes.

I. Disequilibrium, Capital Mobility, Dynamics

The classical paradigm that dominated international macroeconomic thinking until the First World War depicted a self-regulating global economy based on the gold standard. The classical world is a stable dynamical system in which adjustment of national price levels and the free flow of specie can be relied on to swiftly restore both full employment and equilibrium in national balances of payments. This picture of near-frictionless adjustment, with sovereign economic interventions limited by rules of the game, is a gross exaggeration even of the conditions existing under the Victorian Pax Britannica. But the classical paradigm, despite its positive shortcomings, serves as a useful theoretical benchmark. And it reminds us that dynamic considerations have been at the heart of international macroeconomics at least since the days of Gervaise and Hume.

During the interwar period, extreme economic dislocations promoted an overly idyllic view of prewar conditions. These dislocations included nationalistic measures that sharply reduced economic integration among countries: fiat monies trading at floating exchange rates, preferential trade arrangements, direct state trading, default on foreign debts, and exchange controls. In earlier years economists had regarded such nationalistic experiments, when they occurred in Latin America or other areas of the periphery, with "fascinated disgust."[3] Now, however, similar economic arrangements were painfully relevant among the advanced countries themselves. The classical paradigm had become largely irrelevant to actual international conditions. Moreover, it could not explain the economic cataclysm that had brought those conditions into being.

Keynesian Approaches: From Metzler and Machlup to Mundell

The stage was set for Keynes's "revolution" and for the adaptation of its central ideas to international questions at the hands of Metzler, Machlup, and others. The new models they developed dealt with an essentially static world characterized by rigid wages and prices, unemployment, and limited financial linkages between countries. Key contributions elucidated the effects of trading relations

[3]The apt phrase is that of Bacha and Díaz-Alejandro (1982, p. 3).

on Keynesian multipliers, international repercussions, the effects of devaluation, the determination of floating exchange rates, and the role of the terms of trade in the Keynesian consumption function. The role of monetary factors, so central to the classical approach, was downplayed if not ignored. Metzler's (1948) survey for the American Economic Association was quite explicit in repudiating "the central role which [the classical mechanism] attributes to the monetary system" (p. 212). However, the new approach gave no guide to the alternative mechanisms that would eliminate external imbalances over time, and implicitly assumed instead that sterilization policies could be followed indefinitely.[4]

Meade's magisterial treatise *The Balance of Payments* (1951), published exactly a half-century ago, attempted to embed the Keynesian developments within a much broader framework that also embraced monetary factors. Meade's book is remarkable both in its ambitions and in its accomplishments. It summarized and (to a lesser extent) synthesized international monetary thinking as it had developed over the centuries. Meade sought to present a systematic account of economic problems and their solutions in an open economy, entertaining a wide variety of assumptions on price flexibility and international payments arrangements with the goal of guiding policy choice. In so doing, he discovered much that would be rediscovered later and set a large portion of the research agenda for the subsequent decades.

Indeed, it became fashionable for a time to dismiss much of subsequent international economic research with the remark "It's all in Meade"—an assertion difficult to refute given the work's nearly impenetrable expository style. The forbidding facade, however, repelled would-be readers and greatly reduced its impact. Mundell (1968, p. 113) rated the work as a "landmark in the theory of international trade and economic theory in general," much underestimated by contemporary reviewers, but he lamented the "defects of its organization and presentation." Meade himself (1951, p. viii) pointed to one major gap in his theoretical treatment of international macroeconomics:

> But I must confess frankly that there is one piece of modern technique in economic analysis which is very relevant to the problems discussed in this volume, but of which I have made no use. I refer to the analysis of the dynamic process of change from one position of equilibrium to another. The method employed in this volume is first to consider a number of countries in at least partial or temporary equilibrium, domestically and internationally; then to consider the new partial or temporary equilibrium which the economies will attain when the direct and indirect effects of the disturbing factor have fully worked themselves out; and finally to compare the new position of equilibrium with the old. In other words, this is a work not on dynamics, but on comparative statics, in economics.

Meade criticized the lack of any explicit mathematical account of how the economy gets from one "partial or temporary" equilibrium to another. A related problem, already noted above and highlighted by Meade's "partial or temporary"

[4]For further discussion, see Obstfeld (1987).

qualifier, was even more fundamental to much of the Keynesian theorizing of the 1940s and 1950s. Situations of external imbalance necessarily imply that stocks of domestic wealth—money and perhaps other assets—are not stationary and, thus, that the economy's temporary equilibrium must evolve over time, even in the absence of exogenous impulses. But what intrinsic dynamics would operate in a world seemingly at odds with the assumptions driving Hume's analysis of the economy's movement toward a long-run equilibrium? In particular, would this dynamical process be a stable one, and how would its nature depend on the activist economic policies that might be in play? Despite Alexander's important formulation of the absorption approach in the early 1950s (Alexander, 1952), an approach that brought to the fore the role of desired wealth changes in generating international imbalances, surprisingly little progress on these questions was made until Mundell's work in the early 1960s.

In a pathbreaking series of articles, Mundell took up the challenge of filling the gap that Meade's omission of dynamics had left. By so doing, he reintroduced the idea of a self-regulating adjustment mechanism that had been central to the classical framework. In line with the evolution of world financial markets since Meade's book, Mundell put private international capital flows at center stage in his dynamic analysis. Had his achievement been entirely technical, it might have had little impact. Instead, through a rare combination of analytical power and Schumpeterian "vision," Mundell distilled from his mathematical formulations important lessons that permanently changed the way we think about the open economy.

Mundell followed Meade in emphasizing the monetary sector, using a liquidity-preference theory of money demand to tie down the short-run equilibrium. Metzler (1968), in work done around the same time, took a similar tack, but he was less successful, whether his work is judged by its theoretical elegance or by immediate policy relevance. Fleming (1962), working in parallel, developed a model quite similar to Mundell's basic short-run equilibrium framework, and the two justly share credit for this contribution. Fleming did not, however, formally address the long-term adjustment process implicit in Keynesian models; he confined himself to some prescient remarks on the long- versus short-term responsiveness of the capital account.

Mundell focused squarely on the dynamic effects of payments imbalances in his paper on "The International Disequilibrium System" (Mundell, 1961a). Even in a world of rigid prices, Mundell argued, an "income-specie-flow mechanism" analogous to Hume's price-specie-flow mechanism ensures long-run equilibrium in international payments. An increase in a country's money supply, for example, would depress its interest rate, raise spending, and open an external deficit that would be settled, in part, through money outflows. For a small economy, the end process would come only when the initial equilibrium had been reestablished. Mundell clarified the role of sterilization operations, showing that they can be at best a temporary response to permanent disturbances affecting the balance of payments. This work was influential in indicating the ubiquity of self-regulating mechanisms of international adjustment and, as a corollary, the limited scope for monetary policy with a fixed exchange rate, even under Keynesian conditions.[5]

[5]Of course, earlier writers, such as Keynes (1930, p. 309), had recognized some of the limitations that fixed exchange rates and capital mobility place on national monetary policies.

While Mundell's "disequilibrium system" argument (1961a) showed how the income-specie-flow mechanism would restore balance of payments equilibrium under Keynesian conditions, the analysis did not delineate automatic forces tending to restore full employment (internal equilibrium). To address that issue, Mundell pursued the idea of a "policy mix" in which fiscal policy would play a central role. Mundell (1962) applied a dynamic approach to the joint use of monetary and fiscal policy to attain internal and external targets under a fixed exchange rate. He observed that thanks to capital mobility, policy dilemma situations that might arise under fixed exchange rates could be solved. Mundell showed that by gearing monetary policy to external balance (defined as a zero official settlements balance) and fiscal policy to internal balance (full employment), governments could avoid having to trade off internal against external goals in the short run. The key to his argument was the claim that either monetary or fiscal expansion can raise output, but they have opposite effects on interest rates. Thus, for example, a country simultaneously experiencing unemployment and an external deficit could couple fiscal expansion with monetary contraction in a way that lifts aggregate demand while attracting a sufficiently large capital inflow to close the foreign payments gap. Without capital mobility, however, this approach could not succeed. Mundell went on to argue that, when capital is mobile and the exchange rate pegged, a stable policy mix requires assigning fiscal policy to internal balance and monetary policy to external balance. A new and subtle insight in this work was that dynamic stability conditions might differ for alternative policy assignments and could therefore be used to assess the appropriateness of the policy mix.

Related work by Mundell (1960) investigated the relative efficacy of fixed and flexible exchange rates in helping countries adjust to economic shocks. Mundell showed that the answer depended on government policy rules, the speed of domestic price-level adjustment in the face of excess or deficient demand, and the degree of capital mobility. Mundell's emphasis on the role of differential sector adjustment speeds in determining an economy's dynamic behavior proved influential in other contexts—for example, in Dornbusch's (1976) Mundellian model of exchange-rate overshooting.

In one of his most celebrated contributions, Mundell (1963) took the speed of capital market adjustment to an extreme. With perfect capital mobility, he showed, only fiscal policy affects output under fixed exchange rates; monetary policy serves only to alter the level of international reserves. In contrast, fiscal policy might be dramatically weakened under floating rates. One implication of this analysis, which was not seen right away, was that the balance of payments might be a misleading indicator of external balance in a world where central banks could in principle borrow reserves in world capital markets. A more relevant concept of external balance would have to focus on the long-run solvency of the private and public sectors, taking into account vulnerabilities that might expose a country to a liquidity crisis.

The Mundellian idea of the policy mix was a major conceptual advance and seemingly offered an elegant way to avoid unpleasant tradeoffs. But the approach had at least two theoretical drawbacks. First, Mundell's theoretical specification of the capital account as a flow function of interest rate levels (a formulation used by

Fleming (1962) as well) was theoretically ad hoc. It implied, implausibly, that capital would flow at a uniform speed forever even in the face of a constant domestic-foreign interest differential. The second problem, already mentioned, was the definition of external balance in terms of official reserve flows, rather than in terms of attaining some satisfactory sustainable paths for domestic consumption and investment. As a medium-term proposition, it would be unattractive, perhaps even infeasible, to maintain balance of payments equilibrium through a permanently higher interest rate. The results of such a policy—crowding out of domestic investment and an ongoing buildup of external debt—would eventually call for a sharp drop in consumption.[6] While Mundell's framework was perhaps useful for thinking about very short-run issues (such as the need to maintain adequate national liquidity), it failed completely to bridge the gap from the short run to the longer term.

Indeed, the theory of the policy mix had little practical significance under Bretton Woods. In his detailed study of nine industrial countries' policies during the postwar period to the mid-1960s, Michaely (1971, p. 33) found only two episodes in which the prescription of the Mundellian policy mix was consistent with the official measures authorities actually took. Most of the time, Michaely concluded, fiscal policy simply was excluded from the list of available instruments.[7]

Classicism Redux: Monetary and Portfolio Approaches

By the mid-1960s, Mundell's dissatisfaction with his own early rendition of monetary dynamics led him to pursue the monetary approach to the balance of payments. The approach is also associated, in differing forms, with Harry G. Johnson and with the IMF's Research Department under Jacques J. Polak (see Frenkel and Johnson, 1976, and International Monetary Fund, 1977).[8]

If one thought of the University of Chicago style of monetary approach as being primarily a retrogression to the classical paradigm, one might reckon its intellectual impact as being rather transitory. I think that conclusion would be wrong, however, and that the monetary approach in reality made three enduring contributions. Along with research of the late 1960s on closed-economy models of money and growth, it helped drive home to the profession key distinctions between stocks and flows in dynamic international macroeconomic analysis. Furthermore, it provided a set of consistent long-run models that, aside from their intrinsic theoretical interest, could serve as benchmarks for more realistic analyses. Finally, with its formal elegance and the extravagance of its claims, the monetary approach breathed new life and brought new blood into a field that was becoming a bit tired.

I argued earlier that Mundell's treatment of capital flows in his work on the policy mix emphasized the monetary component of wealth at the expense of other

[6]Meade (1951, p. 104n) recognized clearly that in choosing between monetary and fiscal policy, "[t]he question of the optimum rate of saving is involved." Mundell (1968) briefly discusses problems of the composition of the balance of payments, likening them in Chapter 10 to problems of the proper division of national product between consumption and saving. Purvis (1985) includes a nice discussion of fiscal deficits and the external debt burden from the perspectives of the Mundell-Fleming and subsequent models.

[7]For a more detailed discussion of practical problems in deploying fiscal policy, see Obstfeld (1993).

[8]For a perspective on alternative interpretations of the monetary approach, see Polak (2001).

forms, notably net external assets. As a result, the distinction between stock equilibrium in asset markets and flow equilibrium in output and factor markets was blurred. These failings would have appeared even more glaring had Mundell's models of the early 1960s been applied to longer-term issues, rather than to the short-run Keynesian stabilization questions for which they were designed. Mundell presumably intended to include his own earlier work when he remarked, in his "Barter Theory and the Monetary Mechanism of Adjustment" (Mundell, 1968, p. 112):

> Innovations in the field since the 1930s have stressed the application of Keynesian economic concepts to the international sphere, rather than the integration of Keynesian international economics with classical barter theory or classical international monetary economics, creating a weakness in the area.

Indeed, the model Mundell developed here as a "start on the problem" did allow for sticky domestic prices, slowly adjusting to a carefully specified underlying classical equilibrium. Later work, by both Mundell and his students at Chicago, was to take the classical assumptions more literally (see, e.g., Mundell, 1971). Although most of the work of the monetary approach school oversimplified wildly in abstracting from assets other than money, a major element, as noted above, was the careful attention paid to the equilibrating role of output and factor prices in the transition from temporary to long-run equilibrium. While the approach lacked realism, it clarified the precise mechanics of Humean international adjustment, demonstrated the longer-run links between growth and the balance of payments, and showed how a focus on money supply and demand could help one to quickly ascertain the balance of payments effects of various disturbances. However, because of the ongoing growth of world financial markets, the appropriateness of relying on the balance of payments money account as an indicator of external balance was becoming increasingly questionable as the monetary approach developed, especially for industrial countries with reliable access to world capital markets.

Models incorporating a broader spectrum of assets were being developed concurrently. The work of McKinnon and Oates (1966) is an early attempt along these lines, as is Chapter 9 of Mundell (1968). Tobin's (1969) seminal contribution to monetary theory set off a surge of research on multi-asset portfolio-balance models better equipped than those of the monetary school to describe international adjustment in a world of mobile capital. Foley and Sidrauski's (1971) elegant dynamic closed-economy rendition of the portfolio-balance approach provided a model for intertemporal applications in open-economy settings. The monetary and portfolio-balance approaches essentially merged in the mid-1970s, producing useful descriptive models of the long-run adjustment of monetary flows, current accounts, goods prices, and, somewhat later, floating exchange rates.[9] Following

[9]For a more detailed discussion, see Obstfeld and Stockman (1985). A notable intellectual landmark here is the May 1976 conference issue of the *Scandinavian Journal of Economics*. The monetary approach to exchange rate determination is one strand in this literature; generally that approach builds on a version of the flexible-price monetary model in which the law of one price holds and money supplies rather than exchange rates are exogenous while exchange rates rather than money supplies adjust to equilibrate simultaneously the goods and asset markets. See, for example, the essays in Frenkel and Johnson (1978).

Black's (1973) lead, many of these floating-rate models took from macroeconomics proper the then-novel modeling assumption of exchange rate expectations that are rational, that is, consistent with the economy's underlying structure (including the statistical distribution of the relevant exogenous forces). Of course, the rational expectations assumption also figured prominently in the many extensions of the Mundell-Fleming framework that continued to be fruitfully pursued, starting with Dornbusch's (1976) landmark "overshooting" version of Mundell-Fleming, which incorporated output-price, but not wealth, dynamics.

These modern exchange rate models share a view of the exchange rate as an asset price (the relative price of two currencies), determined so as to induce investors willingly to hold existing outside stocks of the various assets available in the world economy. Mussa (1976) offers what is perhaps the classic exposition of this asset view of exchange rate determination. The enduring insight of the exchange rate's asset-price nature was obscured in versions of the Mundell-Fleming model that modeled the capital account analogously to the current account, as a flow function of the level of relative interest rates. By postulating that the exchange rate is determined by the condition of a zero net balance of payments, those models missed the exchange rate's role in reconciling stock demands and supplies that are normally orders of magnitude greater than balance of payments flows. Thus, the Mundell-Fleming model, in its earlier incarnations, offered no account of high exchange rate volatility.

Intertemporal Approaches to the Current Account

A final important branch in these dynamic developments was the application of optimal growth theory, in the style of Ramsey, Cass, and Koopmans, to open economies. Notable contributions along these lines were made early on by Bardhan (1967), Hamada (1969), and Bruno (1970).

Building on these approaches in the early 1980s, a number of researchers developed an intertemporal approach to the current account in which saving and investment levels represent optimal forward-looking decisions.[10] The new approach contrasted with the Keynesian approaches in which net exports are determined largely by current relative income levels and net foreign interest payments are, for the most part, ignored. These new models, unlike the earlier open-economy growth models, were applied to throw light on short-run dynamic issues—such as the dynamic effects of temporary and permanent terms-of-trade shocks—and not just the transition to a long-run balanced growth path. They could also be used to think rigorously about the policy implications of national and government intertemporal budget constraints.

The intertemporal approach, unlike the Keynesian or monetary approaches, provided a conceptual framework appropriate for thinking about the important and interrelated policy issues of external balance, external sustainability, and equilibrium real exchange rates (for a recent example, see Montiel, 1999). All of these concepts are intimately connected with the intertemporal tradeoffs that an

[10]For a more extensive survey of the area, see Obstfeld and Rogoff (1995a).

economy faces. Another major advantage of the intertemporal approach was its promise of a systematic welfare analysis of policies in open economies—an analysis on a par, in rigor, with those already applied routinely to intertemporal tax questions. The approach shifts attention from automatic adjustment mechanisms and dynamic stability considerations to intertemporal budget constraints and transversality conditions for maximization, although those perspectives may well, of course, be mutually consistent.

II. Models vs. Reality

Like the monetary approaches to the balance of payments and to exchange rates, the intertemporal mode of current account analysis developed in the 1980s generally assumed perfectly flexible domestic prices. It thereby abstracted from short-run price rigidities and the concomitant disequilibriums in goods and factor markets. The issues at the heart of the Mundell-Fleming model and its successors, such as the Dornbusch model, were simply put aside. The monetary and intertemporal models also, in general, assumed a rather high degree of economic integration among the economies being modeled. Presumably, a high level of integration among economies might justify abstraction from price rigidities, because these could not survive long in the face of international goods arbitrage.

Was this level of abstraction justified? In a well-known paper published after nearly a decade of floating exchange rates, McKinnon (1981) argued that the world economy had moved far away from the "insular" economic pattern of the 1950s and 1960s, in which countries carried out some foreign trade but were otherwise largely closed to external influences. In the new world of more open economies, the earlier Keynesian (and elasticities) approach to open-economy macroeconomic questions had become outmoded. Instead, the type of assumption underlying the monetary approach—highly open economies with goods and capital markets open to the forces of international competition—was a better approximation of reality.[11] Twenty years farther on in the process of postwar globalization, shouldn't the McKinnon arguments, if valid when they were advanced, carry even greater force?

Evidence on Insularity

The answer that seems to come resoundingly from the data is "no." Even today, the world's large industrial economies (along with many smaller economies) remain surprisingly insular, to use McKinnon's term. McKinnon rightly identified a trend of increasing openness, but jumped the gun in declaring the age of insularity to be over.

There are several well-known manifestations of persistent insularity. For many goods, transport costs are sufficiently high that a large proportion of GDP can be

[11]McKinnon differed from the monetary approach in questioning the existence of a stable national money demand function, in the absence of which, he argued, fixed exchange rates were preferable to floating rates.

considered effectively nontradable. But as Meade (1951, p. 232) pointed out in an even more insular era, nontradability is only an extreme consequence of trade costs, which attach to all goods in varying degrees:

> Products range with almost continuous variation between those for which the cost of transport is negligibly low in relation to their value and those for which the costs of transport are so high as to be in all imaginable circumstances prohibitive.

One consequence of pervasive transport costs (and other costs of trade such as official impediments) is the existence of a fairly sizable "transfer effect" due to changes in countries' net foreign assets.[12] This transfer effect can be seen both in countries' terms of trade and in their real exchange rates. Regarding the latter, Lane and Milesi-Ferretti (2000), using the most comprehensive cross-country panel on national net foreign asset positions developed to date, estimate that a 50 percent of GDP fall in a country's net foreign asset position (corresponding, perhaps, to a 2 percent of GDP fall in the long-run current account balance) would be associated with a 16 percent real currency depreciation. They find that this effect is potentially much larger for bigger and less open economies. In addition, we see fairly large home biases in consumption and trade. Of course, standard versions of the Mundell-Fleming model assume a transfer effect arising from (generally unexplained) home consumption preference.

We also observe puzzling symptoms of capital-market segmentation, notably the Feldstein-Horioka cross-section correlation of saving and investment and the home bias in equity portfolios. While imperfections intrinsic to capital markets lie in part behind these capital-market puzzles, costs of trade in goods can go a long way in generating "insular" capital-market behavior, as argued by Obstfeld and Rogoff (2000b).

Some of the most dramatic evidence on insularity—certainly the hardest to rationalize in terms of internationally divergent consumer tastes or other devices—is the evidence on international price discrepancies for supposedly tradable goods. Because of all the evidence on segmentation, which on international prices bears most directly on the appropriateness of competing open macromodels and on the role of the exchange rate, I will focus on price behavior for the balance of this section.

Evidence on International Pricing

A large body of empirical work weighs in against the proposition that international goods-market arbitrage is effective in quickly eliminating price differentials. The most convincing evidence began accumulating in the 1970s. Not coincidentally, the timing coincides with the availability of evidence on international pricing relationships under floating exchange rates. Isard's (1977) classic study was one of the first to present evidence against the Law of One Price (LOOP), showing that the

[12] See Mundell (1991) for a discussion of theory relating to the transfer problem. As Mundell points out, even with nontradable goods, there need be no transfer problem—see also Chapter 4 in Obstfeld and Rogoff (1996) for a model along these lines. But the conditions for this result are very stringent and unrealistic.

common currency unit values for similar tradable goods categories typically have diverged widely. These types of results continue to be confirmed in later data.[13] Therefore, at the micro level, there is evidence that either arbitrage is inoperative or it operates with significant lags.

At the macro level, some of the most striking evidence on international prices was assembled in an important paper by Mussa (1986). Mussa documented that, systematically and across a wide range of industrial country episodes, real exchange rates become much more variable when the nominal exchange rate is allowed to float. Real exchange rate variability tends to be almost a perfect reflection of nominal rate variability, with changes in the two rates highly correlated and independent movements in price levels playing a minor, if any, role. The overwhelming evidence that a key real relative price depends systematically on the monetary regime amounts to a powerful demonstration that domestic price levels are quite sticky. Some of the regime changes Mussa examined—such as Ireland's switch from its currency board sterling link to the European Monetary System—amount virtually to natural experiments, and it therefore is hard to argue that the regime switches themselves are endogenous responses to underlying shifts in the volatility of international prices. When the exchange rate is cut loose, its variability is vastly accentuated while nominal goods prices continue to move sluggishly. The sole exceptions seem to be episodes in which domestic inflation is extremely high, in which case prices, like the exchange rate, come unhinged and the correlation between real and nominal exchange rate changes drops (see Obstfeld, 1998).

The Mussa results also have a bearing on hypotheses about cross-border goods market integration. If arbitrage works strongly to keep international goods prices in line, then very large real exchange rate fluctuations would be ruled out. At the very least, large fluctuations would be rather temporary, as profit-maximizing traders quickly move to reap extra-normal profits, driving real exchange rates back into line. In fact, the evidence contradicts this idea as well. As shown by many studies (see Rogoff, 1996, for a survey), real exchange rate movements are highly persistent, so much so that it has been difficult to reject the statistical hypothesis that real exchange rate processes contain unit roots—a violation of even a weak form of long-run purchasing power parity that allows for deterministic trends. The best current estimates of real exchange rate persistence suggest that under floating nominal exchange rate regimes, the half-lives of real exchange rate shocks range from 2 to 4.5 years.

Such macrolevel evidence may not be viewed as entirely convincing. For one thing, real exchange rates are calculated with respect to the overall CPI including nontradables (or some other comparably broad price index). Thus, it could be the case that there is actually a considerable degree of arbitrage among the most tradable goods entering these price indexes. Furthermore, there is the theoretical possibility that much of the persistence in real exchange rates is due to real shocks, shocks that alter international relative prices permanently without necessarily creating opportunities for arbitrage. Work based on disaggregated price data for CPI compo-

[13]For more complete references, see the valuable surveys by Rogoff (1996) and Goldberg and Knetter (1997).

nents, however, suggests that both of these hypotheses are not very relevant. As Engel (1993) shows, Mussa-style results also hold for international comparisons of the consumer prices of similar tradable goods. Regarding real shocks as a source of persistence in real exchange rates, it is much harder to argue that real shocks are responsible for changes in the relative international prices of very similar, supposedly tradable goods. Yet movements in these relative prices are just as persistent as movements in real exchange rates. Rogers and Jenkins (1995), for example, perform unit root tests on the relative United States–Canada prices of 54 narrowly defined categories of goods and services. They find that they can reject the null hypothesis of a unit root at the 10 percent level for only 8 of the 54 categories (all food products). But even for food products, not all relative prices seem to be detectably mean reverting. Obstfeld and Taylor (1997) document similar persistence at a disaggregated level. This, it seems to me, is persuasive evidence against the theory that real shocks are the main source of real exchange rate persistence. What recurrent real shocks do we imagine would be buffeting the relative supermarket price of Canadian and U.S. flour? The weight of evidence suggests that whatever factors allow the LOOP deviations documented by Isard (1977) and many others also lie behind the big and persistent swings in countries' real exchange rates.

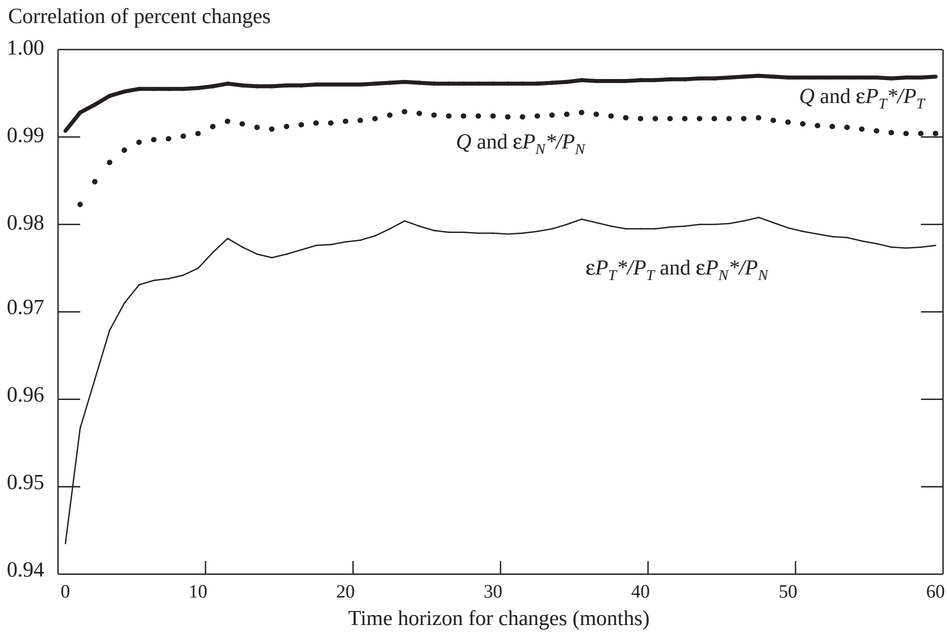
Accounting for Real Exchange Rate Changes

In recent important work, Engel (1999a) offers a striking way of illustrating just how pervasive the segmentation between countries' consumer markets is. Engel suggests decomposing a CPI real exchange rate change into (1) the component due to changes in international differences in two countries' relative prices of nontradable to tradable goods and (2) the component due to changes in the countries' relative consumer price of tradables.[14] Under classic theories of real exchange rate determination, such as the Harrod-Balassa-Samuelson account (see Obstfeld and Rogoff, 1996, chap. 4), tradables as a category closely obey the LOOP and so all variability in real exchange rates is attributable to factor (1) above. Engel's work shows that the opposite is true for real exchange rates against the United States. Even for real exchange rate changes over fairly long horizons, nearly all variability can be attributed to component (2), the relative consumer prices of tradables. This is a striking contradiction of the Harrod-Balassa-Samuelson theory. International divergences in the relative consumer price of "tradables" are so huge that the theoretical distinction between supposedly arbitraged tradables prices and completely sheltered nontradables prices offers little or no help in understanding U.S. real exchange rate movements, even at long horizons. Apparently, consumer markets for tradables are just about as segmented internationally as consumer markets for nontradables.[15]

[14]As Engel (1999a) explains, this is not an orthogonal decomposition. However, I do not believe that issue is central in interpreting his results, and I henceforth follow Engel in leaving it aside. Rogers and Jenkins (1995) earlier provided extensive evidence pointing to the same kinds of results that Engel emphasizes.

[15]Of course, the results are subject to the caveat made above that tradability is a matter of degree. Notwithstanding that fact, one can still view them as evidence that goods commonly considered to be "tradable" due to relatively low transport costs appear to be not very tradable at all if they are defined to include the services that bring them from the point of production to the consumer.

Figure 1. United States and Japan, 1973–95



Engel's findings can be summarized by graphs such as Figures 1–4. These figures are based on monthly 1973–95 data from Engel (1999a, sec. I). They show bilateral comparisons based on three floating exchange rates, dollar/yen, dollar/French franc, and deutsche mark/Canadian dollar. Let ε denote the nominal exchange rate, P the overall CPI, and P_T and P_N, respectively, the CPIs for tradables and nontradables.[16] In Figures 1–4, the behavior of the overall CPI-based real exchange rate, $Q = \varepsilon P^*/P$, is compared with that of the tradable and nontradable real exchange rates, $\varepsilon P_T^*/P_T$ and $\varepsilon P_N^*/P_N$. Each panel shows a plot against time, t, of the correlation between t-period percentage changes in the two variables shown.

As suggested by Engel's findings, the data reveal no significant difference between short-term and long-term correlations, consistent with the hypothesis that mean reversion in the relative international price of consumer tradables is extremely slow. Strikingly, it seems not to matter much whether tradables or nontradables are used to compute real exchange rates. Indeed, it is remarkable that relative tradables prices consistently tend to display a higher correlation with real exchange rates than do relative nontradables prices, though the discrepancies are small and statistically insignificant. For the countries shown, the behavior of relative international tradables prices is so similar to that of relative international nontradables prices, even for horizons out to five years, that one is led to question whether the distinction is even meaningful in discussing how real exchange rates behave under floating. At the consumer level, one sees no evidence here of greater cross-border price coherence for tradables.

[16]Engel (1999a, app. A) outlines his methodology for constructing the CPI subindexes. Engel's tradables comprise the OECD's "all goods less food" and "food," his nontradables, "services less rent," and "rent."

Figure 2. United States and France, 1973–95

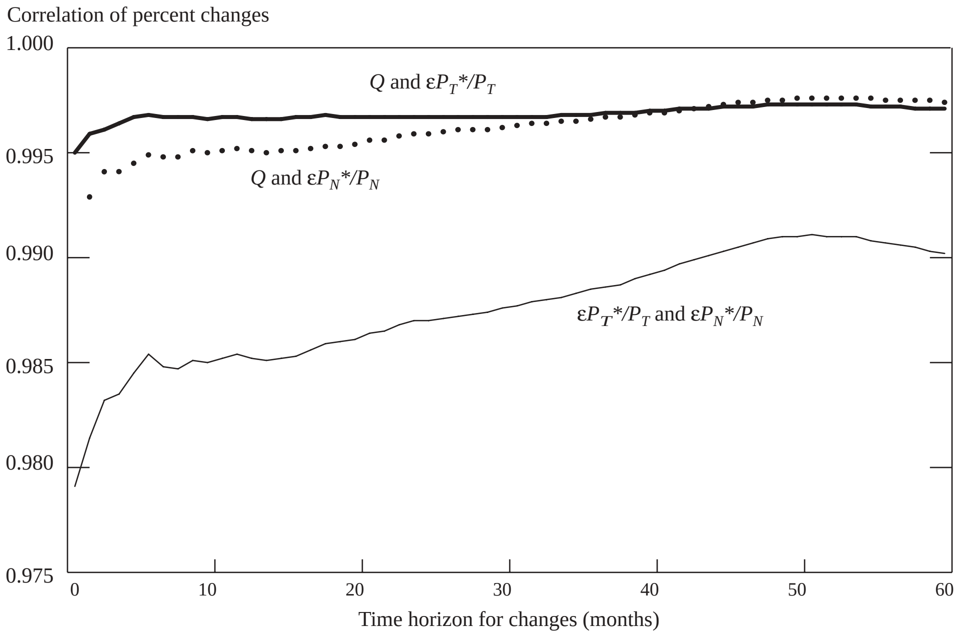


Figure 3. Germany and Canada, 1973–95

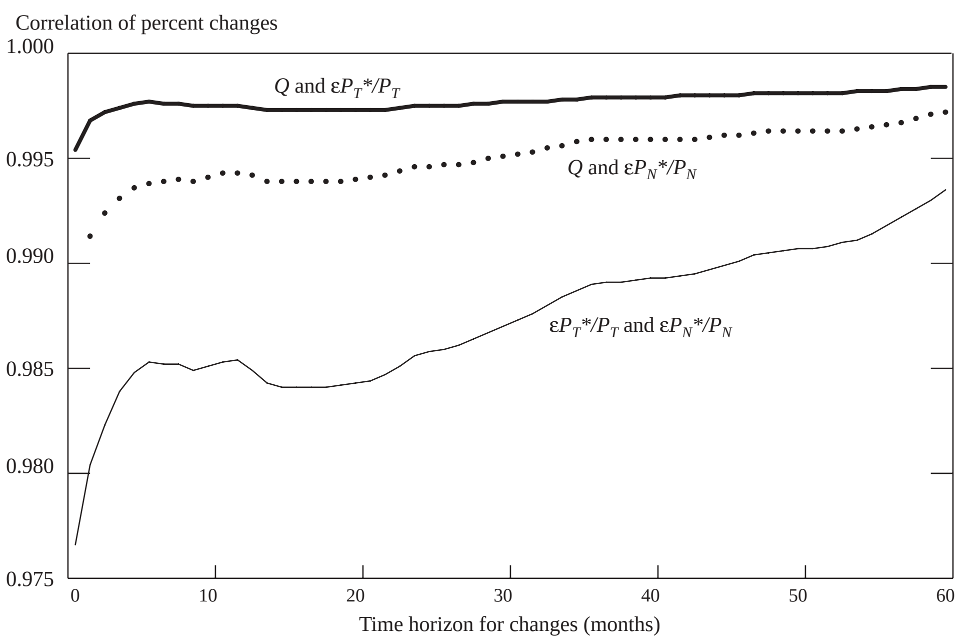
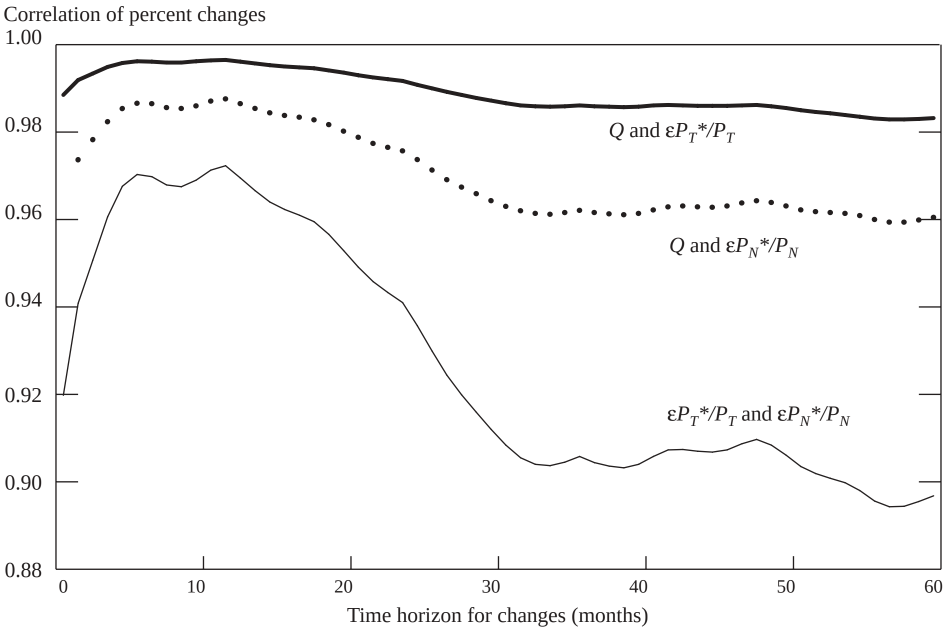


Figure 4. Germany and Japan, 1973–95



High exchange rate volatility is what makes the preceding results so dramatic. Given the sluggish behavior of nominal consumer prices and the lack of operational arbitrage between consumer markets, the behavior of nominal exchange rates dominates these data. The role of exchange-rate volatility in masking domestic relative price movements is illustrated in Figures 5–7, which use the monthly 1972–97 data from section IV of Engel (1999a), in which the producer price index (PPI) is used to proxy the price of tradables. The figures are constructed as follows. For horizons $t = 1$ through $t = 18$, I average the mean squared error (MSE) of the 18 t-period changes in the "traded goods" component of the CPI, $\log(\varepsilon \times PPI^{*}/PPI)$, each expressed as a fraction of the MSE of the t-period change in log Q. The resulting ratios, measured by the vertical axes of Figures 5–7, are plotted against the standard deviation of month-to-month changes in log ε, which can be read off the horizontal axis. A more nuanced picture now emerges. Figure 5 shows that, in pairings against the United States, Canada is an outlier, showing both the lowest nominal exchange rate variability and the lowest share of real exchange rate variability explained by tradables, just under 70 percent.[17] When we examine all non-U.S. pairings in Figure 6, however, we see that there are other instances in which low nominal exchange rate variability is associated with relatively low shares of tradables in real exchange rate variability, shares that can be as low as 50 percent. Putting all the pairings together in Figure 7, U.S./Canada no longer appears as an outlier. Indeed, when nominal exchange rate volatility is suppressed, factors other than changes in the relative inter-

[17]The countries paired with the United States in Figure 5 are Austria, Canada, Denmark, Finland, Germany, Greece, Japan, the Netherlands, Spain, Sweden, Switzerland, and the United Kingdom.

Figure 5. Pairings Against the United States

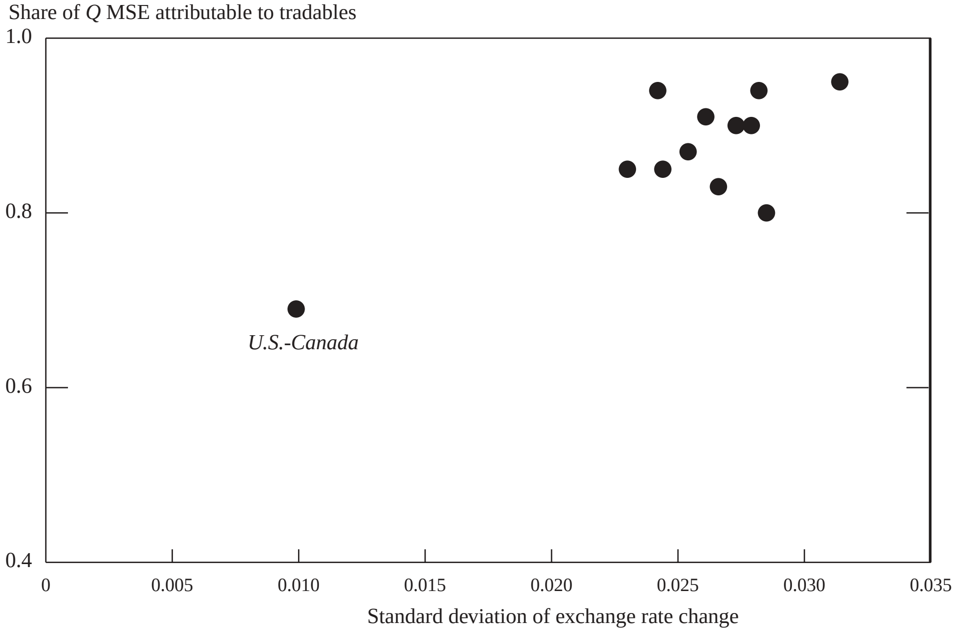


Figure 6. Non-U.S. Pairings

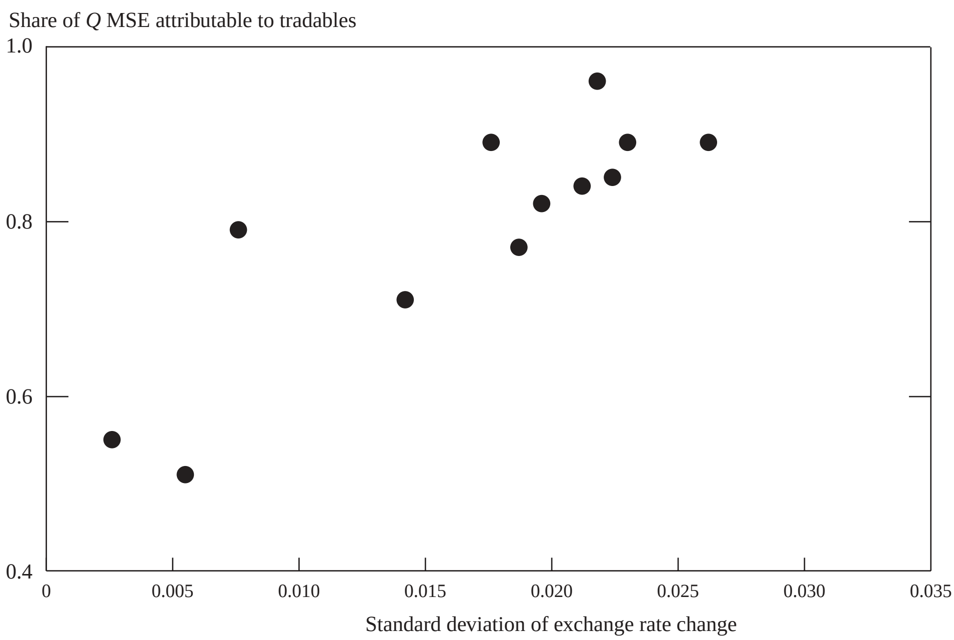
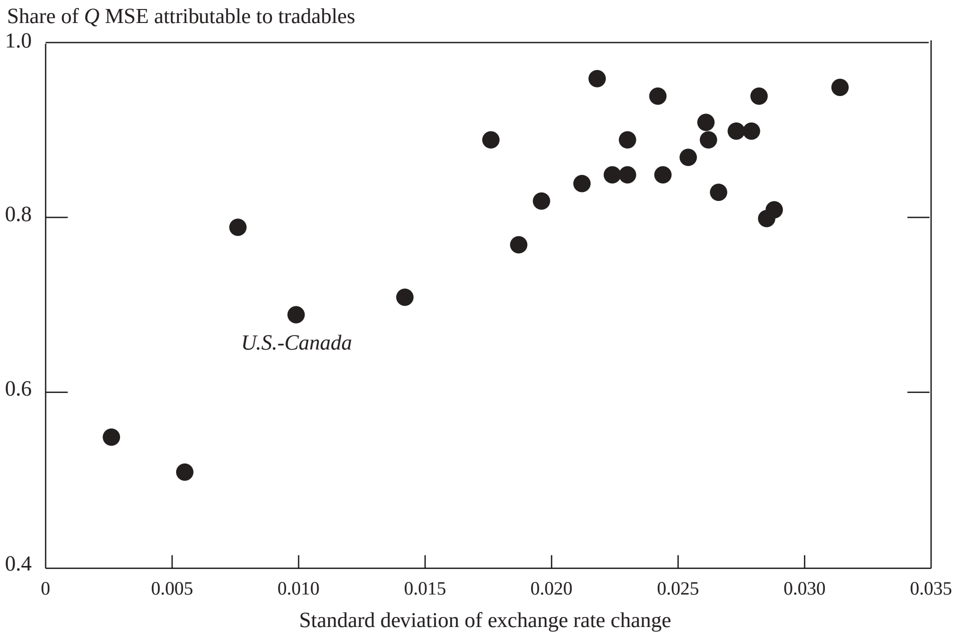


Figure 7. All Industrial Country Pairings



national price of consumer tradables appear to play a significant role in determining real exchange rates. They are no longer swamped by huge nominal exchange rate changes, as in Figures 1–4.[18]

Figures 5–7 nonetheless confirm the main conclusions we have already reached. Even for fixed exchange rate pairings such as Austria/Germany, relative tradables prices still play a very big role (over 50 percent) in explaining real exchange rate changes. This number still suggests considerable market segmentation at the consumer level. That nominal exchange rate changes alone seemingly can induce large, persistent changes in relative tradables prices, without setting into motion any prompt, noticeable arbitrage mechanisms, is a further indication of segmentation. Finally, the fact that nominal volatility plays so strong a role in driving relative international price changes is more evidence of stickiness in domestic nominal prices. Indeed, the data behave as if all consumer prices are sticky in domestic currency terms, even the prices of goods that may be imported from abroad.

Direct Evidence on Pricing to Market

The preceding evidence leads to the finding of both sticky domestic prices for consumer goods and high barriers between countries' consumption-goods markets. Assumptions on consumer prices are key components of any macromodel

[18]These types of results also occur in the bilateral comparisons carried out by Rogers and Jenkins (1995), but they do not systematically compare the correlation between nominal volatility and the importance of LOOP deviations in determining real exchange rates.

because consumer decisions are based on those prices and will influence the economy's response to disturbances. Because the ultimate consumer is several steps removed from the port of entry of import goods, however, findings such as Engel's (1999a) have only an indirect bearing on the height of barriers to international trade between firms, which accounts for most of international trade. Consumer prices, in addition to incorporating the import prices of the underlying commodities purchased, also reflect the costs of nontradable components such as retailing costs, internal shipping, and the like. These nontraded inputs make it difficult to assess the specific role of barriers to international trade in the underlying "tradable" commodities. They also make it harder to draw conclusions about the stickiness of import prices.

Further ambiguities come from the impossibility of ensuring that even disaggregated CPI data from different countries represent in any sense the prices of identical goods. Not only does index composition differ across countries with respect to subcategories of the tradable, there is also no way to ensure that even very similar tradables included in two indexes originate from the same producer.

Recent evidence on "pricing to market" (PTM) in international trade has helped to resolve these difficulties. The term PTM, popularized by Krugman (1987), refers to third-degree price discrimination by an exporter, based on the location of importers.[19]

Using detailed disaggregated data on the different prices that individual firms set for the same good exported to different locations, the econometrician can control for unobserved marginal production cost while ascertaining how exchange rate changes relative to different destinations affect prices charged. Under perfectly competitive conditions and costless international trade, an exporter's home currency price is determined entirely by domestic marginal cost; thus, given marginal cost, the exporter will raise price in any destination country fully in proportion to an appreciation in the source country's nominal exchange rate against the destination country. In other words, the extent of exchange rate pass-through is unitary. When pass-through is incomplete, however, there is evidence of PTM.

The extent of PTM differs across source countries and products, of course. In their excellent survey of studies on international pricing, Goldberg and Knetter (1997, p. 1244) conclude that "a price response equal to one-half the exchange rate change would be near the middle of the distribution of estimated responses for shipments to the U.S." The markup adjustment following an exchange rate change, according to them, generally occurs within a year.

[19]Another seminal contribution is that of Dornbusch (1987). Under first-degree price discrimination, a monopolistic producer can perfectly exploit the heterogeneity among consumers by quoting each individual buyer a different price (of course, resale must be prevented). Under second-degree price discrimination, the monopolist does not observe any signal of consumer type and can exploit heterogeneity only by inducing self-selection on the part of consumers. Under third-degree price discrimination, the monopolist bases price on an observable signal about consumer type—in the present context, national location. (For further discussion see Tirole, 1988, p. 135.) As under first-degree price discrimination, trade impediments must rule out arbitrage between different consumer types. That is, pricing to market cannot take place unless there is international market segmentation.

On the Need for a Synthesis

Perhaps the most salient feature of the data is that nominal exchange rate changes are associated with virtually commensurate fluctuations in real exchange rates. Moreover, relative international consumer prices of even tradable manufactured goods seem to move virtually one-for-one with the nominal exchange rate. At the level of consumers, the pass-through from exchange rates to import prices is virtually zero in the short run. Further up the distribution chain, where imports first enter a country, the pass-through of exchange rate changes to prices generally is positive, but substantially below one. Market segmentation allows exporters to change destination-specific markups in response to exchange rate movements.

The accumulation of such evidence highlighted how some basic assumptions shared by the monetary and intertemporal approaches contradict central policy-relevant facts. Both approaches fail to incorporate short-run price rigidities, and both assume complete pass-through of exchange rate changes to import prices.

Despite building in nominal rigidities, the Mundell-Fleming model, taken literally, also assumes unitary pass-through from the exchange rate to import prices. That assumption is central to the expenditure-switching effect of exchange rates, which is the key feature giving monetary policy its efficacy under flexible exchange rates, or allowing exchange rate changes to counter nation-specific shocks in Mundell's (1961b) optimum currency area analysis.

The empirical failures of the standard models developed before 1990 were crippling not only from a positive point of view, but also because they reduced applicability to questions of policy. The Mundell-Fleming model, for example, makes no distinction between retail and wholesale import prices, and it would have to be modified to capture both the near-zero pass-through of the exchange rate to consumer prices of imported goods and the partial (but positive) pass-through of the exchange rate to the prices exporters charge. The precise way this is done, however, has critical policy implications. If one abstracts from partial exchange-rate pass-through at the wholesale level, as Engel (2000) does, then the expenditure-switching effect of the exchange rate disappears entirely: exchange rate shifts do not alter the prices consumers face, and there is no firm-to-firm trade. On the other hand, if partial pass-through by exporters does affect economic decisions, the expenditure-switching effect is present, albeit perhaps in a muted form.

As another example, its failure to incorporate price rigidities dramatically reduces the policy utility of the intertemporal approach (except, perhaps, for very long-run issues). How can one accurately evaluate an economy's departure from external balance without some notion of its distance from internal balance—that is, a state of zero output gap and near-target inflation? How can one evaluate the equilibrium real exchange rate without some notion of the kind and height of the barriers separating national markets? How can one conduct welfare analysis without an attempt to model the economy's distortions, including those due to price rigidity? By the late 1980s and early 1990s, the clash of theory and data suggested the need for a coherent synthesis of the Keynesian and intertemporal approaches within an empirically oriented framework.

III. The New Open-Economy Macroeconomics

The most recent synthesis of earlier approaches combines monopolistic producers with nominal rigidities in a dynamic context with forward-looking economic actors. As proponents of the New Keynesian approach to closed-economy macroeconomics argued in the late 1980s, monopoly is a natural assumption in any context with price setting, and imperfect competition helps rationalize the idea that output is demand determined over some range, because price exceeds marginal cost in the absence of unexpected shocks. Moreover, the literature on sunk costs and hysteresis makes it plausible that market power should play some role in explaining the persistence of international relative price movements.[20]

Svensson and van Wijnbergen (1989) provided an early prototype model along these lines, in which output is produced at zero marginal cost up to some limit and asset markets, as an aid to modeling, are assumed to be complete. Obstfeld and Rogoff (1995b, 1996, 1998, 2000a) proposed a more tractable intertemporal monopolistic competition framework with sticky (that is, preset) nominal output prices and incomplete asset markets. The new approach addresses the positive questions asked of the Mundell-Fleming model as well as normative questions that could previously be addressed only within the empirically incomplete intertemporal approach. There have been numerous extensions, which I do not have the space to discuss in any systematic way. Luckily, Lane (2001) has provided a comprehensive survey.

Price Setting in New Open-Economy Models

One of the most important extensions has been to allow for PTM, in contrast to the original Obstfeld-Rogoff model, which assumed complete pass-through of exchange rates to import prices. Betts and Devereux (1996) made the initial contribution along these lines. In an open economy, nominal price rigidities can take a variety of forms because producers can choose to preset product prices in domestic or foreign currency. In the Betts-Devereux setup, some producers preset home prices in home currency and export prices in foreign currency—what Devereux (1997) refers to as "local currency pricing" (LCP)—although home and foreign markups over marginal cost are initially the same. After a shock is realized, however, the home and foreign prices of the good can diverge widely as the exchange rate moves, with international market segmentation preventing arbitrage by consumers. This approach implies zero exchange rate pass-through in the short run for PTM goods and complete pass-through for goods priced in the exporter's currency. It is only one of several possible ways to model PTM, which of course can occur in a flexible-price world. Because the Betts-Devereux setup (like that of Obstfeld and Rogoff, 1995b) assumes constant ex ante markups, it is not amenable to an analysis of possible ex ante variability on markups.[21]

[20]Cheung, Chinn, and Fujii (1999) present some industry-level evidence supporting this idea.

[21]The assumption of constant markups also precludes an analysis of the choice of invoice currency, which of course should be endogenous. See Friberg (1998).

The PTM-LCP framework with constant demand elasticities has been widely adopted, however, because it provides tractability in model-solving while reproducing (for PTM goods) the virtually proportional effect of nominal exchange rate changes on the relative international prices of similar traded goods. Furthermore, the assumption of market segmentation at the consumer level certainly rings true and helps to rationalize why even big exchange rate changes seem to have so little impact on the economy in the short run (see Obstfeld and Rogoff, 2000b, on the "exchange rate disconnect" puzzle). Recent PTM models assume that all imports are priced in the local currency.

Leading examples in this literature include Devereux and Engel (1998, 2000), who adapt the stochastic models in Obstfeld and Rogoff (1998, 2000a) to a PTM-LCP environment with complete nominal asset markets, and Kollmann (2001), Chari, Kehoe, and McGrattan (2000), and Bergin and Feenstra (2001), who incorporate dynamic Calvo (1983) nominal contracts and investigate the ability of the resulting models to replicate a number of business cycle covariances.[22]

These models, however, while capturing the apparent zero pass-through of exchange rates to retail prices, do not reflect the partial pass-through to wholesale import prices implied by the micro studies on pass-through. Indeed, taken literally—as models in which the prices consumers pay for imported goods correspond to the import prices used to define a country's terms of trade—these PTM-LCP models imply that when a country's currency depreciates, its terms of trade improve. The reason is simply that import prices are given in domestic currency, whereas export prices, which are rigid in foreign-currency terms, rise in home-currency terms when the home currency depreciates.

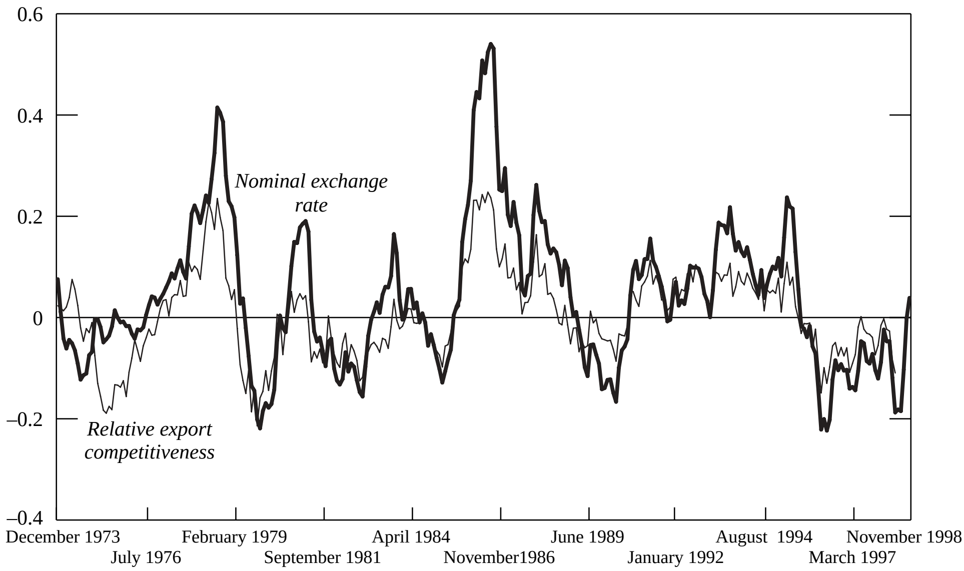
That prediction is wildly at odds with the data, as Obstfeld and Rogoff (2000a) show. The discrepancy is illustrated in Figures 8–11, which plot 12-month percent changes in bilateral exchange rates against 12-month changes in relative export prices, using monthly 1974–98 data on four country pairs. The relative export price is defined as $\varepsilon P_X^*/P_X$, an increase in which reflects an increase in the home country's overall export competitiveness, and if export prices are somewhat sticky in the exporters' currencies, we would expect this relative price to display a positive correlation with the nominal exchange rate. On the other hand, if exporters practice LCP on their foreign sales, the correlation could well be negative. The extent of positive correlation is strikingly apparent, although there is a suggestion of PTM for some episodes in which relative export prices respond in a damped fashion to exchange rate changes. These relationships are consistent with a model in which domestic marginal cost (consisting mostly of wages) is sticky in domestic currency terms, and export prices are set as a (perhaps somewhat variable) markup over marginal cost.[23]

Results such as those in Figures 8–11 illustrate the likelihood of quite divergent behavior by wholesale and retail import prices. A natural question, however,

[22]Obstfeld and Rogoff (1998, 2000a) assume that full exchange-rate pass-through to import prices is a reasonable approximation of reality, although their basic results hold qualitatively with partial (but positive) pass-through.

[23]That wages exhibit substantial stickiness in domestic currency terms strikes me as indisputable. For some U.S. evidence, see Altonji and Devereux (1999).

Figure 8. U.S. Dollar/Yen Exchange Rate and Relative Export Competitiveness
(12-month proportional changes)



is whether these correlations are central to understanding the macroeconomic implications of exchange rate changes. Most current PTM-LCP models effectively shut down any mechanism by which exchange rate changes might redirect expenditure internationally. In essence, when all the prices domestic actors face are preset in domestic currency, there is no room for the exchange rate to change the relative prices they face. Thus, the implicit assumption is that price changes such as those shown in Figures 8–11 are economically unimportant. Devereux and Engel (1998, 2000), following Engel (2000), argue that because of PTM-LCP, the size of the expenditure-switching effect central to the Mundell-Fleming model is likely to be very small. Devereux, Engel, and Tille (1999) explicitly model the distinction between wholesale and retail import prices, but in a model where retailers hold no inventories and simply respond passively to consumer demand, so that once again, exchange rates are assumed not to alter any relative prices relevant to economic agents' decisions.

This line of reasoning takes the implications of some very restrictive models much too seriously. In reality, there is copious evidence that exchange rate changes do indeed redirect global expenditure, though perhaps with lags—see Krugman (1991) for an overview of evidence through around 1990. That effect should be built into our macroeconomic models because it is central for conclusions about the efficacy of macroeconomic policies and the performance of alternative exchange rate regimes. There is no reason models characterized by PTM-LCP cannot simultaneously imply strong expenditure-switching effects, as I now illustrate. Indeed, in the model I describe below, PTM-LCP is a rather incidental feature; despite it, the

Figure 9. U.S. Dollar/Pound Sterling Exchange Rate and Relative Export Competitiveness
(12-month proportional changes)

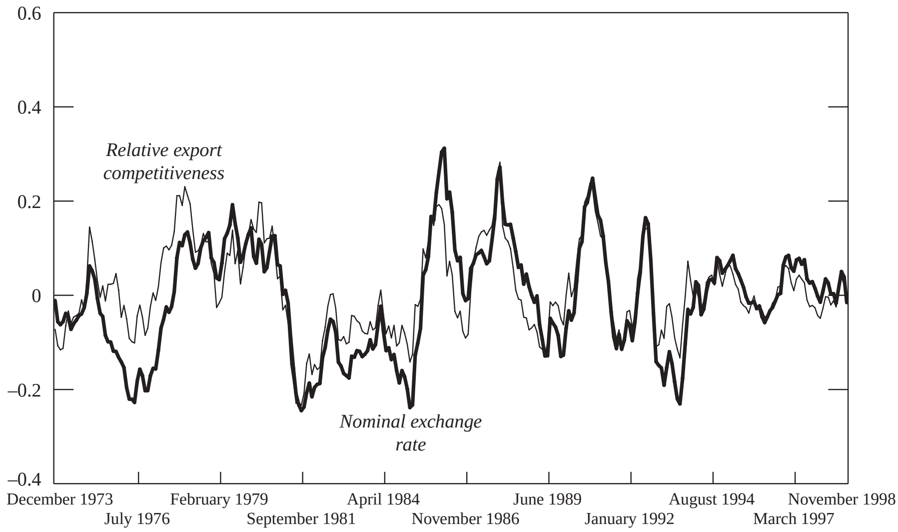


Figure 10. U.S. Dollar/Mark Exchange Rate and Relative Export Competitiveness
(12-month proportional changes)

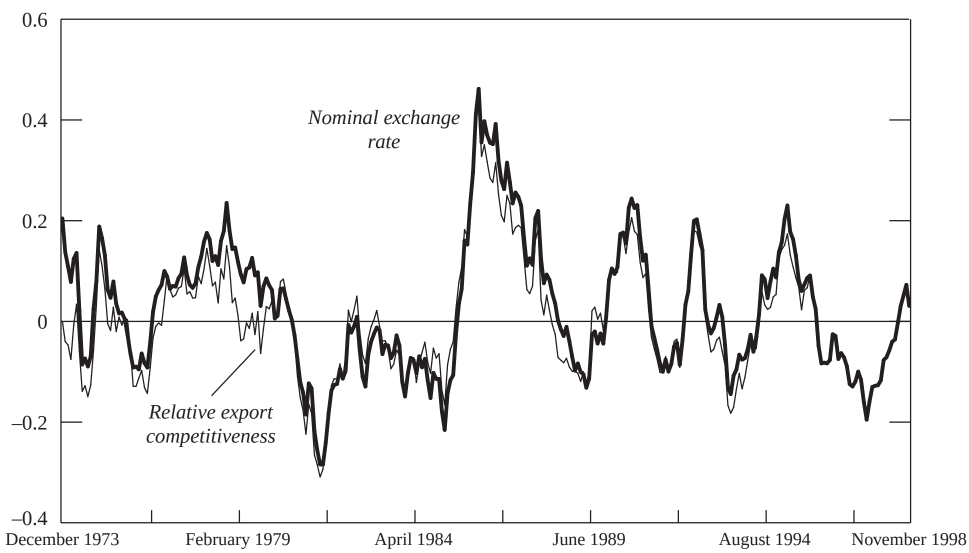
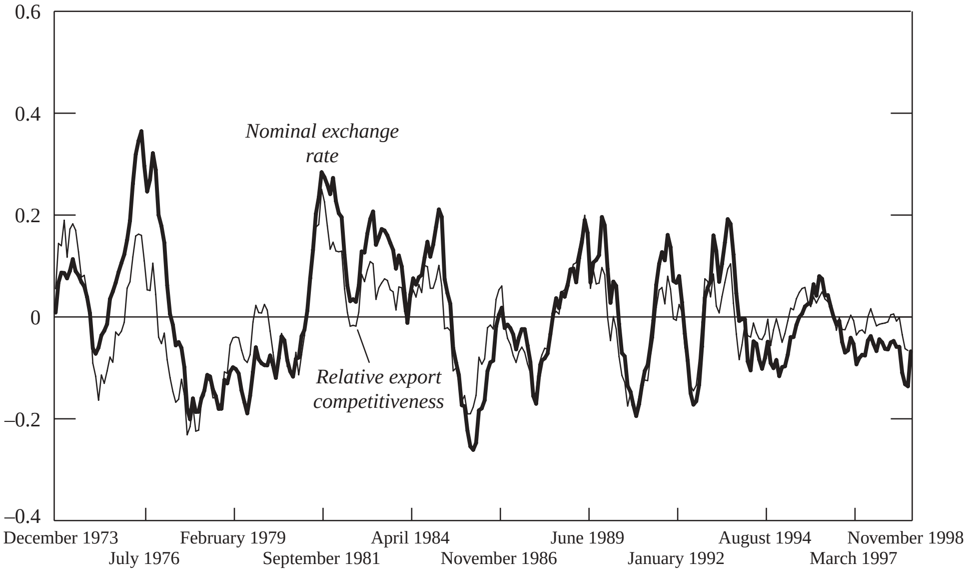


Figure 11. Canadian Dollar/Pound Sterling Exchange Rate and Relative Export Competitiveness
(12-month proportional changes)



model is isomorphic in its essential implications to the non-LCP model of Obstfeld and Rogoff (1998). The main action occurs in firm-to-firm trade that is driven by exchange rate fluctuations.

A Stochastic Model with Local Currency Pricing to Market

Multiperiod dynamics are not central to the effects I wish to explore here, so I specify a model in which all economic action save the setting of nominal wages and consumer prices takes place within a single period. Nominal wages and consumer prices are set before the market period. The model combines PTM-LCP for final consumption goods with marginal cost, source-country currency pricing for intermediate goods. It can, alternatively, be interpreted as a model in which firms produce some intermediate imports at foreign subsidiaries, rather than importing them from separate entities located abroad. Rangan and Lawrence (1999) stress sourcing decisions as a major channel through which exchange rate movements influence trade flows and, hence, aggregate demands for countries' outputs.

There are two countries, Home and Foreign. Home contains a unit interval [0,1] of workers indexed by *i*. Each supplies, in a monopolistic fashion, a distinctive variety of labor services. Home and Foreign have identical preferences,

$$U = \frac{C^{1-\rho}}{1-\rho} - \frac{K}{v} L^{v},$$

where $\rho > 0$, $v > 1$, and the real consumption index C is a composite of a continuum of *final* commodities indexed by $j \in [0,1]$,

$$C = \left[\int_0^1 C(j)^{\frac{\theta-1}{\theta}} dj \right]^{\frac{\theta}{\theta-1}}, \quad \theta > 1.$$

In what follows P is the usual CPI function of the individual nominal commodity prices $P(j)$. Foreign is symmetric, but with prices and quantities denoted by asterisks. Importantly, K is a stochastic shock to labor supply that the monetary authorities may be able to respond to after sticky nominal prices are set.

Home produces a homogeneous intermediate good Y_H. Its nominal domestic currency price is P_H, and with free trade in intermediates, $P_H^* = P_H/\varepsilon$, where ε, the nominal exchange rate, is the Home currency price of Foreign currency. The Home intermediate good is produced under competitive conditions out of all of the distinctive varieties of domestic labor services. (Similarly, Foreign produces the intermediate Y_F, with foreign currency price P_F^*, etc.) The assumption of full and immediate pass-through for intermediates is not realistic, but it simplifies the model and as long as there is an economically significant pass-through, as suggested by Figures 8–11, the main results will go through. The production function for either intermediate is

$$Y = \left[\int_0^1 L(i)^{\frac{\phi-1}{\phi}} di \right]^{\frac{\phi}{\phi-1}}, \quad \phi > 1.$$

Nominal wages $W(i)$ ($W^*(i)$ in Foreign) are set in advance to maximize *expected* utility, EU^i. The demand for labor variety i in this setting is

$$L(i) = \left[\frac{W(i)}{W} \right]^{-\phi} Y$$

(in Home or Foreign), where

$$W = \left[\int_0^1 W(i)^{1-\phi} di \right]^{\frac{1}{\phi-1}}.$$

Because intermediates markets are perfectly competitive, $P_H = W$ and $P_F^* = W^*$.

A Home final-goods producer (or distributor) j "manufactures"' final consumption $Y(j)$ out of the Home and Foreign intermediates according to the production function

$$Y(j) = 2Y_H(j)^{1/2} Y_F(j)^{1/2}, \tag{1}$$

where $Y_H(j)$, for example, is input of the Home-produced intermediate into production of final consumption good j. But, as noted above, substitution between production inputs can be viewed as a sourcing decision [for Foreign, $Y^*(j) = 2Y_H^*(j)^{1/2} Y_F^*(j)^{1/2}$]. The Home (Foreign) distributor distributes exclusively in Home (Foreign), so that in a sense, final consumption goods are nontradables and in equilibrium, $C(j) = Y(j)$ and $C^*(j) = Y^*(j)$. I assume that consumers have no way to arbitrage across international markets.

The final goods firm must hold domestic money in order to transform intermediates into retail consumer goods. Specifically, a Home firm j will choose

$$M(j) = \alpha P_H^{1/2} P_F^{1/2} C(j),$$

while a Foreign firm chooses

$$M^*(j) = \alpha P_H^{*1/2} P_F^{*1/2} C(j).$$

(Note that $P_H^{1/2} P_F^{1/2}$ is the minimal Home currency cost of producing a unit of final consumption good, given the production function of equation (1).) This "money in the production function" formulation is one way of imposing a demand for money on the model; Henderson and Kim (1999) describe a related device in the context of consumer money demand. Aggregate money supplies M and M^*, like K and K^*, are random variables with realizations that do not become known until after wages and final product prices are set.

The model assumes an extreme home bias in equity ownership, such that Home (Foreign) residents own all claims to the profits of the Home (Foreign) distributor. The (ex post) budget constraint of representative Home resident i is

$$PC^i = W(i)L(i) + \int_0^1 \Pi(j)dj,$$

where $\Pi(j)$ denotes nominal profits of firm j, and his/her first-order condition for the preset nominal wage, $W(i)$, is

$$E\left\{\frac{C^{-\rho}}{P}(1-\phi)L(i) + \frac{\phi K L(i)^{\nu}}{W(i)}\right\} = 0$$

or

$$\frac{W(i)}{P} = \left(\frac{\phi}{\phi - 1}\right)\frac{E\left\{KL(i)^{\nu}\right\}}{E\left\{L(i)C^{-\rho}\right\}}. \tag{2}$$

Recall that in the present setup with the CPI preset in domestic currency terms, P is deterministic and can be passed through the expectations operator $E\{\cdot\}$. Aside from that modification, this first-order condition is the same as in Obstfeld and Rogoff (1998, 2000a).

The more novel element is the first-order condition for the final goods firm, which presets consumer prices in local currency. Let T denote real government transfers to Home firms. Consider the maximization problem of Home firm j, which chooses $P(j)$ in advance to maximize the expected value (to its domestic owners) of profits:

$$E\left\{\left[P(j)C(j)-P_H^{1/2}P_F^{1/2}C(j)+PT+M_0^j-\alpha P_H^{1/2}P_F^{1/2}C(j)\right]C^{-\rho}\right\},$$

subject to

$$C(j)=\left[\frac{P(j)}{P}\right]^{-\theta}C.$$

That is, the firm (in effect) maximizes

$$E\left\{\left[\frac{P(j)^{1-\theta}}{P^{-\theta}}-(1+\alpha)P_H^{1/2}P_F^{1/2}\left[\frac{P(j)}{P}\right]^{-\theta}\right]C^{1-p}\right\}$$

with respect to $P(j)$, a problem that yields the first-order condition

$$P(j)=P=\left(\frac{\theta}{\theta-1}\right)\frac{E\left\{(1+\alpha)P_H^{1/2}P_F^{1/2}C^{1-\rho}\right\}}{E\left\{C^{1-\rho}\right\}}=\left(\frac{\theta}{\theta-1}\right)\frac{E\left\{(1+\alpha)(WW^*)^{1/2}\varepsilon^{1/2}C^{1-\rho}\right\}}{E\left\{C^{1-\rho}\right\}}.$$

Of course, the Foreign CPI is preset at the level

$$P^*=\left(\frac{\theta}{\theta-1}\right)\frac{E\left\{(1+\alpha)(WW^*)^{1/2}\varepsilon^{-1/2}C^{1-\rho}\right\}}{E\left\{C^{1-\rho}\right\}}.$$

I have written the preceding equation for P^* in terms of C rather than C^* because the model implies that $C = C^*$ in equilibrium, PTM notwithstanding. To see why, notice that the Home budget constraint (in equilibrium, after eliminating the government budget constraint) gives

$$PC=WL+\Pi=WL+\left[P-W^{1/2}(\varepsilon W^*)^{1/2}\right]C$$

or

$$C=\left(\frac{\varepsilon W^*}{W}\right)^{-1/2},\quad L=\left(\frac{\varepsilon W^*}{W}\right)^{-1/2}Y_H. \tag{3}$$

For Foreign, one finds that

$$C^*=\left(\frac{\varepsilon W^*}{W}\right)^{1/2}Y_F.$$

Clearing of the markets for Home and Foreign intermediates gives

$$Y_H = \frac{1}{2}\left(\frac{\varepsilon W^*}{W}\right)^{1/2} C + \frac{1}{2}\left(\frac{\varepsilon W^*}{W}\right)^{1/2} C^*,$$

$$Y_F = \frac{1}{2}\left(\frac{\varepsilon W^*}{W}\right)^{-1/2} C + \frac{1}{2}\left(\frac{\varepsilon W^*}{W}\right)^{-1/2} C^*.$$

Substituting for C and C^* in either of these yields the equilibrium relative price

$$\frac{\varepsilon W^*}{W} = \frac{P_F}{P_H} = \frac{Y_H}{Y_F},$$

from which it follows that

$$C = C^* = Y_H^{1/2} Y_F^{1/2}.$$

Let us now assume that all of the exogenous variables driving the economy are log-normally distributed. It then becomes relatively straightforward to combine the preceding first-order conditions to obtain log-linear price and consumption equations that parallel precisely those derived in Obstfeld and Rogoff (1998, 2000a). These equations, importantly, involve the second as well as the first moments of the (random) endogenous variables. The log-linearized equations for CPIs (with lowercase letters denoting natural logarithms and $e \equiv \log \varepsilon$) are

$$p = \log\left[\frac{\theta(1+\alpha)}{\theta - 1}\right] + \frac{1}{2}Ee + \frac{1}{2}\left(w + w^*\right) + \frac{(1-\rho)^2}{2}\sigma_c^2 + \frac{1}{8}\sigma_e^2 + \frac{(1-\rho)}{2}\sigma_{ce},$$

$$p^* = \log\left[\frac{\theta(1+\alpha)}{\theta - 1}\right] - \frac{1}{2}Ee + \frac{1}{2}\left(w + w^*\right) + \frac{(1-\rho)^2}{2}\sigma_c^2 + \frac{1}{8}\sigma_e^2 - \frac{(1-\rho)}{2}\sigma_{ce},$$

which together imply

$$Ee + p^* - p = -(1-\rho)\sigma_{ce}.$$

This is the equation for the ex ante CPI real exchange rate. (The intuition turns on how production costs—the exchange rate term—and hence profit covaries with demand and with the marginal utility of consumption; see Obstfeld and Rogoff, 2000a.)

To derive the (log) expected terms of trade, use equation (3) to rewrite equation (2) (in a symmetric equilibrium) as

$$\frac{W}{P} = \left(\frac{\phi}{\phi - 1}\right)\frac{E\left\{KY_H^{\nu}\right\}}{E\left\{Y_H C^{-\rho}\right\}} = \left(\frac{\phi}{\phi - 1}\right)\frac{E\left\{K\left(\frac{\varepsilon W^*}{W}\right)^{\frac{\nu}{2}} C^{\nu}\right\}}{E\left\{\left(\frac{\varepsilon W^*}{W}\right)^{\frac{1}{2}} C^{1-\rho}\right\}};$$

in Foreign,

$$\frac{W^*}{P^*}=\left(\frac{\phi}{\phi-1}\right)\frac{E\left\{K^*\left(\frac{\varepsilon W^*}{W}\right)^{-\frac{v}{2}}C^v\right\}}{E\left\{\left(\frac{\varepsilon W^*}{W}\right)^{-\frac{1}{2}}C^{1-\rho}\right\}}.$$

Let us assume that the first and second moments of $\kappa \equiv \log K$ and $\kappa^* \equiv \log K^*$ are the same. Log-linearize the preceding equations in the usual way, and combine them with the equations for p and p^* above. The result is the very familiar pair of equations for the expected terms of trade and expected consumption (see Obstfeld and Rogoff, 1998, 2000a):

$$Ee+w^*-w=-v\sigma_{ce}-\frac{1}{2}\left(\sigma_{\kappa e}+\sigma_{\kappa^* e}\right)+\left(\sigma_{\kappa^* c}-\sigma_{\kappa c}\right)\equiv E\tau, \tag{4}$$

$$Ec=\omega-\left[\frac{v+(1-\rho)}{2}\right]\sigma_c^2-\frac{\frac{v^2}{8}\sigma_e^2+\frac{v}{2}\left(\sigma_{\kappa^* c}+\sigma_{\kappa c}\right)+\frac{v}{4}\left(\sigma_{\kappa e}-\sigma_{\kappa^* e}\right)}{v-(1-\rho)}, \tag{5}$$

where

$$\omega\equiv\frac{1}{v-(1-\rho)}\left\{\log\left[\frac{(\phi-1)(\theta-1)}{\phi\theta(1+\alpha)}\right]-E\kappa-\frac{1}{2}\sigma_\kappa^2\right\}.$$

We can derive ex post levels of consumption and the exchange rate from the monetary equilibrium conditions. The Home and Foreign money demand conditions imply that in equilibrium,

$$m=\log\alpha+\frac{1}{2}w+\frac{1}{2}w^*+\frac{1}{2}e+c,$$

$$m^*=\log\alpha+\frac{1}{2}w+\frac{1}{2}w^*-\frac{1}{2}e+c.$$

From these one derives

$$e=m-m^* \tag{6}$$

and

$$c=\frac{1}{2}\left(m+m^*\right)-\frac{1}{2}\left(w+w^*\right)-\log\alpha. \tag{7}$$

These expressions can be used to express the variances and covariances affecting the economy's equilibrium in terms of the model's exogenous shocks.

A couple of immediate points can be made about the model. First, because p and p^* are predetermined, the CPI real exchange rate will be perfectly correlated with the nominal exchange rate e, close to what one sees in the data. Nominal exchange rate fluctuations induce commensurate changes in the international prices of supposedly tradable consumption goods.

Second, the model includes a substantial expenditure-switching effect of exchange rate changes, one that operates at the firm rather than at the consumer level. Solving the model, one can show that

$$y = m - \frac{1}{2}\left(w + w^*\right) - \log\alpha,$$

$$y^* = m^* - \frac{1}{2}\left(w + w^*\right) - \log\alpha.$$

An increase in a country's money supply depreciates its currency and leads to a proportional rise in output and employment in this model. If Home raises m, Foreign output is unaffected (a knife-edge result) because the negative expenditure-switching effect of the rise in e on y^* is exactly offset by the accompanying rise in world consumption spending c. Nonetheless, domestic monetary policy can differentially affect domestic output through its impact on the nominal exchange rate.[24]

Optimal Policy and Alternative Exchange Rate Regimes

One major advantage of stochastic models in the new open-economy macroeconomics is that they allow a complete analysis of welfare under alternative exchange rate regimes in the presence of sticky prices and uncertainty. That enterprise goes well beyond what was possible before and opens up the prospect of a rigorous evaluation of alternative systems. In the example of this section, countries clearly gain if they can gear monetary policy reaction functions toward offsetting shocks to K and K^*, as in Obstfeld and Rogoff (2000a). That factor increases the relative attractiveness of national monetary policy autonomy, for reasons that Mundell (1961b) spelled out.

It is straightforward to illustrate optimal policies and evaluate alternative monetary regimes in the present model. One simplifying feature of this model, which also holds in my 1998 paper with Rogoff but not in our 2000a paper, is that, regardless of the policy rules the two countries adopt, Home and Foreign always enjoy equal expected welfare levels:

$$EU = EU^*.$$

(See the Appendix for a derivation.) An implication is that there are no potential divergences of interest between the countries; any development that aids or hurts one automatically affects the other identically. This implication of the model is not

[24]Were wages flexible instead of sticky, the impact of domestic money on domestic output would be reduced to $m/\nu < m$.

realistic; however, it greatly simplifies the analysis of policy regimes because coordination issues can be ignored.

What is the preceding common level of global welfare? Making use of another result derived in the Appendix, we see that

$$EU = \frac{v\phi\theta(1+\alpha) - (1-\rho)(\phi-1)(\theta-1)}{v\phi\theta(1+\alpha)(1-\rho)} E\{C^{1-\rho}\},$$

so that expected utility is proportional to

$$E\left\{\frac{C^{1-\rho}}{1-\rho}\right\} = \frac{1}{1-\rho}\exp\left[(1-\rho)Ec + \frac{(1-\rho)^2}{2}\sigma_c^2\right].$$

A further simplification is to express the (log) "productivity" shocks in terms of global and idiosyncratic components,

$$\kappa^w \equiv \frac{\kappa+\kappa^*}{2},\ \kappa^d \equiv \frac{\kappa-\kappa^*}{2},$$

which are mutually orthogonal and satisfy $\sigma_\kappa^2 = \sigma_{\kappa^*}^2 = \sigma_{\kappa^w}^2 + \sigma_{\kappa^d}^2$. Equation (5), finally, implies that we can fully understand the ex ante welfare implications of policy rules by considering their effects on the expression

$$V \equiv Ec + \frac{(1-\rho)}{2}\sigma_c^2 = \omega - \frac{v}{2}\sigma_c^2 - \frac{\frac{v^2}{8}\sigma_e^2 + v\sigma_{\kappa^w c} + \frac{v}{2}\sigma_{\kappa^d e}}{v-(1-\rho)}. \tag{8}$$

Optimal policy rules take the form

$$m - Em = -\delta\kappa^d - \gamma(\kappa^w - E\kappa),\ m^* - Em^* = \delta^*\kappa^d - \gamma^*(\kappa^w - E\kappa).$$

These rules, combined with equations (6) and (7) above, allow us to express the world welfare criterion V defined by equation 8 in terms of the parameters δ, δ^*, γ, and γ^*. For example, the term σ_c^2 in V can be written as

$$\frac{1}{4}(\delta^*-\delta)^2\sigma_{\kappa^d}^2 + \frac{1}{4}(\gamma+\gamma^*)^2\sigma_{\kappa^w}^2.$$

By setting $\partial V/\partial\delta = 0$ (similarly for the other policy parameters) and solving, we find that the optimal policy rules entail

$$\delta = \delta^* = \frac{1}{v},\ \gamma = \gamma^* = \frac{1}{v-(1-\rho)}.$$

These monetary rules have an intuitive interpretation. As one can verify, they allow the global economy to attain the flexible-wage and price real resource allocation ex post, notwithstanding nominal price rigidities. A similar interpretation characterized optimal policies in the non-PTM, traded-nontraded goods model in Obstfeld and Rogoff (2000a).

In that paper, Rogoff and I worked through the properties of a number of possible exchange rate regimes, showing how to carry out exact welfare calculations and rankings. The paper showed that an "optimal float," in which countries commit to optimal monetary rules analogous to those just derived, dominates an "optimal fix," in which national money supplies are perfectly correlated but the world money supply responds optimally to the global shock κ^w. Of course, the latter regime dominates a "global monetarist" regime in which exchange rates are fixed and the world money supply is held constant in the face of the real shocks. All of those results extend directly to this section's model.

An alternative conceptual experiment considers an asymmetrical one-sided peg regime. Suppose that one of the countries (Home, say) can choose the monetary policy rule it prefers on nationalistic grounds while Foreign is required to peg its currency's exchange rate against Home's. One can show in that case that the center country, Home, will choose $\delta = 0$ and $\gamma = 1/[\nu - (1 - \rho)]$ as under an "optimal fix," while the passive country, Foreign, must likewise choose $\delta^* = 0$ and $\gamma^* = 1/[\nu - (1 - \rho)]$ in order to maintain a fixed exchange rate against Home. Global welfare thus is the same here as under an optimal cooperative fixed-rate regime. Why? Under one-sided pegging by Foreign, a Home monetary policy rule that responded in a contractionary fashion to κ^d would force Foreign to shrink its money supply when hit by favorable idiosyncratic real shocks. That would be harmful to Foreign, leading to a contractionary expected output response there that would reduce Home and Foreign ex ante consumption equally. As a result, it is in Home's self-interest (given Foreign's monetary behavior) to weight domestic and Foreign real shocks equally in its monetary policy response rule. This is not a general result. It need not hold, for example, when countries' expected welfare levels can differ as a result of a direct utility effect of the expected terms of trade, $E\tau$, as in my 2000a paper with Rogoff.

Other Applications

The class of model that I have just illustrated can reconcile the "old-time religion" of Mundell and Fleming with the evidence on international prices. But the range of applications goes much further. One of the most striking implications of the model is that uncertainty can affect the first moments of endogenous variables such as the terms of trade and consumption. For example, a rise in Home monetary variability raises the prospects that Home workers will be called on to supply unexpectedly high levels of labor when consumption is high and the desire for leisure greatest. That effect tends to raise domestic relative wages and lower worldwide consumption; see equations (4) and (5).

This natural incorporation of uncertainty under price rigidity suggests that we may finally be close to understanding, at an analytical level, some of the gains monetary unification confers by eliminating exchange rate uncertainty. Those gains are fundamental to the affirmative case for monetary union, as outlined so briefly in Mundell's (1961b) optimum currency area paper, yet progress in understanding them had been so slow that Krugman (1995) was led to identify progress in this area as the major challenge for international finance.

What form is the new research on stochastic dynamic Keynesian models taking? New developments have occurred on several fronts.

- We now have some rigorous general-equilibrium models allowing us to investigate the links between exchange-rate variability and international trade; see, for example, Bacchetta and van Wincoop (2000).
- We have the prospect of understanding the characteristics of the risk premiums in interest rates and forward exchange rates within dynamic Keynesian settings; see Obstfeld and Rogoff (1998) and Engel (1999b).
- We can begin to contemplate a full integration of classical international macroeconomic questions with issues of liquidity and financial constraints (see, e.g., Aghion, Bacchetta, and Banerjee, 2000).
- We can now reformulate the analysis of international policy coordination in terms of coordination on policy rules, a topic that has become quite important as institutional reform of monetary institutions has proceeded at the national level; see Obstfeld and Rogoff (2001).

IV. Conclusion

In this paper I have outlined major challenges facing international monetary analysis at the start of the postwar era, as well as some of the remarkable strides forward that have been made over the half century since the publication of Meade's (1951) landmark work, *The Balance of Payments.* I end on an upbeat note—I think we can now claim to have progressed far beyond the point where anyone can seriously argue that "It's all in Meade," or in Mundell and Fleming, for that matter. But I do not want to minimize, either, the work that remains to be done, both in the areas I have discussed in this paper and in others that I have not touched upon. Though there is much to learn still, I believe that the promising recent developments will promote continued growth in our understanding of international macroeconomic relations.

APPENDIX

Expected Utilities in the PTM-LCP Model

The text established that the first-order condition for nominal wage setting (by worker *i*) is

$$E\left\{\frac{C^{-\rho}}{P}(1-\phi)L(i)+\frac{\phi K L(i)^{\nu}}{W(i)}\right\}=0, \tag{9}$$

that the "retailers" set the nominal price of final consumption goods so that (for every retailer *j*)

$$P(j)=P=\left(\frac{\theta}{\theta-1}\right)\frac{E\left\{(1+\alpha)P_H^{1/2}P_F^{1/2}C^{1-\rho}\right\}}{E\left\{C^{1-\rho}\right\}}=\left(\frac{\theta}{\theta-1}\right)\frac{E\left\{(1+\alpha)\left(WW^{*}\right)^{1/2}\varepsilon^{1/2}C^{1-\rho}\right\}}{E\left\{C^{1-\rho}\right\}}, \tag{10}$$

and that $C = C^*$ always, where C is final consumption. For the Foreign price P^*, the last equality in equation 10 holds with the sole modification that $\varepsilon^{1/2}$ is replaced by $\varepsilon^{-1/2}$.

Using this information, one can evaluate

$$EU = E\left\{\frac{C^{1-\rho}}{1-\rho} - \frac{K}{v}L^{v}\right\},$$

from which it will follow that $EU = EU^*$. To do so, start by invoking the budget constraint,

$$PC = WL + \Pi = WL + \left[P - W^{\frac{1}{2}}\left(\varepsilon W^*\right)^{\frac{1}{2}}\right]C,$$

where Π (as before) denotes the profits of the domestic retailing firms (owned entirely by domestic residents). The preceding equation implies that

$$WL = W^{\frac{1}{2}}\left(\varepsilon W^*\right)^{\frac{1}{2}} C,$$

so that equation (9) becomes (after multiplying through by the predetermined wage and suppressing the i index)

$$\frac{1}{P}E\left\{W^{1/2}\left(\varepsilon W^*\right)^{1/2}C^{1-\rho}\right\} = \frac{\phi}{\phi-1}E\left\{KL^{v}\right\}.$$

(Remember that P is predetermined, too.)

The next step is to substitute equation 10 for P on the left-hand side above. The result is

$$\frac{E\left\{C^{1-\rho}\right\}E\left\{\varepsilon^{1/2}C^{1-\rho}\right\}}{E\left\{\varepsilon^{1/2}C^{1-\rho}\right\}} = E\left\{C^{1-\rho}\right\} = \frac{\phi\theta(1+\alpha)}{(\phi-1)(\theta-1)}E\left\{KL^{v}\right\}.$$

One now concludes that

$$\begin{aligned} EU &= E\left\{\frac{C^{1-\rho}}{1-\rho} - \frac{(\phi-1)(\theta-1)}{v\phi\theta(1+\alpha)}C^{1-\rho}\right\} \\ &= \frac{v\phi\theta(1+\alpha)-(1-\rho)(\phi-1)(\theta-1)}{v\phi\theta(1+\alpha)(1-\rho)}E\left\{C^{1-\rho}\right\} \\ &= \frac{v\phi\theta(1+\alpha)-(1-\rho)(\phi-1)(\theta-1)}{v\phi\theta(1+\alpha)(1-\rho)}\left\{\left(C^*\right)^{1-\rho}\right\} \\ &= EU^*, \end{aligned}$$

as claimed in Section III of this paper.

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