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THE LAW OF ONE PRICE, PURCHASING POWER PARITY AND EXCHANGE RATES: SETTING THE RECORD STRAIGHT

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THE LAW OF ONE PRICE, PURCHASING POWER PARITY AND EXCHANGE RATES: SETTING THE RECORD STRAIGHT*

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ABSTRACT

Exchange-rate economics is filled with puzzles. The asset approach has failed and without it most open-economy models are built on sand. Conventional wisdom rejects the Law of One Price and views Purchasing Power Parity as useful at best in the long run. We show for the first time how recognizing differences between retail, wholesale and auction markets, and recognizing that trade involves time in transit, helps solve the puzzles and provides a theory of exchange rates using auction markets for assets *and* commodities. We also restore the Law of One Price and Purchasing Power Parity to the status of "not rejected".

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1. Introduction.

With the caveat that it might be useful in the long run, conventional exchange-rate economics rejects Purchasing Power Parity. When applied to commodity markets, it also rejects the Law of One Price. We argue that those rejections are unwarranted because they use seriously flawed "semantic rules". After describing the flaws with those tests, we suggest appropriate tests and propose a theory of exchange rates using auction prices that combines an appropriate version of Purchasing Power Parity with Covered Interest Parity.

To clarify the discussion, we use the acronyms LOP and PPP to refer to the *theories* or ideas behind the Law of One Price and Purchasing Power Parity. CLOP and CPPP include the "semantic rules" that conventional tests use to make those theories operational. ALOP and APPP use the more appropriate semantic rules suggested here.

The paper is organized as follows: Section 2 discusses the role of semantic rules in testing theories including the LOP and PPP. Section 3 defines what we mean by the LOP and PPP. Section 4 critically reviews the conventional tests of the LOP and PPP and suggests more appropriate semantic rules. Combining CIP with APPP, Section 5 develops a new approach to the determination of spot exchange rates based on effective arbitrage in auction markets for assets and commodities. Section 6 describes how the ALOP and/or APPP help solve several puzzles in conventional open-economy macroeconomics. Section 7 provides a brief summary.

2. Semantic Rules.

We can have no more confidence in rejecting the LOP, PPP or any other theory than we have in the semantic rules used to test them.[1] *If* we accept the ideas behind the ALOP and APPP, then we should have no confidence in the semantic rules used to date to test the LOP and PPP. In that case, those tests are uninformative and the LOP and PPP should be restored to "not rejected".

The following illustrates the role of semantic rules in testing theories.[2] Let **a**→**b** stand for "if **a** then **b**". **a**→**b** denies that **a** is "true" and that **b** is not true, *i.e.*, n(**a**˄n**b**), which in turn implies that either **a** is not true *or* **b** is true, *i.e.* n**a**˅**b**. The relevant point is that **a**→**b** is "true" when **a** is "false" regardless of whether **b** is "true" or not "true".

Let **T** represent the LOP, PPP or any theory and **S** the corresponding semantic rules. To be empirically meaningful, some of the terms in **T** must be linked to things we can measure.

[1] The relevant literature uses different terms for "semantic rules" that mean essentially the same thing. For example Hempel (1966, 72-75) uses "bridge principles". See Winther (2016) for a survey of the relevant literature.

[2] Sarno (2005) is one of the few economists to recognize the crucial importance of the semantic rules connecting the theoretical term "price index" to something we can measure.

A Scholastic statement that 100 angels can fit on the head of a pin is an example of a statement that is not empirically meaningful because there is no way, even in principal, to measure the number of angels.

One way to express the logical structure involved in testing a theory is as follows: **T→ S→p→q** where **p→q** represents some testable implication of combining **T** and **S**. Note that rejecting the testable implications does *not,* by itself, reject **T**. If **S** is “false”, then **S**→(**p→q**) is “true” even when the evidence rejects (**p→q**). As a result, **T→ (S→p→q)** is “true” and the evidence does not reject **T**.

Theories constrain semantic rules. Take the law of gravity. Dropping a feather and an iron ball from the leaning tower of Pisa does not reject the law because it requires a vacuum. Dropping an iron ball on the moon where it does not accelerate at 32 feet per second does not reject the law of gravity because it depends on mass.

This paper says that we should have no confidence in the semantic rules used by the CLOP to date to reject the LOP, and the CPPP to reject PPP because they are inconsistent with the theories. As a result, the LOP and PPP should be restored to “not rejected”.

3. Definitions.

Definitions of the LOP and PPP in dictionaries, encyclopedias and Wikipedia usually include some semantic rules. The following definitions of the LOP and PPP are based on those definitions, but without any semantic rules.

3.1. LOP

The following is our definition for the LOP: “Arbitrage works to equate prices for the same good in different locations.” For examples of definitions like this one, see Sarno and Taylor (2002a, 52) and Black, Hashimzade and Myles (2012, 234). When we refer to the LOP we mean that theory or core idea.

3.2. PPP

There are several versions of PPP. The utility version for example says that $100 should buy the same amount of “utility” at home and abroad. But the version based on the LOP used here is by far the most common. It is the one found in most textbooks and articles as well as in extended discussions of exchange rates like Isard (1995) and Sarno and Taylor (2002a). If the LOP holds for every good, then the exchange rate must equal the “domestic price level” divided by the “foreign price level” where both “price levels” have the same weights.

Therefore, the following is our definition of PPP: “Arbitrage works to equate exchange rates with ratios of price levels for the two countries where both price levels have the same weights.”

Neither theory is operational. The next section considers the semantic rules used to make them operational, starting with CLOP.

4. Testing.

This section critically reviews how conventional exchange-rate economics has used inappropriate semantic rules to test the LOP and PPP. It also suggests more appropriate semantic rules. It begins with the CLOP.

4.1. CLOP.

This subsection describes the conventional approach to testing the LOP, what we call the CLOP. Ignoring thresholds, Rogoff (1996, 649) describes a conventional partially operational version of the LOP for commodity markets as follows: $P_i = EP^*$ where *E* is the domestic price of foreign exchange while P_i and P^* are prices for the same commodity in two different countries. It is clear from the context that E, P_i and P^* are spot prices.

As it stands, $P_i = EP^*$ is not operational. E, P_i and P^* are purely theoretical terms with no link to things we can observe. "Semantic rules" establish those links. The relevant conventional literature like Rogoff (1996) and the articles cited in the following paragraph link *E* to spot *auction* markets while linking P_i and P^* to spot *retail* markets.

The conventional view that the LOP fails rests largely on influential articles like Engel and Rogers (1996), Asplund and Friberg (2001), and Parsley and Wei (2001).[3] They all link P_i and P^* to current retail prices and *E* to a current auction exchange rate.

These conventional semantic rules seriously bias tests of the LOP and also help create most of the foreign-exchange puzzles discussed in Section 6.

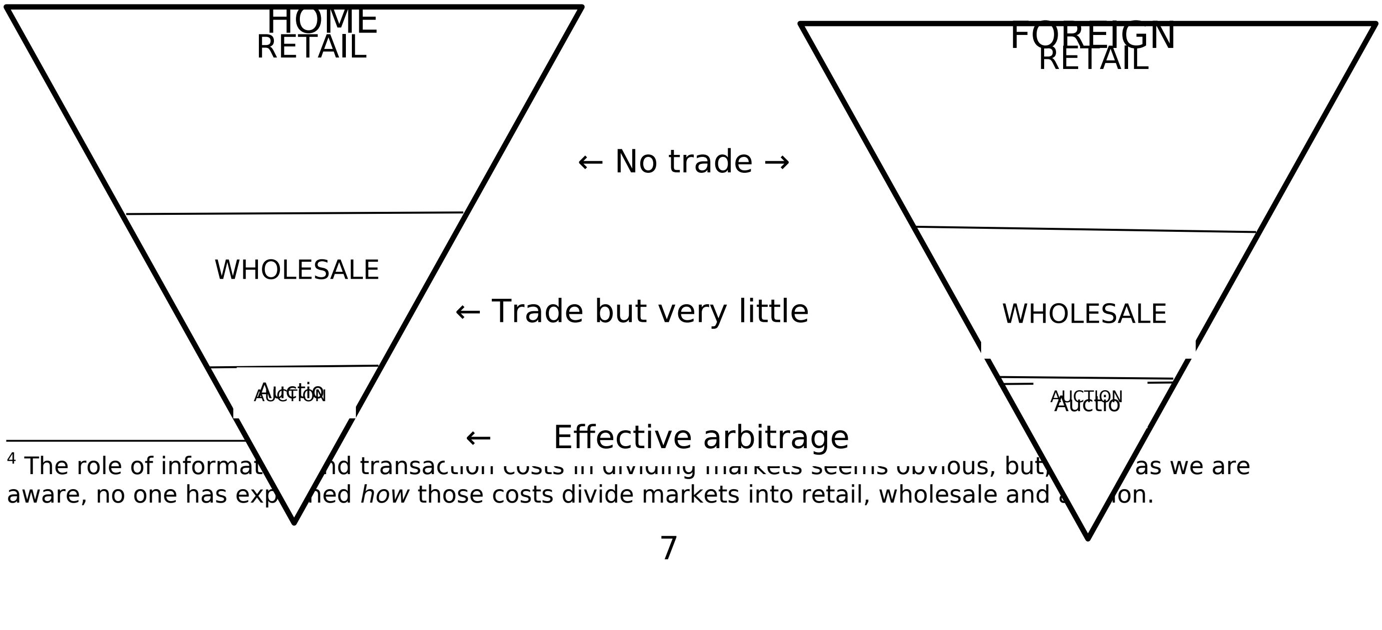
[3] Less widely cited research using spot auction prices and exchange rates provides more support for the LOP. It includes Goodwin (1992), Michael, Nobay and Peel (1994) and Pippenger (2016).

4.2. ALOP.

This subsection discusses the flaws in the conventional tests of the LOP and provides a better way to test the theory. We call it the auction and arbitrage version of the LOP, or ALOP.

The first serious flaw in conventional tests of the LOP like those by Engel and Rogers (1996), Asplund and Friberg (2001), and Parsley and Wei (2001) is that they ignore the difference between retail and auction markets.[4] Whether financial or commodity, there are three major types of markets: retail, wholesale and auction.

In retail commodity markets, bread is traded by the loaf, in wholesale markets by the truck load. In auction markets wheat is traded by the ship load. Whether financial or commodity, transaction and information costs per dollar traded are highest in retail where the quantity traded is lowest and lowest in auction markets where the quantity traded is highest. The relatively high costs in retail markets help explain the absence of trade and arbitrage in international retail markets illustrated in Figure 1.



[4] The role of information and transaction costs in dividing markets seems obvious, but, so far as we are aware, no one has explained *how* those costs divide markets into retail, wholesale and auction.

FIGURE 1
Arbitrage and Trade

Conventional tests of the LOP use commodity prices from retail markets, but there is no arbitrage or even trade between retail markets.[5] No one buys shoes from Macy's in New York and then sells them to Marshall Fields in Chicago. Someone from Chicago might buy shoes in London, Paris or New York and take them home, but that is hardly "trade".

The absence of trade between retail markets does not mean that they are not linked. A firm producing shoes in Milan sells those shoes to retailers in Chicago, London, Paris and New York. Kansas farms produce wheat that is traded in auction markets and that is milled into the flour that bakeries in Chicago, London, Paris and New York use to bake bread. Retail markets are linked, but the links are weak, indirect and work slowly.

The second serious flaw is a direct result of the first. Conventional tests of the LOP mix retail commodity prices with auction exchange rates.[6] This mixture contributes to several of the puzzles in open-economy macroeconomics discussed in Section 6 because it affects conventional tests of PPP.

The third serious flaw in conventional tests of the LOP like those by Engel and Rogers (1996), Asplund and Friberg (2001), and Parsley and Wei (2001) is that they use current prices and exchange rates when commodity arbitrage involves time in transit. Time in transit implies that one cannot buy

[5] As far as we are aware, conventional tests of the LOP have never used wholesale commodity prices.
[6] The conventional LOP literature occasionally recognizes the potential problems created by mixing retail prices and auction exchange rates, but then largely ignores them.

a commodity in one location and *simultaneously* sell it in another location risk free as required by arbitrage.

To the best of our knowledge, Benninga and Protopapadakis (1988) were the first to point out the importance of time in transit for the LOP, but they concentrate on how it affects spot price differentials.[7] This paper argues that time in transit changes how we should think about the LOP itself. In commodity markets, the LOP applies to forward prices and exchange rates, not spot prices and exchange rates.

The logic behind the LOP applying to forward prices and exchange rates rather than spot is as follows: Ignoring thresholds and interest rates for simplicity, effective domestic arbitrage equates the spot and forward prices of *W* in Gulf Ports while effective international arbitrage equates the forward price in Rotterdam times the forward dollar price of the euro with the spot price in Gulf ports. With time in transit, effective arbitrage and the LOP therefore implies that $(\$/€)_{90}(€/W)_{90} = (\$/W)_{90}$ because it implies that $(\$/€)_{90}(€/W)_{90}$ and $(\$/W)_{90}$ both equal $(\$/W)_0$.

Similar arguments do not apply to spot rates because the dimension of one spot price always differs from the dimension of the forward price implied by international arbitrage. As an example, still ignoring thresholds and interest rates for simplicity, effective international arbitrage implies that $(\$/€)_{90}(€/W)_{90} = (\$/W)_0$ where both are in dollars, while effective domestic arbitrage in Rotterdam implies that $(€/W)_{90} = (€/W)_0$ where both are in euros.

[7] Coleman (2009a) and (2009b) develop more general models of how time in transit affects spot price differentials.

$(\$/W)_0$ does not equal $(€/W)_0$ because $(\$/€)_{90}(€/W)_{90}$ does not equal $(€/W)_{90}$. Adding interest rates and thresholds does not change the fact that $(\$/€)_{90}(€/W)_{90}$ is in dollars while $(€/W)_{90}$ is in euros.

Subsections 4.2.1 to 4.2.3 provide an example of how this works with interest rates and thresholds. *W* is a particular variety of wheat with specific protein content and specified values for all the other characteristics normally included in contracts to buy or sell *W* in an auction market. For simplicity, there is no implicit return to holding *W*. Firms like Bunge Ltd. and Cargill Inc. are as willing to hold a ton of *W* spot as to own a claim on that wheat in 90 days. Firms are also as willing to hold a claim on a ton of wheat in a Gulf port as in Rotterdam. Including such costs or returns would only complicate the thresholds discussed in Subsection 4.2.3.

4.2.1. Local intertemporal equilibrium. There is local intertemporal equilibrium when it is impossible to make risk-free profits by buying spot and selling forward or the opposite. Equilibrium also excludes losses. When combined with international intertemporal equilibrium, this local equilibrium produces tests of the LOP using *forward* prices and *forward* exchange rates from *auction* markets.

The United States is the home country. $(\$/W)_0$ is the spot price of W in U.S. Gulf ports and $(\$/W)_{90}$ is the 90-day forward price. $CC\$_{90}(\$/W)_{90}$ is the cost in future dollars of carrying *W* forward 90 days in Gulf ports. It is exogenous because *W* is only one of a wide variety of grains carried forward.

i is the 90-day interest rate in the U.S.   It is exogenous because the borrowing and lending associated with trade in *W* is a miniscule part of the relevant capital market. For simplicity, the discussion ignores the difference between bid and ask prices, and borrowing and lending rates. They would just complicate the thresholds discussed below.

Eq. (1) is one way to write local equilibrium.

$[(\$/W)_{90} – CC\$_{90}(\$/W)_{90}]/(1+ i) = (\$/W)_{0}$

(1)

After accounting for carrying costs, the present value of *W* carried forward equals the spot value of *W*.

If, starting in equilibrium, $(\$/W)_0$ falls, $(\$/W)_{90}$ rises, carrying costs fall or interest rates fall, there are "risk-free" profits.[8] $[(\$/W)_{90} – CC\$_{90}(\$/W)_{90}]/(1+i)$ is greater than $(\$/W)_0$. Arbitragers buy low and sell high. They borrow $W(\$/W)_0$ spot dollars, which they repay with $W(\$/W)_0(1+i)$ future dollars, and buy W spot. They sell *W* forward and carry it forward to meet their future commitment. $[(\$/W)_{90} – {}_0CC\$_{90}(\$/W)_{90}]/(1+ i) – (\$/W)_0$ is the risk-free profit. Spot purchases raise $(\$/W)_0$ and forward sales lower $(\$/W)_{90}$ until arbitrage restores equilibrium.

If, starting in equilibrium, $(\$/W)_0$ rises, $(\$/W)_{90}$ falls, carrying costs rise or interest rates rise, carrying *W* forward produces losses. $[(\$/W)_{90} – CC\$_{90}(\$/W)_{90}]/(1+ i)$ is less than $(\$/W)_0$. Arbitragers respond by selling high and buying low. They "borrow" spot W and sell it short, invest the proceeds

[8] This profit is free of any risk associated with uncertain prices, but it is not completely free of risk. There is always the risk that some contracting agent will default. From this point on we take this exception for granted and omit the "".

and buy forward.[9] Selling spot lowers $(\$/W)_0$ and buying forward raises $(\$/W)_{90}$, but it does not fully restore eq. (1) unless the cost of selling short is zero. Let εW represent the cost of borrowing W for 90 days over and above the interest rate. If ε is zero, as long as $[(\$/W)_{90} - {}_0CC\$_{90}(\$/W)_{90}] < (\$/W)_0(1+ i)$, arbitragers make a risk-free profit by selling spot and buying forward. If ε is positive, selling short produces a risk-free profit only as long as $[(\$/W)_{90} - {}_0CC\$_{90}(\$/W)_{90}] < (\$/W)_0(1+ i + \varepsilon)$.

For simplicity, the discussion beyond this point ignores ε because ε just complicates the thresholds discussed below. How well auction markets respond to such shocks and restore equilibrium is an empirical issue that needs to be addressed more fully. What follows assumes that eq. (1) holds.

Eq. (1) can be written as follows:

$(\$/W)_{90}[1 - {}_0CC\$_{90}] = (\$/W)_0(1+ i)$

(1') After accounting for the carrying costs, the future value of present wheat equals the future value of future wheat.

Similar transactions produce similar equilibria in Rotterdam. The notation for Rotterdam is as follows: $(€/W)_0$ is the spot euro price of W in Rotterdam and $(€/W)_{90}$ is the forward euro price of W in Rotterdam in 90 days. $CC€_{90}(€/W)_{90}$ is the cost in future euros of carrying W forward by 90 days in Rotterdam. It is exogenous for the same reason the carrying cost in Gulf ports is exogenous. i^* is the 90-day euro interest rate. It is exogenous for the same reason i is exogenous. Eq. (2) describes the relevant local equilibrium in Rotterdam.

[9] See Wikipedia for the details of selling short.

$(€/W)_{90}[1 – CC€_{90}] = (€/W)_0(1+ i^*)$

(2)

Full international equilibrium assumes local equilibrium.

4.2.2. International equilibrium. Comparative advantage drives trade. See Wikipedia for a discussion of comparative advantage. With exchange rates exogenous, the direction of trade for *W* depends on where, in the absence of trade, *W* is cheapest in a common currency.

Due to time in transit, where ever *W* is cheapest in the absence of trade, *direct arbitrage between spot commodity markets in different locations is impossible*, as is direct arbitrage between forward markets of the same maturity in different locations. But arbitrage is possible between *t* = x and t = y, as long as *y* is sufficiently greater than *x* to allow for time in transit.[10] In this example, *x* is zero and *y* is 90 days.

$(\$/€)_0$ is the spot dollar price of the euro and $(\$/€)_{90}$ is the 90-day forward price of the euro. $(€/\$)_0$ is the spot euro price of the dollar and $(€/\$)_{90}$ is the 90-day forward price of the dollar. For simplicity, the discussion ignores bid-ask spreads, $(\$/€)_0 = 1/(€/\$)_0$ and $(\$/€)_{90} = 1/(€/\$)_{90}$. Exchange rates are exogenous because the foreign exchange involved in trading *W* is only a minuscule part of the foreign exchange market.

$TC\$_{90}(€/W)_{90}(\$/€)_{90}$ is the cost in future dollars of shipping *W* from a Gulf port to Rotterdam while $TC€_{90}(\$/W)_{90}(€/\$)_{90}$ is the cost in future euros of

[10] Time in transit depends on transportation costs. Fast ships are more expensive per ton than slow ships. Airplanes are faster and more expensive than fast ships. The greater the profit, the smaller the required difference between x and y.

shipping *W* from Rotterdam to a Gulf port. They are exogenous because *W* is only one of many grains traded between Gulf ports and Rotterdam.[11]

Ignoring for a moment transport costs, carrying costs and interest rates, *W* flows from Gulf ports to Rotterdam when, *in the absence of trade*, *W* is cheaper in Gulf ports, *e.g.*, when $(\$/W)_{90}$ is less than $(\$/€)_{90}(€/W)_{90}$.[12] *W* flows from Rotterdam to Gulf ports when $(€/W)_{90}$ is less than $(€/\$)_{90}(\$/W)_{90}$, *i.e.*, when $(\$/W)_{90}$ is greater than $(\$/€)_{90}(€/W)_{90}$. Subsection 4.2.3 discusses the thresholds created by transport and carrying costs.

When Gulf ports have the price advantage, if *W* moves, it moves from Gulf ports to Rotterdam. In that case, one way to express equilibrium is that $(\$/€)_{90}(€/W)_{90}[1 – TC\$_{90}] = (\$/W)_0(1+ i)$. The future dollar value of spot *W* in a Gulf port equals the future dollar value of shipping *W* to Rotterdam, selling it forward there and selling those future euros forward at $(\$/€)_{90}$. Note that trade can continue from day to day in this equilibrium without any risk-free profits or avoidable losses. They become relevant when equilibria are violated.

If, starting in equilibrium yesterday, today $(\$/€)_{90}$ rises, $(€/W)_{90}$ rises, $(\$/W)_0$ falls, *i* falls or $TC\$_{90}$ falls, today there is an arbitrage profit because $(\$/€)_{90}(€/W)_{90}[1 – {}_0TC\$_{90}] > (\$/W)_0(1+i)$. Arbitragers borrow $W(\$/W)_0$ spot dollars which they repay with $W(\$/W)_0(1+i)$ future dollars, buy *W* spot in a

[11] Coleman (2009a) describes a *spot* domestic model with storage in which transport costs are endogenous.

[12] Trade equates *observed* prices. In the absence of all impediments to trade, observed $(\$/W)_{90}$ would equal observed $(\$/€)_{90}(€/W)_{90}$ which-ever way *W* is moving. Observed price differentials are the result of impediments. Larger observed differentials do not necessarily increase the volume of trade, they can reduce trade. Other things equal, larger impediments increase *observed* differentials and *reduce* trade.

Gulf port, ship it to Rotterdam where they sell it forward for W$(€/W)_{90}$ and sell those forward euros for forward dollars. They do all this as closely to simultaneously as possible. Purchases raise $(\$/W)_0$ and sales reduce $(€/W)_{90}$, restoring equilibrium.

If, starting in equilibrium yesterday, today $(\$/€)_{90}$ falls, $(€/W)_{90}$ falls, $(\$/W)_0$ rises, i rises, or $TC\$_{90}$ rises, then $(\$/€)_{90}(€/W)_{90}[1 - TC\$_{90}] < (\$/W)_0(1+i)$. If these changes are large enough, Gulf ports may lose their advantage and W moves from Rotterdam to Gulf ports, lowering $(\$/W)_0$ by lowering $(\$/W)_{90}$ and raising $(€/W)_{90}$.

If the shock does not shift the advantage to Rotterdam, but reduces the Gulf port advantage so that it no longer covers the net transaction costs, trade stops. $(€/W)_{90}$ rises as imports stop and $(\$/W)_0$ falls as exports stop, but this absence of trade does not necessarily restore equilibrium. The discussion of thresholds in Subsection 4.2.3 describes what happens in that case.

If Gulf ports retain the price advantage and trade continues, arbitragers sell spot W short in Gulf ports and buy W forward in whichever forward market is cheapest. With ε the cost of selling W short, arbitrage restores equilibrium up to the point where $(\$/W)_{90}(€/W)_{90}[1–{}_0TC\$_{90}] = (\$/W)_{90}[1–{}_0CC\$_{90}] = (\$/W)_0(1+i+\varepsilon)$. For simplicity, the discussion below ignores ε, which just complicates the thresholds.

Full international equilibrium requires local equilibrium. Using the equilibrium condition in Gulf ports that $(\$/W)_{90}[1–{}_0CC\$_{90}] = (\$/W)_0(1+i)$, international equilibrium with trade from Gulf ports to Rotterdam can be written as follows: $(\$/€)_{90}(€/W)_{90}[1–TC\$] = (\$/W)_{90}[1–CC\$]$. Solving that equation for $[(\$/W)_{90}/(€/W)_{90}]$ yields eq. (3).

$$[(\$/W)_{90}/(€/W)_{90}] = [(\$/€)_{90}(1–TC\$)]/[1–CC\$]$$

(3) Exogenous exchange rates, transport costs and carrying costs determine relative prices in equilibrium.

Using the approximation that *log(1+a)* equals *a* when *a* is small, eq. (3) can be written in logarithmic form as eq. (3’).

$$\log[(\$/W)_{90}/(€/W)_{90}] = \log(\$/€)_{90} – [TC\$–CC\$]$$

(3’)

Transactions similar to those discussed above produce equilibria for buying in Rotterdam and selling in Gulf ports: $(€/\$)_{90}(\$/W)_{90}[1–TC€] = (€/W)_0(1+i^*)$.

Using the local Rotterdam equilibrium that $(€/W)_{90}[1–CC€] = (€/W)_0(1+i^*)$, the international equilibrium that $(€/\$)_{90}(\$/W)_{90}[1–TC€] = (€/W)_0(1+i^*)$ can be written as eq. (4).

$$(\$/W)_{90}/(€/W)_{90}= [1–CC€]/\{(€/\$)_{90}[1–TC€]\} = \{(\$/€)_{90}[1–CC€]\}/[1–TC€]$$

(4) In equilibrium, exogenous exchange rates, transport costs and carrying costs determine $(\$/W)_{90}/(€/W)_{90}$.

Using logarithms, eq. (4) can be written as eq. (4’).

$$\log[(\$/W)_{90}/(€/W)_{90}] = \log(\$/€)_{90} + [TC€ –CC€]$$

(4’)

Eqs. (3’) and (4’) differ by [TC$ – CC$] and [TC€ –CC€], the thresholds.

4.2.3. Thresholds. To see how transaction costs create thresholds, consider first a world without transport costs, carrying costs or interest rates, but with a given exchange rate. Let $(\$/€)_{90}$ be that rate. For $(\$/W)_{90}/(€/W)_{90}$ $< (\$/€)_{90}$ *in the absence of trade*, Gulf ports export to Rotterdam because in dollars *W* is cheaper in Gulf ports.

As $(€/W)_{90}$ in the absence of trade falls or $(\$/€)_{90}$ in the absence of trade rises, that advantage declines until it reaches a point where $(\$/W)_{90}/(€/W)_{90} = (\$/€)_{90}$. Trade stops. Call that $(\$/W)_{90}/(€/W)_{90}$ tipping point *T*.

As $(\$/W)_{90}/(€/W)_{90}$ in the absence of trade rises beyond *T*, the advantage switches to Rotterdam because the dollar price of *W* in the absence of trade is now lower in Rotterdam than in Gulf ports.

Now consider the effect of just transport costs. For a range of $\$/€)_{90}(€/W)_{90}$ below *T*, transport costs prevent Gulf ports from exporting to Rotterdam. Call that tipping point *L* where L = T(1–TC\$). For Rotterdam to export to Gulf ports, Rotterdam's advantage must cover its transport costs. Call that higher tipping point *U* where U = T(1+TC€).

Ignoring carrying costs, *U* is the upper threshold and *L* is the lower threshold. Between those thresholds the equilibrium conditions developed above do not hold. As a result, $(\$/W)_{90}/(€/W)_{90}$ can move more or less freely between *U* and *L*. Including carrying costs changes *U* and *L*, but it does not change the logic behind thresholds.[13]

[13] When there are carrying costs, log(L) = log(T) – $[{}_0TC\$_{90} - {}_0CC\$_{90}]$ and Log(U) = log(T) + $[{}_0TC€_{90} - {}_0CC€_{90}]$.

This section describes carrying and transport costs so that they create log linear thresholds, but that simplification hides some of the complexity of the thresholds. The Appendix uses more "realistic" carrying and transport costs.

The primary objective of Sections 4.2.1 to 4.2.3 is to make it clear that, with time in transit, the LOP holds for forward prices and exchange rates, not spot prices and exchange rates.

Exchange rates, interest rates and carrying costs are exogenous here for simplicity. As the number of goods traded increases as in PPP, they become endogenous.

4.4. PPP.

Most conventional tests of Purchasing Power Parity assume, implicitly or explicitly, that they are testing the arbitrage version adopted here that depends on an effective Law of One Price, and, therefore, on effective arbitrage.

4.4.1. CPPP. Using the CLOP as a foundation, Rogoff (1996, 650) describes conventional absolute PPP as follows: $P_i = EP^*$, or $E = P_i/P^*$, where these sums are *over consumer price indexes*.[14] The explicit semantic rule for "price" in Rogoff (1996) is that it is a consumer, i.e., a retail, price.[15] As with the CLOP, the implicit semantic rule for *E* is that it is an asset price, *i.e.*, an

[14] Officer (1976) does something similar.

[15] A few CPPP use retail and wholesale prices. See for example Kim (1990), Kouretas (1997) and Kargbo (2009). The evidence is not totally one sided, but the weight of evidence favors wholesale prices. While providing more support for long-run PPP, wholesale prices still reject short-run PPP. For simplicity, the following discussion of CPPP ignores wholesale prices because they produce results similar to retail prices and the vast majority of CPPP tests use retail prices.

auction price. It is clear that these are *current* prices. Following conventional views, Rogoff rejects absolute PPP in favor of the relative version.

Like most of the literature, Rogoff skims over the changes necessary to shift from testing the Law of One Price to testing Purchasing Power Parity. With the Law of One Price, exchange rates and the relevant transaction costs are often treated, implicitly or explicitly, as exogenous. With Purchasing Power Parity, they become endogenous. The shift from exogenous to endogenous is the same for CPPP and APPP, but it needs to be examined more closely.

4.4.2. APPP. This subsection discusses the flaws in the conventional tests of PPP, which are the same as for CPPP and suggests a better way to test Purchasing Power Parity. We call that better way the auction and arbitrage version of PPP, or APPP.

The first flaw in CPPP tests of the PPP is that they use retail commodity prices where there is no trade and arbitrage is not possible. Whatever CPPP tests test, it is not the PPP based on the LOP because the LOP is based on arbitrage and arbitrage is impossible between retail markets.

The second flaw is that CPPP tests mix retail commodity prices with auction exchange rates. This mixture causes most of the open-economy puzzles discussed in Section 6.

The third flaw is that CPPP use spot prices to test PPP when time in transit implies that the LOP, which is the basis for PPP here, does not apply to spot prices. Whatever CPPP tests test, it is not the PPP based on the LOP because the LOP is based on arbitrage and arbitrage, which requires "simultaneous" purchases and sales, is not possible between spot commodity markets.

APPP implies a different way of testing PPP. Ignoring thresholds, let $\Pi(t+y)$ denote a domestic basket of forward auction prices at t for $t+y$ where the interval between t and y is large enough to cover time in transit. In Section 4.2.2, $(\$/W)_{90}$ is such a price. Let $\Pi^*(t+y)$ denote a foreign basket of forward auction prices at t for $t+y$ with the same weights as $\Pi(t+y)$. In Section 4.2.2, $(€/W)_{90}$ is such a price. Let $F(t+y)$ denote the forward exchange rate at t for $t+y$. In Section 4.2.2, $(\$/€)_{90}$ is such an exchange rate.

Eq. (5) describes APPP:

$$F(t+y) = \Pi(t+y)/\Pi^*(t+y) \qquad (5)$$

where the exchange rate and commodity prices are all auction prices. Unlike CPPP, there is no reason to dismiss even short-run absolute APPP out of hand.

There are far fewer auction commodity prices than retail commodity prices, but there are probably more auction commodity prices than most economists realize. In addition, unlike retail prices that are "sticky", auction commodity prices like auction exchange rates are, to a reasonable first approximation, martingales. Table 1 provides a sample of such prices and a simple test for white noise for first differences in logs.

TABLE 1
Auction Prices*

Weekly Energy Prices: Source EIA[w]

Port	Diesel Fuel No. 2	D/W	$-^2$	Interval
New York	$\Delta P(t) = 0.004 - 0.185\Delta P(t-1)$ (0.308) (0.828)	1.97	0.000	1-7-2004 to 12-27-2006
U.S. Gulf	$\Delta P(t) = 0.004 + 0.008\Delta P(t-1)$ (0.392) (0.94)	1.99	0.000	1-7-2004 to 12-27-2006
Los Angeles	$\Delta P(t) = 0.004 + 0.099\Delta P(t-1)$ (0.415) (0.278)	1.96	0.003	1-7-2004 to 12-27-2006
Port	**Fuel Oil**			**Interval**
New York	$\Delta P(t) = 0.002 + 0.073\Delta P(t-1)$ (0.598) (0.528)	1.95	0.000	1-7-2004 to 12-27-2006
U.S. Gulf	$\Delta P(t) = 0.003 + 0.113\Delta P(t-1)$ (0.479) (0.316)	2.01	0.017	1-7-2004 to 12-27-2006
Los Angeles	$\Delta P(t) = 0.002 + 0.212\Delta P(t-1)$ (0.524) (0.014)	1.93	0.037	1-7-2004 to 12-27-2006
Rotterdam	$\Delta P(t) = 0.004 - 0.056\Delta P(t-1)$ (0.325) (0.524)	1.97	0.000	1-7-2004 to 12-27-2006
Singapore	$\Delta P(t) = 0.004 - 0.143\Delta P(t-1)$ (0.156) (0.124)	1.97	0.014	1-7-2004 to 12-27-2006
Port	**Jet Fuel**			**Interval**
New York	$\Delta P(t) = 0.004 + 0.031\Delta P(t-1)$ (0.353) (0.739)	1.96	0.000	1-7-2004 to 12-27-2006
U.S. Gulf	$\Delta P(t) = 0.004 + 0.103\Delta P(t-1)$ (0.444) (0.300)	1.95	0.004	1-7-2004 to 12-27-2006
Los Angeles	$\Delta P(t) = 0.004 + 0.000\Delta P(t-1)$ (0.379) (0.998)	2.00	0.000	1-7-2004 to 12-27-2006
Rotterdam	$\Delta P(t) = 0.004 + 0.014\Delta P(t-1)$			1-7-2004 to 12-27-2006

(0.236) (0.865) 1.99 0.000

Singapore $\Delta P(t) = 0.004 + 0.030\Delta P(t\text{-}1)$ 1-7-2004 to 12-27-2006

(0.278) (0.764) 1.99 0.000

Port Regular Gasoline Interval

New York $\Delta P(t) = 0.004 - 0.182\Delta P(t\text{-}1)$ 1-7-2004 to 12-27-2006

(0.503) (0.310) 2.02 0.026

U.S. Gulf $\Delta P(t) = 0.004 - 0.112\Delta P(t\text{-}1)$ 1-7-2004 to 12-27-2006

(0.565) (0.470) 2.04 0.006

Los Angeles $\Delta P(t) = 0.004 - 0.099\Delta P(t\text{-}1)$ 1-7-2004 to 12-27-2006

(0.467) (0.455) 2.00 0.003

Rotterdam $\Delta P(t) = 0.004 - 0.036\Delta P(t\text{-}1)$ 1-7-2004 to 12-27-2006

(0.393) (0.690) 1.99 0.000

Singapore $\Delta P(t) = 0.003 + 0.016\Delta P(t\text{-}1)$ 1-7-2004 to 12-27-2006

(0.486) (0.813) 2.01 0.000

Weekly Metal Prices: Source USAGold[M]

Commodity D/W -^{2} Interval

Silver $\Delta P(t) = 0.002 - 0.054\Delta P(t\text{-}1)$ 10-2-2017 to 9-28-2020

(0.580) (0.742) 1.99 0.000

Tin $\Delta P(t) = -0.001 + 0.037\Delta P(t\text{-}1)$ D/W -^{2} 10-2-2017 to 9-28-2020

(0.570) (0.660) 1.95 0.000

Zinc $\Delta P(t) = -0.002 - 0.072\Delta P(t\text{-}1)$ 10-2-2017 to 9-28-2020

(0.428) (0.353) 1.97 0.000

Weekly Grain and Soybean Prices: Source USDA[W]

Port Corn D/W -^{2} Interval

U.S. Gulf $\Delta P(t) = 0.000 - 0.267\Delta P(t\text{-}1)$ 12-6-2018 to 9-30-2020

(0.923) (0.109) 1.98 0.060

Port Soybeans Interval

U.S. Gulf $\Delta P(t) = 0.002 - 0.196\Delta P(t\text{-}1)$ 12-6-2018 to 9-30-2020

(0.410) (0.096) 2.02 0.028

Port Soft Red Winter Wheat Interval

U.S. Gulf	$\Delta P(t) = 0.001 - 0.256\Delta P(t\text{-}1)$			12-6-2018 to 9-30-2020
	(0.897) (0.066)	1.98	0.054	

Port	Dark Norther Spring Wheat			Interval
U.S. Gulf	$\Delta P(t) = -0.002 - 0.031\Delta P(t\text{-}1)$			12-6-2018 to 9-30-2020
	(0.555) (0.751)	1.97	0.000	

Other Weekly Agricultural Products: Source USAGold[M]

Commodity		D/W	$-^2$	Interval
Coffee	$\Delta P(t) = -0.001 - 0.031\Delta P(t\text{-}1)$			10-2-2017 to 9-28-2020
	(0.805) (0.649)	1.99	0.000	
Cotton	$\Delta P(t) = -0.001 - 0.044\Delta P(t\text{-}1)$			10-2-2017 to 9-28-2020
	(0.853) (0.572)	1.99	0.000	
Orange Juice	$\Delta P(t) = -0.003 - 0.071\Delta P(t\text{-}1)$			10-2-2017 to 9-28-2020
	(0.361) (0.317)	1.96	0.000	

* Significance in parentheses. [W] Wednesdays. [M] Mondays.

Using APPP, the next section develops an asset and commodity theory of exchange rates, *i.e.*, ACTFX. For ACTFX it is convenient to express APPP logarithmically as $$f(t + y) = \pi(t+y) - \pi^*(t+y).$$

5. ACTFX.

This section develops a theory of exchange rate determination based on arbitrage in *auction* markets for both *assets* and *commodities*. It begins with Covered Interest Parity where *i(t+y)* is the domestic interest rate at *t* with maturity *y* and *i*(t+y)* is the foreign interest rate at *t* with maturity *y*. In Section 4, *i* equaled *i(t+90)* and *i** equaled *i*(t+90)*.

5.1. CIP

There is substantial empirical support for CIP. See for example Akram, Farooq and Sarno (2008). CIP says that $F(t+y)/S(t) = [1+i(t+y)]/[1+i^*(t+y)]$, where $S(t)$ is the spot exchange rate and $F(t+y)$ is the forward rate at t for $t+y$ as in APPP above. CIP is usually expressed in a logarithmic approximation as $f(t+y) – s(t) = i(t+y) – i^*(t+y)$.

CIP is an example of the ALOP in financial markets where all prices are auction prices. Suppose $f(t+y)$ equals $s(t)$, but $i^*(t+y)$ is less than $i(t+y)$. Ignoring transaction costs, there are risk-free profits. Large money market banks borrow a million euro at $i^*(t+y)$, use that million euro to buy a million dollars, invest that million dollars at the higher $i(t+y)$ and sell those dollars forward for euros, earning an almost instantaneous risk-free profit of €1,000,000.00[1+$i(t+y)$] minus €1,000,000.00[1+$i^*(t+y)$]. As Akram, Farooq and Sarno (2008) point out, in financial auction markets opportunities for such profits do not last much longer than a few minutes.

After accounting for the different transaction costs and the fact that commodities require time in transit, we would expect arbitrage to be as effective in commodity markets as in financial markets. Why would traders in one market ignore risk-free profits that traders in another market do not?

The usual interpretation of CIP is that $i(t+y) – i^*(t+y) + s(t)$ determines $f(t+y)$. That interpretation is reasonable because the volume of transactions in spot foreign exchange markets is greater than in any individual forward market. But that interpretation is less convincing when we compare the combined volume of transactions in *all* forward markets to the volume in the spot market.

Eq. (5) is an aggregate version of CIP where each maturity is weighted by the relative volume of transactions in forward markets, w_y. As far as we are aware, no one has ever expressed CIP in this way before.

$$s(t) = w_y\{f(t+y) – [i(t+y) – i^*(t+y)]\} \quad (5)$$

5.2. APPP.

The next step to ACTFX adds the role of auction commodity markets where, ignoring thresholds, $f(t+y) = \pi(t+y) – \pi^*(t+y)$. Using APPP, replace $f(t+y)$ in eq. (5) with $\pi(t+y) – \pi^*(t+y)$. That replacement produces eq. (6), an ACTFX without thresholds.

$$s(t) = w_y\{\pi(t+y) – \pi^*(t+y) – [i(t+y) – i^*(t+y)]\} \quad (6)$$

ACTFX describes how the interaction between auction markets for financial assets, $i(t+y) – i^*(t+y)$, and auction markets for commodities, $\pi(t+y) - \pi^*(t+y)$, affects spot exchange rates through arbitrage. For APPP alone, *i.e.*, $w_y\ \pi(t+y) – \pi^*(t+y)$ alone, to determine spot exchange rates, $w_y[i(t+y) – i^*(t+y)]$ must be zero. For financial markets alone, i.e., $w_y[i(t+y) – i^*(t+y)]$, to determine spot exchange rates, $w_y\pi(t+y) – \pi^*(t+y)$ must be zero. That last condition can help explain why the asset approach to exchange rates fails.

Two advantages of eq. (6) are that it should hold for levels as well as changes because it does not use price indexes and that data should be available on a daily basis. There also is no reason to dismiss short-run ACTFX out of hand.

Eq. (6) is directly relevant only for those countries with appropriate auction markets. That requirement restricts it to developed countries and not to all developed countries. But the economics behind eq. (6) applies to all countries. At the retail level all goods are non-traded. Arbitrage is rare at the wholesale level and routine only in auction markets. In addition, trading commodities involves time in transit.

6. Puzzles.

In Rogoff (1996), *The Purchasing Power Parity Puzzle*, the puzzle is the very high short-run volatility of real exchange rates combined with the very slow rate at which the half-lives for deviations from Purchasing Power Parity die out. His explanation is that, in spite of progress, international commodity markets remain highly segmented. When Rogoff refers to international commodity markets being highly segmented, he means retail commodity markets.[16]

The earlier distinction between retail, wholesale and auction markets provides a better explanation. By their very nature, international *retail* markets are highly segmented and always will be because of their high

[16] At one point, p. 650, Rogoff indirectly refers to auction markets. The prices for gold in his Table 2 appear to be from auction markets. But he quickly dismisses such prices for PPP.

transaction costs. But international *auction* markets are highly integrated and have been for a long time.

In the years since 1996, the puzzles have increased and been refined. Rogoff's puzzle has become three related puzzles: "excessive" exchange rate volatility, short-run versus long run and long half-lives for deviations. Two additional puzzles are that Purchasing Power Parity appears to work during inflation, but not in normal times, and the lack of any fundamentals that explain the behavior of exchange rates.

The following subsections take up these puzzles in the following order: (1) Purchasing Power Parity works when there is inflation, but not in normal times, (2) It may work in the long run, but not in the short run, (3) Long half-lives for real Purchasing Power Parity differentials, (4) Exchange rate volatility is excessive, (5) A lack of fundamentals.

6.1. Inflation versus normal.

Frenkel (1981) is a seminal source of the idea that PPP works during inflation but fails in normal times. Using wholesale and cost of living price indexes, he compares the performance of Purchasing Power Parity during the inflationary 1920s to its performance during the "normal" 1970s. His results for wholesale and cost of living indexes are similar. He concludes that Purchasing Power Parity worked during the inflationary 1920s, but failed during the more normal 1970s.

Davutyan and Pippenger (1985) point out that his conclusion is a statistical illusion due to thresholds. A simple example makes their point.

Suppose CPPP is essentially constant and exchange rates never exceed the thresholds. CPPP always holds, but -^{2}*s* are close to zero and regression coefficients imprecise because within the wide thresholds there is no link between relative prices and exchange rates.

Now consider the case where CPPP and exchange rates both rise due to inflation and exchange rates often exceed the thresholds. CPPP often fails, but -^{2}*s* are much larger and coefficients more precise. In the presence of thresholds, regressions must be interpreted carefully.

This puzzle is primarily the result of mixing retail prices with auction exchange rates in the context of thresholds. In normal times CPPP volatility is small due to sticky retail prices and thresholds are very wide because at retail all goods are non-traded. Wholesale prices are less sticky and thresholds narrower, but empirically they do only slightly better in normal times.

As inflation increases, retail and wholesale prices become more flexible. Thresholds are less important. In hyperinflation those prices become very flexible and threshold effects largely disappear.

With auction prices, the difference between inflationary and normal times should largely disappear. With or without inflation, auction prices are very flexible and thresholds relatively narrow. The problem with -^{2} largely disappears and with it the apparent distinction between inflationary and normal times.[17]

6.2. Long run versus short run.

[17] This should be true even with spot auction prices.

The evidence clearly rejects relative CPPP for the short-run. But there is some support for it as a long-run theory. See for example Sarno and Taylor (2002b) and Taylor (2006).

The solution for this puzzle is essentially the same as for Inflation versus Normal. Replace “Inflation” with “long run” and “Normal” with “short run”. Relative CPPP fails in the short run because sticky retail prices, time in transit and very wide thresholds disconnect spot exchange rates from spot retail prices. Wholesale prices do a little better. In the long run, retail and wholesale prices become more flexible and thresholds narrower, producing more long-run support for PPP.

With forward auction prices, the difference between short run and long run should largely disappear. In both the short run and long run, auction prices are flexible and thresholds narrow because information and transaction costs per dollar are low.[18]

6.3. Long half-lives.

Obstfeld and Rogoff (2000) list long half-lives for real CPPP differentials as one of the six major puzzles in international macroeconomics. Wholesale prices reduce half-lives, but they remain long.

Again, the primary sources of the problem are sticky prices and wide thresholds combined with volatile exchange rates. Half-lives using CPPP are very long because most tests use prices from retail markets where all goods

[18] Without restrictions, appealing to information and transaction costs can explain anything, which means they explain nothing. Our position is simple. We assume that such costs behave like other costs. More precisely, they behave like the postulates on costs in Alchian (1959).

are non-traded. It should not be a surprise that real price differentials between *non-traded* goods have half-lives measured in years.

Half-lives using APPP should be much shorter. Auction prices are far more flexible and thresholds are much narrower because information and transaction costs per dollar are much smaller in auction markets where commodities are traded by the shipload rather than by the pound or ounce.[19]

APPP indexes do not yet exist. But comparing CLOP and ALOP provides some insight into what we can expect. As pointed out above, the evidence rejects CLOP. But the evidence supports ALOP. As Pippenger (2016) reports, real half-life differentials between commodity auction prices are measured in just a few weeks despite the fact that ALOP does not hold for spot auction markets.

6.4. Excessive volatility.

As is well known, the volatility of exchange rates is much larger than the volatility of corresponding CPPP. This difference in volatility is the primary evidence behind the belief that exchange-rate volatility is "excessive". Again, a major source of the problem is mixing sticky retail prices with volatile auction prices.

Exchange rates between the U.S. and Canada have been floating for over 25 years. As an example of "excessive" volatility with CPPP, using monthly data from 1975 through 2020, the variance of the change in the log of the Canadian price of U.S. dollars is 0.000226 while the variance in the

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[19] Comparing how using wholesale rather than retail prices would affect this puzzle and the next one would be an interesting dissertation topic.

change in the log of the corresponding CPPP using consumer price indexes is only 0.000018, a ratio of over 12 to 1.[20] Exchange rate volatility is 12 times greater than CPPP volatility.

The explanation for this puzzle is similar to the one for the three previous puzzles. Exchange rates are from auction markets while commodity prices are from retail markets. We are unaware of any articles comparing the volatility of relative wholesale price indexes to the volatility of exchange rates.

No one should be surprised to find that the volatility of the price of a common variety of wheat on the Chicago Board of Trade, whose price changes from minute to minute, is 12 times greater than the volatility of the price of bread in Chicago grocery stores, whose price often does not change for days. Why are we surprised by a ratio of 12 to 1 when we compare auction exchange rates to relative retail price levels?

We do not yet have data for APPP, but we do have data for individual auction commodity markets, which can give us some insight into APPP. At least it compares auction to auction. Using weekly data from spot auction markets, Bui and Pippenger (1990) find that the volatility of spot exchange rates implied by spot relative prices, *e.g.* $[(\$/W)_0 \backslash (€/W)_0]$, is slightly *greater* than the volatility of actual spot exchange rates.[21] Instead of 12 to 1, the ratio is about 1.

[20] All data are from FRED.
[21] Investigating this point would be an interesting dissertation topic, particularly if it could use forward prices and exchange rates.

Of course, their results apply to spot auction markets, not forward auction markets. In addition, they use individual auction prices, not indexes. But their results suggest that using APPP rather than CPPP would greatly reduce, if not eliminate, the primary evidence for excessive volatility.

6.5. Exchange-rate disconnect.

The exchange-rate disconnect refers to the lack of any clear link between exchange rates and economic fundamentals. It is one of the six major puzzles in Obstfeld and Rogoff (2000). ACTFX has the potential to solve this puzzle.

Casual observation suggests that relative price levels and financial markets are two important fundamentals. CPPP fails for the reasons discussed above. Why the asset approach to exchange rates fails is not yet obvious, possibly because it ignores relative price levels.

Using auction markets for assets *and* commodities, ACTFX combines relative commodity price levels and financial markets. It has the potential to resolve the exchange-rate disconnect by linking exchange rates to financial *and* commodity markets. Only careful research can determine whether or not that potential is realized. Even if it is realized, ACTFX will only be a bridge to a deeper understanding of the links between fundamentals and exchange rates.

Collecting the data necessary to compare the CLOP and CPPP to the ALOP and APPP will take time and be expensive. Is the game worth the candle? The ability of APPP and/or ACTFX to explain so many puzzles suggests that the game is worth the candle.

7. Summary and Conclusions.

Information and transaction costs play important roles in exchange-rate economics. They are the source of market imperfections, sticky prices and so called “non-traded” goods like haircuts. But conventional exchange-rate economics ignores another effect of such costs: the division of markets into retail, wholesale and auction. That division has at least two important implications: (1) At the retail level all goods, not just haircuts, are non-traded. As a result, the conventional rejection of the Law of One Price and Purchasing Power Parity, which is based primarily on retail prices, is unwarranted, (2) Comparing the behavior of sticky retail prices to the behavior of flexible auction exchange rates compares apples to oranges and it is the source of several puzzles in conventional exchange-rate economics discussed above.

Conventional exchange-rate economics also ignores the fact that, for commodities, international trade involves time in transit. Time in transit means that the Law of One Price and the most common version of Purchasing Power Parity, which is based on the LOP, cannot hold for spot commodities as is assumed in conventional tests of the LOP and PPP. As shown above, with effective arbitrage, the Law of One Price and Purchasing Power Parity hold for forward commodity prices and exchange rates from auction markets.

As a result of problems with the way conventional exchange-rate economics tests the LOP and PPP, this paper argues that the LOP and PPP should be reclassified as “not rejected” It also suggests a new way of thinking about the LOP and PPP based on time in transit and auction prices that we call ALOP and APPP. ALOP and APPP solve several of the puzzles associated with conventional exchange-rate economics.

Time in transit and the distinction between retail, wholesale and auction markets also suggest a theory of exchange rates that we develop here for the first time based effective arbitrage in auction markets for commodities *and* assets. We call it ACTFX. ACTFX provides a potential link between exchange rates and fundamentals, and a potential solid foundation for open-economy macro models.

Testing the relative merits of ALOP and APPP versus conventional LOP and PPP and comparing the relative merits of the asset approach to spot exchange rates versus ACTFX creates many opportunities for future research.

APPENDIX

In Section 4 $CC\$_{90}(\$/W)_{90}$ is the cost of storing *W* in Gulf ports and $CC€_{90}(€/W)_{90}$ is the cost of storing *W* in Rotterdam, the first in future \$ the second in future €. $TC\$_{90}(€/W)_{90}(\$/€)_{90}$ is the cost of shipping a unit of *W* from a Gulf port to Rotterdam and $TC€_{90}(\$/W)_{90}(€/\$)_{90}$ describes the cost of shipping a unit of *W* from Rotterdam to a Gulf port, the first in future \$ and the second in future €. These storage and transportation costs hide the complexity of the thresholds.

In this Appendix the cost of storing a unit of *W* in Gulf ports is $C\$_{90}$ and $C€_{90}$ is the cost of storing a unit of *W* in Rotterdam, the first in future \$ the second in future €. The cost of transport for a unit of *W* from Gulf ports to Rotterdam is $T\$_{90}$ and the cost from Rotterdam to Gulf ports is $T€_{90}$, the first in future \$ and the second in future €. As in Section 4, they are exogenous.

Gulf to Rotterdam.

Equilibria: $[(\$/W)_{90}–(C\$_{90})]=(\$/W)_0(1+ i)$ and $(€/W)_{90}(\$/€)_{90}–(T\$_{90})=(\$/W)_0(1+i)$

Therefore $[(\$/W)_{90}–(C\$_{90})]= (€/W)_{90}(\$/€)_{90}–(T\$_{90})$.

Rotterdam to Gulf.

Equilibria: $(€/W)_{90}–(C€_{90})=(€/W)_0(1+ i^*)$ and $(\$/W)_{90}(€/\$)_{90}–(T€_{90})=(€/W)_0(1+i^*)$.

Therefore $(€/W)_{90}–(C€_{90})=(\$/W)_{90}(€/\$)_{90}–(T€_{90})$.

Thresholds.

$(\$/W)_{90}/(€/W)_{90} = (\$/€)_{90} – [(T\$_{90}) – (C\$_{90})]/(€/W)_{90}$

$[(\$/W)_{90}/(€/W)_{90}] = (\$/€)_{90} + [(T€_{90})– (C€_{90})][(\$/€)_{90}/(€/W)_{90}]$

As in Section 4, in the absence of carrying and transportation costs, the exogenous exchange rate determines relative prices. As in Section 4, carrying and transportation costs create thresholds, but here prices and exchange rates explicitly affect thresholds.

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