Terms of Trade Gains and U.S. Productivity Growth*

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Abstract

Since 1995, growth in productivity in the United States appears to have accelerated dramatically. A large number of researchers have investigated this productivity performance, with the common conclusion that its primary cause has been accelerated productivity growth in the information technology (IT) sector. The main evidence favoring this conclusion is faster declines since 1995 of the prices for these IT goods. In this paper we investigate an alternative explanation for these IT price movements, and by implication for the apparent acceleration in U.S. productivity: gains in the U.S. terms of trade, especially for IT products. The global engagement of the IT sector deepened after 1995 with both the dollar appreciation in the Asian financial crisis and the move to global free trade via the WTO's Information Technology Agreement. We find that a superlative index of the terms of trade has improved by over 3% per year during 1997 – 1999, and that this can account for 0.1 – 0.2 percentage points annual growth in multifactor productivity for the aggregate U.S. economy.

* The views expressed in this paper are those of the authors, not those of the Bureau of Economic Analysis nor of the Bureau of Labor Statistics. Email: rcfeenstra@ucdavis.edu; Marshall.Reinsdorf@bea.gov; matthew.j.slaughter@dartmouth.edu Harper.Mike@bls.gov. Prepared for the NBER-CRIW conference, July 25, 2005. We draw heavily upon Alterman, Diewert and Feenstra (1999), and the authors are indebted to Bill Alterman and Erwin Diewert for that earlier study which we apply here to U.S. productivity growth. For financial support Feenstra and Slaughter thank the National Science Foundation.

1. Introduction

Since 1995, growth in aggregate labor productivity in the United States appears to have accelerated markedly. The U.S. Bureau of Labor Statistics (BLS) reports that from 1973 to 1995, output per worker hour in the nonfarm business sector grew on average at just 1.4 percent per year. From 1995 through 2004 this rate accelerated to an average of 3.1 percent per year.[1]

It is widely acknowledged that the rate of productivity growth is the single most important determinant of a country's overall economic performance. In his famous work on the previous generation's productivity slowdown, Krugman (1990, pp. 9-13) put it this way.

> Productivity isn't everything, but in the long run it is almost everything. A country's ability to improve its standard of living over time depends almost entirely on its ability to raise its output per worker … the essential arithmetic says that long-term growth in living standards … depends almost entirely on productivity growth … Compared with the problem of slow productivity growth, all our other long-term economic concerns—foreign competition, the industrial base, lagging technology, deteriorating infrastructure, and so on—are minor issues. Or more accurately, they matter only to the extent that they have an impact on our productivity growth.

This perspective on the centrality of productivity growth has also been endorsed by a number of policymakers, perhaps most prominently Federal Reserve Chairman Alan Greenspan.[2]

The sheer magnitude of the speed-up in U.S. productivity growth will, if sustained, carry dramatic implications for the U.S. economy. At the previous generation's average annual growth rate of 1.4 percent, average U.S. living standards were taking 50 years to double. Should the current average annual growth rate of 3.1 percent persist, then average U.S. living standards will take just 23 years to double—over a generation faster.

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[1] These calculations are based on BLS data series identification #PRS85006092, as reported on-line for historical data at www.bls.gov and, for recent years, in the June 2, 2005 Data Release, "Productivity and Costs: First Quarter 2005, Revised."

[2] In remarks before the Independent Community Bankers of America, Honolulu, Hawaii, March 13, 2002, Chairman Greenspan stated that, "the nation's fortunes, to a very great degree, depend on the evolution of the growth of productivity … It is structural productivity growth that determines how rapidly living standards rise over time. Productivity growth is an unmitigated good for the large majority of the American people.

This is one reason why studies of the sources of economic growth often focus on labor productivity. A common procedure is first to separate this productivity growth rate into contributions from increased capital intensity and from multifactor factor productivity growth (MFP), and then to study factors contributing to each of these, such as contributions of specific types of capital, contributions of changing work force composition, and contributions of MFP growth in specific industries. Many sources of growth may be identified, and although they may often seem small, a contribution of one or two tenths of a percent to the annual growth rate of labor productivity can be quite significant if sustained over a period of years.

In recent years a number of researchers have investigated the speed-up in US labor productivity growth, finding that has been accompanied by an acceleration of MFP.[3] Researchers also have been examining whether the acceleration has been broadly enjoyed across many industries or concentrated in certain sectors.[4] Much of this body of research has reached a common conclusion: the information-technology (IT) sector is at the core of the boom in aggregate productivity. The consensus from a range of academic studies is that about one-third of the acceleration in aggregate labor productivity has been accounted for by faster growth in MFP in the *production* of IT goods and services. About another third has accounted for by greater *use* of IT capital and services throughout the economy.

Quality-adjusted prices for many IT products have been falling for decades, but after 1995 many of these price declines accelerated. Faster IT price declines have been widely interpreted as evidence of faster MFP growth. Indeed, many studies use industry price changes as a proxy for industry MFP growth without fully considering the effects of price changes of

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[3] The BLS publishes measures of MFP for the private business sector. Using a new system to produce preliminary measures, the BLS found TFP grew 3.1 percent in 2003 and 3.3 percent in 2004, rates which were very high by historical standards and which account for much of the rapid labor productivity growth in those years. See Meyer and Harper (2005).

[4] Prominent studies include Baily and Lawrence (2001), Bosworth and Triplett (2000), Gordon (2000, 2003), Jorgenson (2001), Jorgenson and Stiroh (2000a,b), Nordhaus (2001, 2005), and Oliner and Sichel (2000, 2002).

inputs, particularly—as we shall see—of imported intermediate inputs.[5] These falling IT prices have also been identified as the link from IT-producing firms to IT-using firms. For example, Jorgenson (2001, p. 22) finds that, "In response to these [IT] price changes, firms, households, and governments have accumulated computers, software, and communications equipment much more rapidly than other forms of capital."

In this paper we investigate an alternative explanation for these IT price movements, and by implication for the apparent acceleration in overall U.S. labor productivity: gains in the U.S. terms of trade, especially for IT products. Theoretical results due to Diewert and Morrison (1986) and Kohli (1990, 2004) state that a rise in price of a nation's exports relative to its imports can affect its standard of living in a way that is observationally equivalent to faster MFP growth. Here we focus on potential mismeasurement of the U.S. import and export prices indexes, causing the terms of trade gains to be conflated with productivity growth. We are not the first to suggest that mismeasurement of the import or export price indexes would bias real GDP and therefore productivity growth. Hamada and Iwata (1984) noted that this may have occurred during the oil shocks of the 1970's, for example. But we know of no study that systematically investigates whether the accelerated decline in IT prices—and thus accelerated increase in productivity—may be due in part to international trade, not technology.[6]

Our analysis starts from the largely overlooked fact that IT is one of the most globally engaged sectors in the U.S. economy. IT firms have long been establishing global production

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[5] For example, Jorgenson (2001, p.22) argues that, "The Domar aggregation formula [for working with industry-level MFP growth] can be approximated by expressing the declines in prices of computers, communications equipment, and software relative to the price of gross domestic income, an aggregate of the prices of capital and labor services. The rates of relative IT price declines are weighted by ratios of the outputs of IT products to the GDP. Table 7 reports details of this MFP decomposition …" This line of analysis leads links directly to overall productivity growth: "The accelerated information technology price decline signals faster productivity growth in IT-producing industries. In fact, these industries have been the source of most of aggregate productivity growth throughout the 1990s" (p. 2). Similarly, Oliner and Sichel (2000, p. 17) state that, "In accord with the 'dual' framework described above, we have interpreted the sharp decline in semiconductor prices after 1995 as signaling a pickup in that sector's MFP growth."

networks via FDI and trade, such that now much of their output entails multiple production stages across multiple countries. Indeed, as will be documented below, in the 1990s, in the two key IT industries of computers and office equipment and electronic components (e.g., semiconductors) the United States began to run large trade *deficits* with the rest of the world. By 2000 this deficit exceeded $50 billion, or about 16 percent of the non-oil U.S. trade imbalance that year.

On many measures, the global engagement of U.S. IT firms deepened after 1995—precisely the period of accelerated price declines that have been interpreted as MFP. Two factors are especially notable. First, in the second half of the 1990s, IT was the only industry in the world that had a multilateral trade liberalization under the World Trade Organization. Ratified in 1997 by dozens of countries accounting for nearly 95 percent of world IT trade, the Information Technology Agreement (ITA) eliminated all world tariffs on hundreds of IT products in four stages from early 1997 through 2000. Second, what is now widely known as the Asian financial crisis started with the July 2, 1997 devaluation of the Thai baht. This crisis entailed large depreciations of the currencies of many countries that export IT products to the United States, and its effects were felt for many years.

This timing suggests that the ITA and the Asian financial crisis may have played an important role in the post-1995 trends in IT prices. It also suggests that previous estimates of productivity growth in IT-producing industries may have been overstated because of overlooked effects of price declines in imported intermediate inputs. In turn, such an overstatement would carry important implications for the understanding and sustainability of the recent acceleration in the growth of aggregate U.S. labor productivity and living standards.

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[6] Slaughter (2002) is the first study we are aware of to conjecture a link among globalization, IT prices, and productivity. Mann (2003) subsequently addresses these ideas as well.

The aim of this paper is to systematically explore this line of reasoning. We do so in several steps. First, in Section 2 we document the rising global engagement of the U.S. IT industry over the past generation. Section 3 lays out our accounting framework for productivity growth in an open economy. Section 4 applies this framework to our case of interest, recent U.S. terms of trade in IT products. Sections 5 and 6 use these findings to develop a range of calculations for the fraction of the recent acceleration in productivity growth – both in the aggregate economy and IT products – that should properly be attributed to gains from international trade. Section 7 concludes.

2. Globalization of the Information Technology Industry

2.1 Trade in U.S. Industries

To gauge the role of international trade in the production of IT goods and services, a sensible starting point is to present trade flows for some specific IT industries. Take, for example, computers and office equipment (SIC 357), and electronic components and accessories (SIC 367, which includes items such as semiconductors and circuit boards). These two industries represent some of the most high-profile IT sectors.

Table 1 reports current-dollar trade flows in these two industries for three years spanning most of the 1990s —1992, 1996, and 2000. The bottom of Table 1 also reports the share of economy-wide exports and imports flows accounted for by these two industries.[7] Over the 1990s exports in these industries have been rising faster than the national total, such that their share of that total rose from 10 percent to 14.2 percent. But a more striking feature is the even higher level of imports in these ICT industries. Over the 1990s their national import share ranged from 11.8 percent to 15.6 percent.

[7] Trade data for SIC industries comes from Bureau of the Census, 1992-2000, and for the total U.S. comes from the *Economic Report of the President*, 2004, Table B-104, where we use total exports of goods and total non-petroleum imports.

All this means that these two central IT industries are substantial net importers whose trade imbalance widened during the decade. Computers and office equipment shows a steadily increasing trade deficit throughout the 1990s, whereas the imbalance in electronic components peaked in the middle of the decade and was reduced thereafter, due to increased semiconductor exports. By 2000 the combined trade deficit in these IT industries was over $50 billion, or fully 16.2 of the non-oil U.S. trade deficit that year.

Table 2 offers some additional evidence on the trade intensity of IT industries, defined as trade flows as a share of output. For 1997, Table 2 shows exports, imports, and net exports, all as a share of output for two IT industries – computers and peripheral equipment, and semiconductors and electronic components. (These two IT industries differ somewhat from the SIC classifications used in Table 1.) The key message of Table 2 is that IT industries are much more trade intensive than the overall U.S. economy. In these industries both exports and imports as a share of output range between 19 and 38 percent. These measures of trade intensity are higher than manufacturing industries in general, for which exports and imports were just 14–21 percent of output. Taken together, Tables 1 and 2 indicate that many of the central IT industries in the United States are more trade-intensive than is the rest of the economy, and are substantial net importers.

Have these IT industries always displayed these trade patterns? Or are high trade intensities and trade deficits relatively new? Answers might offer some insight about the overall economic performance of these industries, which became particularly important during the 1990s. To offer a longer-term perspective on IT industries beyond just the 1990s, Figure 1 shows trade data from 1960 through 2000 for computers and office equipment (SIC 357). The data shown are the same as in Table 1: exports, imports, and trade balances, but now measured as a share of value-added.[8] In the 1960s and 1970s export intensity grew steadily with basically unchanged import intensity, such that overall the United States ran a positive and growing trade surplus with the rest of the world. By 1980, this industry's trade surplus peaked at about 25 percent of value added. Shortly thereafter import intensity began surging rapidly, far outpacing continued growth in export intensity. By the late 1980s the trade surplus had disappeared, and by 2000 imports and the trade deficit in this industry both reached 100 percent of the industry's value-added.

There is now substantial evidence that the post-1980 changes in Figure 1 reflect the creation and spread of global production networks (for an overview of such networks, see Feenstra, 1998). For example, in the early 1980s the first personal computers were produced predominantly in the United States—such as in facilities on Sand Hill Road in Silicon Valley. But computer firms soon realized the cost savings possible by spreading different activities around the world (e.g., see the comprehensive account for hard-disk drives in McKendrick, Doner, and Haggard, 2000). Many companies ended up retaining in the United States just the skill-, technology-, and capital-intensive activities, with all else performed around the world via both arm's-length and in-house networks. As an telling example, consider the fact that by 2003, Dell, Inc. reported that of its $35 billion in global revenue, only about 10% was accounted for by Dell's own value-added. **[Rob/Matt: can you insert a citation to a source here?]**

2.1 Globalization during the 1990s

In 1997, two events in the global economy further encouraged the globalization of the IT industry. First, under the auspices of the World Trade Organization, an Information Technology Agreement (ITA) committed signatory countries to eliminate all tariffs on a wide range of nearly 200 ICT products. These products covered both finished and intermediate goods including

[8] Trade and value-added data for these industries come from the National Bureau of Economic Research (2001).

computers and networking and peripheral equipment; circuit boards and other passive/active components; semiconductors and their manufacturing equipment; software products and media; and telecommunications equipment.

The original Ministerial Declaration on Trade in Information Technology Products was concluded in December 1996 at the first WTO Ministerial in Singapore. This declaration stipulated that for the ITA to take effect, signatory countries would have to collectively represent at least 90 percent of world trade in the covered products. The 29 original signatories accounted for only about 83 percent of covered trade. But by April 1997 many more countries had signed on to push the share over 90 percent, and the agreement entered into force in July 1997. Ultimately there were more than 50 ITA signatories that accounted for more than 95 percent of world trade in the covered ITA products.

All ITA signatories agreed to reduce to zero their tariffs for all covered ITA products in four equal-rate reductions starting in 1997 and ending no later than the start of 2000. Some developing countries were granted permission to extend rate cuts beyond 2000, but no later than 2005. Also, an ITA Review Committee was established to monitor compliance. The overarching goal of the ITA was to eliminate world tariffs in a wide range of IT products. Thanks to the number and commitment of signatory countries, it has virtually achieved that goal.

A second event leading to increased global sourcing was the devaluation of currencies following the Asian financial crisis, which started with the July 2, 1997 devaluation of the Thai baht. As the crisis spread, the currencies of other Asian countries were sharply devalued, including Indonesia, Malaysia, Korea, Taiwan, Singapore and the Philippines. Many of the countries with large depreciations of their currencies supplied substantial amounts of IT products to the United

States, thereby lowering their prices and contributing to a terms of trade gain for the United States, as we shall document in section 4.

3. Measurement of Productivity Growth

3.1 Approach based on the GDPFunction with a Translog Specification

In this section we review results from Diewert and Morrison (1986) regarding the measurement of real GDP and productivity growth. We work with a GDP function for an economy, though our results can also be applied to a sector of the economy, to an industry, or even to an individual firm. In either case, we suppose that imports are composed entirely of intermediate inputs purchased by the industry or economy. Our goal is to show how changes in the terms of trade are incorporated into productivity growth, and more specifically, how any measurement errors in the terms of trade are reflected in productivity growth.

Let $p = (p_1,\ldots p_N)$ denote a positive vector of output prices that producers face in period t and $q = (q_1,\ldots q_N)$ denote their output choices. Then the *revenue or GDP function* using period t technology is defined as:

$$G^t(p,v) \equiv \max_q \{ p'q \;\; : \;\; (q,v) \in S^t \}, \tag{1}$$

where S^t is a closed, convex technology set. Thus, $G^t(p,v)$ is the maximum value of output that the economy can produce, given the vector of endowments v and using the period t technology. We allow some of the net outputs q_i to be *negative*, meaning that they are actually *imported intermediate inputs*. In cases where a commodity i is used only for final consumption, q_i contains only the domestic production of commodity i; imports of commodities for final consumption have no role in the GDP function.

The goal of productivity analysis is to measure the change in the GDP function over time, holding fixed both prices and endowments. To this end, we follow Diewert and Morrison (1986) and define the *theoretical productivity index*:

$$R(p,v) = G^1(p,v)/ G^0(p,v) . \qquad (2)$$

To implement this index we need to choose particular values of the fixed prices and factor endowments fixed. We are interested in two special cases: (a) the Laspeyres-perspective productivity index, $R_L \equiv R(p^0,v^0) = G^1(p^0,v^0)/ G^0(p^0,v^0)$, which uses prices and endowments from period 0; (b) the Paasche-perspective productivity index, $R_P \equiv R(p^1,v^1) = G^1(p^1,v^1)/ G^0(p^1,v^1)$, which uses prices and endowments from period 1.

Both the Laspeyres-perspective and Paasche-perspective productivity indexes are in principal unobservable, because the former uses the hypothetical GDP $G^1(p^0,v^0)$ and the latter uses the hypothetical GDP $G^0(p^1,v^1)$. But Diewert and Morrison (1986) have identified conditions under which the geometric mean of these indexes can in fact be measured.[9] Their results are obtained by using the translog form for the GDP function, where we allow some of its parameters to vary over time due to technological change:

$$\begin{aligned}\ln G^t(p,v) = \alpha_0^t + \sum_{i=1}^{N}\alpha_i^t \ln p_i + \sum_{k=1}^{M}\beta_k^t \ln v_k + \tfrac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N}\gamma_{ij}\ln p_i \ln p_j \\ + \tfrac{1}{2}\sum_{k=1}^{M}\sum_{\ell=1}^{M}\delta_{k\ell}\ln v_k \ln v_\ell + \sum_{i=1}^{N}\sum_{k=1}^{M}\phi_{ik}\ln p_i \ln v_k .\end{aligned} \qquad (3)$$

In order to ensure that the translog GDP function is homogeneous of degree one in prices, we impose symmetry $\gamma_{ij} = \gamma_{ji}$ and the requirements,

[9] See also Kohli (1990; 2004), and Fox and Kohli (1998).

$$\sum_{i=1}^{N}\alpha_i^t = 1 \text{ and } \sum_{i=1}^{N}\gamma_{ij} = \sum_{i=1}^{N}\phi_{ik} = 0\,. \qquad (4)$$

In addition, to ensure that the GDP function is homogeneous of degree one in endowments, we impose symmetry $\delta_{k\ell} = \delta_{\ell k}$ and the requirements,

$$\sum_{k=1}^{M}\beta_k^t = 1 \text{ and } \sum_{k=1}^{M}\delta_{k\ell} = \sum_{k=1}^{M}\phi_{ik} = 0. \qquad (5)$$

Then the following result can be obtained:

Theorem (Diewert and Morrison, 1986)

Assuming that the GDP function takes on the translog form and the observed quantities q^t solve problem (1), then:

$$(R_L\, R_P)^{1/2} = \left(\frac{p^{1\prime}q^1}{p^{0\prime}q^0}\right) / \,[P_T(p^0,p^1,q^0,q^1)\; Q_T(w^0,w^1,v^0,v^1)]\,, \qquad (6)$$

where $P_T(p^0,p^1,q^0,q^1)$ is a Törnqvist price index of GDP,

$$\ln P_T(p^0,p^1,q^0,q^1) = \sum_{i=1}^{N}\left(\frac{1}{2}\right)\left(\frac{p_i^0 q_i^0}{p^{0\prime}q^0} + \frac{p_i^1 q_i^1}{p^{1\prime}q^1}\right)\ln(p_i^1 / p_i^0)\,, \qquad (7)$$

and $Q_T(w^0,w^1,v^0,v^1)$ is a Törnqvist quantity index of factor endowments, defined by:

$$\ln Q_T(w^0,w^1,v^0,v^1) \equiv \sum_{i=1}^{N}\left(\frac{1}{2}\right)\left(\frac{w_i^0 v_i^0}{w^{0\prime}v^0} + \frac{w_i^1 v_i^1}{w^{1\prime}v^1}\right)\ln(v_i^1 / v_i^0)\,. \qquad (8)$$

Thus, productivity growth defined by the average of R_L and R_P can be measured the change in nominal GDP on the right-hand side of (6), deflated by two indexes: the first index in

(7) is a Törnqvist price index of the components of GDP, and the second index in (8) is a factor-share weighted average of the growth in primary inputs for the economy. Notice that under our assumption (5) that the GDP function is linearly homogeneous in v, then $p^{t\prime}q^t = w^{t\prime}v^t$, so the shares in the Törnqvist price index (7) and the Törnqvist quantity index (8) are both measured relative to total GDP.

To clarify the role of imported intermediate inputs, let us identify three groups of commodities: those for final domestic demand (quantity $q^t_{di} > 0$ and price $p^t_{di} > 0$, i =1,…,N_d); those for export ($q^t_{xi} > 0$ and $p^t_{xi} > 0$, i =1,…,N_x); and imported intermediate inputs ($q^t_{mi} < 0$ and $p^t_{mi} > 0$, i =1,…,N_m). The quantity vector for all commodities is $q^t = (q^t_d, q^t_x, q^t_m)$, with prices $p^t = (p^t_d, p^t_x, p^t_m)$. Then the GDP function for the economy is still defined as in (1), where q^t is the revenue-maximizing choices by firms. We continue to assume that the GDP function takes on the translog form.

We can then take the Törnqvist price index of GDP that appears in (7) and decompose it into the portion dealing with domestic goods, exports, and imports:

$$\ln P_T(p^0,p^1,q^0,q^1) = \sum_{i=1}^{N_d}\left(\frac{1}{2}\right)\left(\frac{p^0_{di}q^0_{di}}{p^{0\prime}q^0}+\frac{p^1_{di}q^1_{di}}{p^{1\prime}q^1}\right)\ln(p^1_{di}/p^0_{di}) \tag{9}$$

$$+\sum_{i=1}^{N_x}\left(\frac{1}{2}\right)\left(\frac{p^0_{xi}q^0_{xi}}{p^{0\prime}q^0}+\frac{p^1_{xi}q^1_{xi}}{p^{1\prime}q^1}\right)\ln(p^1_{xi}/p^0_{xi})+\sum_{i=1}^{N_m}\left(\frac{1}{2}\right)\left(\frac{p^0_{mi}q^0_{mi}}{p^{0\prime}q^0}+\frac{p^1_{mi}q^1_{mi}}{p^{1\prime}q^1}\right)\ln(p^1_{mi}/p^0_{mi}) .$$

We will refer to the first summation on the right of (9) as the gross domestic purchases index, because it uses the quantities and prices of final demand. The exponent of this first summation is denoted by the Törnqvist price index $P_T(p^0_d, p^1_d, q^0_d, q^1_d)$, where the shares are computed relative to total GDP $p^{t\prime}q^t$. Combining the second and third terms gives the difference between the export and import log price indexes—recall that $q^t_{mi} < 0$. Let us denote the exponent of these combined summations by the Törnqvist terms-of-trade index $P_T(p^0_{xm}, p^1_{xm}, q^0_{xm}, q^1_{xm})$, where again, the shares are computed relative to total GDP $p^{t\prime}q^t$.

We can now re-write the result in (6) in the following form:

$$(R_L\, R_P)^{1/2} = \left(\frac{p^{1\prime}q^1}{p^{0\prime}q^0}\right) / \left[P_T(p^0_d, p^1_d, q^0_d, q^1_d)\, P_T(p^0_{xm}, p^1_{xm}, q^0_{xm}, q^1_{xm})\, Q_T(w^0, w^1, v^0, v^1)\right]. \qquad (10)$$

Productivity growth for the economy is thus measured by the ratio of nominal GDP deflated by three terms: a gross domestic purchases price index, a terms-of-trade index, and a quantity index of factor endowment growth.

In practice, equation (10) is implemented by calculating the indexes on the right, and therefore obtaining a measure of productivity growth on the left. Applications include Cas, Diewert and Ostensoe (1989) for Canada, Kohli (2004) for Switzerland, and Kohli (2005) for Hong Kong. In these applications, there is no *necessary* correlation between changes in the terms of trade and productivity growth. An improvement in export prices, for example, will be reflected in both higher nominal GDP and an increase in the terms-of-trade index. If "true" productivity growth $(R_L\, R_P)^{1/2}$ has not changed, then the increase in nominal GDP and the improvement in the terms of trade will just cancel out, so the right side of (10) is constant. Similarly, if import prices rise, then both nominal GDP and the terms-of-trade index fall. Again, if "true" productivity growth has not changed, then the fall in $p^{1\prime}q^1$ and the terms-of-trade index on the right of (10) must just offset each other.

If the terms of trade are calculated with error, however, then this will automatically create a correlation between measured productivity growth and the terms of trade. Errors in the terms-of-trade index can arise due to formula bias, for example (i.e. using an index number formula that is not superlative). In practice, the Bureau of Labor Statistics calculates the import and export price indexes using Laspeyres formulas, as described in the next section. Let us denote a Laspeyres terms-of-trade index by $P_L(p^0_{xm}, p^1_{xm}, q^0_{xm}, q^1_{xm})$. Then suppose that productivity growth is measured by:

$$\text{Prod} = \left(\frac{p^{1\prime}q^1}{p^{0\prime}q^0}\right) / \left[P_T(p^0_d, p^1_d, q^0_d, q^1_d)\, P_L(p^0_{xm}, p^1_{xm}, q^0_{xm}, q^1_{xm})\, Q_T(w^0, w^1, v^0, v^1)\right]. \quad (11)$$

Comparing (11) and (10), it immediately follows that measured productivity is:

$$\text{Prod} = (R_L\, R_P)^{1/2}\left[P_T(p^0_{xm}, p^1_{xm}, q^0_{xm}, q^1_{xm}) / P_L(p^0_{xm}, p^1_{xm}, q^0_{xm}, q^1_{xm})\right]. \quad (12)$$

That is, measured productivity equals "true" productivity times the ratio of the Törnqvist and Laspeyres terms-of-trade indexes. If the Laspeyres index *understates* the Törnqvist index, for example, then measured productivity growth will *overstate* the "true" growth. This potential bias in measured productivity growth arises because it is conflating the true productivity with changes in the terms of trade (which are not being accurately measured).

3.2 Nonparametric Approach based on Aggregate and Industry-Level Theoretical Divisia Indexes

Since the imports that influence the value of the GDP function are used as intermediate inputs, we should be able to measure their effect in a growth accounting framework that explicitly models the role of intermediate inputs. In particular, if we separately account for the effect of every industry's use of intermediate inputs and then aggregate, we should find a net effect of prices imported intermediate inputs consistent with the aggregate effect implied by the GDP function.

Hulten (1978) shows that for a perfectly competitive, closed economy, aggregate MFP change defined as the rate of expansion of the social production possibilities frontier may be measured by an index of expenditure-share-weighted log-changes in outputs less a similar index of the log-changes in primary inputs. Similarly, for individual industries, the rate of change in the production function, or industry-level MFP, may be measured by the log-change in gross output less the index of share-weighted log-changes in primary and intermediate inputs. Then aggregation of the index number measures of industry-level MFP change using Domar weights (which are defined as ratios of industry gross output to aggregate value added) also yields the index that measures aggregate MFP change.[10]

In appendix A, we extend Hulten's (1978) result to the open economy case by including imported intermediate commodities as inputs and exported commodities as outputs in the function describing the social production possibilities frontier. The index measuring aggregate MFP is seen to included imported intermediate commodities and exported commodities with weights proportional to their expenditures (defined as positive for outputs and negative for inputs.) For small changes, this theoretical Divisia index is closely approximated by the Törnqvist index in equation (9) above, and if the technology is translog, it equals that index. Moreover, aggregating the MFP indexes for individual industries—which include as inputs both

[10] Jorgenson, Gollop and Fraumeni (1987, chapter 2) allow input prices to vary between industries and find that aggregate productivity is affected by reallocation of inputs between industry in addition to the effects of productivity change within industries. Basu and Fernald (2002) discuss reallocation effects caused by differences in mark-ups. However the ability to realize gains by resource reallocation would imply that the economy is not solving the maximization problem in equation (1).

imported and domestically-produced intermediate commodities—also yields the index that measures aggregate MFP change.

The result in appendix A shows that we can analyze the effect of imported intermediate inputs on an industry-by-industry basis. In future work we plan to do this using data from BEA's GDP-by-Industry accounts. Moreover, Yuskavage and Reinsdorf (2004) found that Törnqvist indexes of double-deflated value added provide very good approximations to Fisher indexes. BEA uses Fisher indexes to estimate real output growth, so this approximation property of the Törnqvist formula is useful for gauging the effect on official growth rate estimates of the use of alternative price indexes for intermediate inputs and gross output.

4. U.S. Terms of Trade and High-Technology Products

The International Price Program (IPP) of the BLS calculates import and export prices using a Laspeyres formula calculated over the "long-term price relatives." Letting p_i^{ht} denote the price for disaggregate commodity i in month h and year t, and p_i^0 denote a base-period price for the same commodity, then the long-term price relative is (p_i^{ht} / p_i^0). The IPP used the base period 1990 up until December 1996, and base period 1995 thereafter, and obtains base-period export and import expenditures $p_i^0 q_i^0$ from Census. Denote the trade weights of commodity i in the overall export or import sector k by $w_i^0 \equiv p_i^0 q_i^0 / \sum_{i \in I_k} p_i^0 q_i^0$. Then the Laspeyres index from that the base period to month h in year t is,

$$P_L^{ht} \equiv \frac{\sum_{i \in I_k} q_i^0 p_i^{ht}}{\sum_{i \in I_k} q_i^0 p_i^0} = \sum_{i \in I_k} w_i^0 (p_i^{ht} / p_i^0). \tag{13}$$

The left-side of (1) shows the textbook Laspeyres formula, while the right-side of (13) introduces notation that is similar to that actually used by the IPP. We can think of (13) as a *long-term Laspeyres* index from a particular month in 1990 to month h in year t, for the export or import sector k (e.g. exports or imports within a three-digit SIC industry).[11]

The *month-to-month Laspeyres-ratio* index is then computed by taking the ratio of (13) in months h and h-1, obtaining,

$$P_{LR}^{h\text{-}1,h,t} = \frac{\sum_{i \in I_k} w_i^0 (p_i^{ht} / p_i^0)}{\sum_{i \in I_k} w_i^0 (p_i^{h-1,t} / p_i^0)}. \tag{14}$$

In this case we let $I_k = I_k^{h-1,t} \cap I_k^{ht}$ denote the set of commodities that have price data available within both months h-1 and h of year t. We call the month-to-month index in (14) a *Laspeyres ratio*, and this formula differs from the usual Laspeyres formula computed from prices between months h-1 and h.

The reason for the use of long-term relatives in the Laspeyres formula (13) is that this guarantees that the index number formula will satisfy the "time-reversal" test. That is, suppose that prices change from $p_i^{h-1,t}$ to p_i^{ht} and then back to $p_i^{h-1,t}$ in month h+1. Then the long-term Laspeyres index in (13) will change from $P_L^{h\text{-}1,t}$ to P_L^{ht} and then return to $P_L^{h\text{-}1,t}$ in month h+1. If we cumulate the month-to-month indexes in (14), we obtain:

$$P_{LR}^{h\text{-}1,h,t} \times P_{LR}^{h,h+1,t} = \frac{P_L^{ht}}{P_L^{h\text{-}1,t}} \times \frac{P_L^{h\text{-}1,t}}{P_L^{ht}} = 1. \tag{15}$$

In other words, the price changes will cancel out when cumulated in the month-to-month indexes. This is a highly desirable property that the IPP indexes satisfy by construction. As

[11] In principle, we should also subscript this index by the product group k being aggregated over, but for simplicity we omit this.

shown in appendix B, it would not be satisfied by a Laspeyres-like index that used short term relatives and failed to update the weights for the effects of price change from time 0 to time t–1.

However, the use of long-term Laspeyres indexes to measure import and export prices leads to another type of bias in the indexes. If instead of bouncing up and down, prices instead exhibit a long-term secular rise or fall, then the long-term Laspeyres index in (13) will have a consistent bias. In particular, it will tend to *understate* the true price decline when commodities have falling prices, such as for semiconductors and other IT products. That feature of the Laspeyres indexes is demonstrated in appendix B, and occurs because the weights used in (13) are held fixed at historical values, rather than being updated.

An alternative index that would not suffer from the secular bias is the Törnqvist index. A true Törnqvist index would require the use of monthly weights for imports and exports. We have instead used annual weights w_i^t from Census data year t.[12] Then the month-to-month Törnqvist index for exports or imports in sector k is:

$$P_T^{h-1,h,t} = \exp\left[\sum_{i \in I_k} w_i^t \ln\left(\frac{p_i^{ht}}{p_i^{h-1,t}}\right)\right]. \tag{16}$$

This month-to-month index is cumulated or chained in order to obtain a long-term Törnqvist index, for each export or import sector k.

A third index we consider, which might be expected to lie in-between the Laspeyres and Törnqvist indexes, is the Geometric index, defined by the formula:

$$P_G^{h-1,h,t} = \exp\left[\sum_{i \in I_k} w_i^0 \ln\left(\frac{p_i^{ht}}{p_i^{h-1,t}}\right)\right]. \tag{17}$$

[12] In practice, the monthly trade weights are too volatile to be reliable.

This formula is similar to the Törnqvist index but uses the base-period rather than current annual weights. Again, the month-to-month index is chained in order to obtain a long-term Geometric index, for each export or import sector k. We report the values of the Laspeyres, Geometric and Törnqvist indexes below, after first describing the price data we shall use.

4.1 Data on U.S. Import and Export Prices

We have used two datasets provided by the IPP program of the BLS. The first dataset spans September 1993 to December 1996, and was used extensively in Alterman, Diewert and Feenstra (1999). That dataset contains long-term price relatives (that is, p_i^{ht} / p_i^0) at the "classification group" level, which is similar to the 10-digit Harmonized System (HS) level. The classification groups have been carefully concorded to the HS system, so that the base-period weights (for 1990) used by the IPP program can be replaced by current annual import and export expenditures in order to calculate the Törnqvist indexes for imports and exports in (16). That is, current annual weights are used in the Törnqvist index when aggregating from the classification group level to the Standard Industrial Classification (SIC) level. Alternatively, the base-period weights (for 1990) can be used to construct the Geometric index.

A second dataset spans 199701 to 199912. The classification groups used in that dataset differ somewhat from those used in 199309 to 199612, so we have developed an (incomplete) concordance between them. The price data available for this latter period are actually more detailed than the classification group level, and go down to the "item" level at which individual companies provide price quotes. So for this latter period, we first need to aggregate from the item level to the classification group level, and then aggregate from the classification groups to the SIC level. The lower-level aggregation (from the item level to the classification group) can done using the base-period (1995) weights and the Laspeyres formula, as in (13), which follows the BLS procedure. Alternatively, the lower-level aggregation can be done using the base-period weights and a Geometric formula in (17), where I_k then denotes the item-level quotes within a classification group.

After constructing Geometric indexes at the lower-level, we can proceed in two methods: (i) again apply the Geometric index formula at the upper-level of aggregation, from the classification group to the SIC level; or (ii) apply the Törnqvist index to aggregate the indexes for the classification groups to the SIC level. We shall refer to the first method as a Geometric index, and the second method as a Törnqvist index, though it should be understood that the Törnqvist index in the latter time period is actually using a Geometric formula at the lower-level of aggregation. In contrast, for the earlier time period the long-term price relatives for the classification groups are Laspeyres aggregates of the item-level price quotes calculated by BLS. So the Geometric and Törnqvist indexes for the earlier time period use Laspeyres aggregates at the lower level of aggregation.

4.2 Aggregate Import and Export Indexes

We begin by reviewing the annual averages of the U.S. terms of trade for the longest time period possible, 1985-2005, as shown in Figure 2. The terms of trade there is the ratio of the published BLS export price index to the BLS non-petroleum import price index. We also show the annual average yen/$ exchange rate. As the dollar depreciated starting in 1985, the terms of trade also fell. This pattern results from the well-documented finding that U.S. import prices have greater pass-through of exchange rates than do U.S. export prices. Therefore, a dollar of depreciation leads to a larger increase in import prices than in export prices, and a fall in the terms of trade.

As the dollar began to recover in 1995, the terms of trade also rose, until mid-1997. After that year the close connection between the terms of trade and the yen/$ exchange rate is broken: the terms of trade continues to rise while the dollar again depreciates against the yen. One reason for this, of course, is the Asian financial crisis, which resulting in a strong depreciation of other Asian currencies, such as the Korean won, in late 1997. While the dollar was depreciating against the yen, it was appreciating against these other currencies, resulting in a falling import prices from those countries. It appears from Figure 2 that the behaviour of the terms of trade prior to 1998 and its behaviour thereafter are quite different. Fortunately, our sample period of 199309-199912 includes this new movement in the terms of trade.

In Figures 3 and 4 we show the published BLS export and non-petroleum import price indexes over our sample period, along with Laspeyres indexes that we have constructed using equation (13). Our Laspeyres indexes are nearly identical to the published BLS price indexes for 199309-199612, but differ slightly in the latter period 199701-199912. The differences in the latter period reflect concordances used there that are not fully accurate, but the differences seem small enough to proceed.[13]

Also shown in Figures 3 and 4 are the Geometric indexes and the Törnqvist indexes. The Törnqvist indexes are rewritten here to distinguish exports and imports:

$$P_X^{h-1,h,t} = \exp\left[\sum_{i=1}^{N_x}\left(\frac{p_{xi}^t q_{xi}^t}{p_x^{t\,\prime} q_x^t}\right)\ln\left(\frac{p_{xi}^{ht}}{p_{xi}^{h-1,t}}\right)\right], \quad P_M^{h-1,h,t} = \exp\left[\sum_{i=1}^{N_m}\left(\frac{p_{mi}^t q_{mi}^t}{p_m^{t\,\prime} q_m^t}\right)\ln\left(\frac{p_{mi}^{ht}}{p_{mi}^{h-1,t}}\right)\right]. \quad (18)$$

[13] We thank Bill Alterman for providing us with the concordance between the classification group and HS numbers used after 1997. Because the HS numbers change over time, however, that concordance is not fully accurate for 1998 and 1999. In addition, we constructed a concordance between the pre-1997 and post-1997 classification group numbers, which is also not fully accurate.

For both export and imports, the Geometric and Törnqvist price indexes are *below* the Laspeyres indexes, but are quite close to each other, especially by the end of the sample period. The slower growth (or faster decline) of the Geometric index compared to the Laspeyres index reflects the theorem that geometric means are less than similarly-weighted arithmetic means. The Törnqvist index falls below the Laspeyres index because the commodities with the greatest price declines have rising import and export quantities. The negative correlation between prices and quantities seems obvious for imports, but is surprising for exports. This pattern was also found in Alterman, Diewert and Feenstra (1999). As they explain, it can be understood as resulting from technological improvement in the supply of exports, leading to higher quantity and falling prices along the foreign demand curve.

4.3 Imports of Commodities for Final Uses

In the theory of the GDP function, the trade balance is measured as the difference between all exports and imports of intermediate commodities; imported commodities for final uses are excluded. Less than one-third of imports of goods are for intermediate uses in the National Income and Product Accounts (see table 4.2.5.) Although this suggests that most imports should be excluded from estimates of the GDP function, this conclusion is too superficial. Imported commodities in personal consumption expenditures pass through the domestic distribution industries (wholesale and retail trade) and are generally deflated by an appropriate CPI, not by an import price index from the IPP program. Therefore, for an imported commodity for personal consumption, a revision to an import price index will affect only the amount of constant-dollar imports subtracted in the calculation of constant-dollar GDP, just as if this commodities were an imported intermediate commodity. The deflation of consumption expenditures will be unaffected. Therefore, for purposes of investigating the effects of revisions to import price indexes on the estimate of real GDP, about three-quarters of imports must be treated as intermediate inputs.

In contrast, in measuring constant-dollar investment, imported investment goods are generally deflated by the same import price index used in measuring constant-dollar imports. Consequently, after combining the effects on real investment and the effects on real imports, revisions to import price indexes for capital equipment, including computers purchased by business, have virtually no effect on the estimate of real GDP change. For our purposes, the conceptual limitation of imports in the GDP function to imported intermediate inputs means that imports used for fixed investment should be excluded from estimates of effects on real GDP or real value added. Nevertheless, these import price indexes do affect the estimation of MFP because they affect real investment and hence inputs of capital services. Below, we compare the effect of adjusting capital inputs on the MFP estimate to the effect of simply treating imported capital goods as if they were intermediate inputs.

4.4 Terms-of-trade indexes

In Figure 5 we show five measures of the U.S. terms of trade. These measures **include** capital goods in imports; in future work we plan to calculate separate indexes for capital goods and all other imports. The first measure is the ratio of published BLS export and import prices indexes. The second measure, which is the ratio of our constructed Laspeyres indexes, rises slightly faster than the ratio of the published BLS indexes, but again, this difference is not too large. The third measure is the ratio of the Geometric export and import prices indexes in (17). The fourth measure is the ratio of the Törnqvist export and import prices indexes in (18), and is labelled as “Törnqvist1” in Figure 5:

$$\text{Törnqvist1 index} \equiv \left(\frac{P_X^{h-1,h,t}}{P_M^{h-1,h,t}} \right).$$

Both the Geometric and Törnqvist1 indexes rise substantially faster than the Laspeyres index during 1997-1999. Comparing December 1996 to December 1999, the Geometric index rises 7.1 percent and the Törnqvist1 index rises 6.1 percent as compared to the Laspeyres terms of trade, which rises 4.4 percent. So the difference between the Geometric or Törnqvist1 indexes and the Laspeyres terms of trade is 1.7-2.7 percentage points over the three years. These amounts are shown in the final column of Table 3, where we report the values of the indexes re-normalized to 199612 = 100, and also their differences. Comparing the Geometric and Törnqvist1 indexes with the BLS-based terms of trade over 199612-19912, the Geometric index rises 5.0 percentage points more over the three years, implying a growth rate difference of 1.6 percent per year, and the Törnqvist1 index rises 4.0 points more, implying a growth rate difference of 1.3 percent per year.

In addition to the Törnqvist1 ratio, we also report a Törnqvist terms-of-trade index in Figure 5 that includes an adjustment for the trade imbalance. This adjusted terms-of-trade index is therefore useful for investigating the effects of alternative treatments of imported capital stock goods. If formula effects within the capital goods component of imports are the same as in the overall index for imports, the Törnqvist1 terms-of-trade index is unaffected by the inclusion of imported capital goods used for fixed investment. On the other hand, the Törnqvist2 index is affected, because their inclusion swings the trade balance from about zero in 1997-1999 to significantly negative. (To be more precise, had capital goods been excluded from imports, the adjustment for the merchandise trade imbalance would have been approximately 0 in 1999, and its sign would have been reversed in 1997-1998.) Because the average trade surplus after excluding imports of capital goods and of petroleum is approximately zero in 1997-1999, we will take the Törnqvist1 index as our comprehensive measure of terms-of-trade effects, and use the difference between the Törnqvist2 index and the Törnqvist1 index to measure the effects of treated imported capital goods as if they were intermediate inputs.

Our adjusted terms-of-trade index is constructed as implied by Diewert and Morrison (1986) and equation (9). Recall that the second and third summations on the right of (9) have the export and import price log-changes weighted by their expenditures relative to GDP. Changing notation slightly to reflect our use of monthly prices but annual expenditures, we rewrite the second and third summations of (9) as:

$$
\begin{aligned}
\ln P_T^{h-1,h,t} &= \sum_{i=1}^{N_x} \frac{p_{xi}^t q_{xi}^t}{p^{t\prime} q^t} \ln\left(\frac{p_{xi}^{ht}}{p_{xi}^{h-1,t}}\right) + \sum_{i=1}^{N_m} \frac{p_{mi}^t q_{mi}^t}{p^{t\prime} q^t} \ln\left(\frac{p_{mi}^{ht}}{p_{mi}^{h-1,t}}\right) \\
&= s_x^t \sum_{i=1}^{N_x} \left(\frac{p_{xi}^t q_{xi}^t}{p_x^{t\prime} q_x^t}\right) \ln\left(\frac{p_{xi}^{ht}}{p_{xi}^{h-1,t}}\right) - s_m^t \sum_{i=1}^{N_m} \left(\frac{p_{mi}^t q_{mi}^t}{p_m^t q_m^t}\right) \ln\left(\frac{p_{mi}^{ht}}{p_{mi}^{h-1,t}}\right) \\
&= \left(\frac{s_x^t + s_m^t}{2}\right) \ln\left(\frac{P_X^{h-1,h,t}}{P_M^{h-1,h,t}}\right) + \left(\frac{s_x^t - s_m^t}{2}\right) \left(\ln P_X^{h-1,h,t} + \ln P_M^{h-1,h,t}\right), \qquad (19)
\end{aligned}
$$

where the second line introduces the terms $s_x^t \equiv p_x^{t\prime} q_x^t / p^{t\prime} q^t$ and $s_m^t \equiv -p_m^{t\prime} q_m^t / p^{t\prime} q^t$ as the (positive) shares of exports and imports in GDP; and the third line follows by algebra after defining the export and import prices indexes as in (18).

Equation (19) shows that terms-of-trade index should be adjusted by a trade balance term, which is the last term on the right of (19), to be consistent with the theory in Diewert and Morrison (1986) and Kohli (2004). Let us re-write (19) slightly as:

$$\ln P_T^{h-1,h,t} = \left(\frac{s_x^t + s_m^t}{2}\right)\left[\ln\left(\frac{P_X^{h-1,h,t}}{P_M^{h-1,h,t}}\right) + \left(\frac{s_x^t - s_m^t}{s_x^t + s_m^t}\right)\left(\ln P_X^{h-1,h,t} + \ln P_M^{h-1,h,t}\right)\right]. \qquad (19')$$

We define the Törnqvist2 index as the term in brackets on the right:

$$\text{Törnqvist2 index} \equiv \exp\left[\ln\left(\frac{P_X^{h-1,h,t}}{P_M^{h-1,h,t}}\right) + \left(\frac{s_x^t - s_m^t}{s_x^t + s_m^t}\right)\left(\ln P_X^{h-1,h,t} + \ln P_M^{h-1,h,t}\right)\right]$$
$$= \text{Törnqvist1 index} \times \exp\left[\left(\frac{s_x^t - s_m^t}{s_x^t + s_m^t}\right)\left(\ln P_X^{h-1,h,t} + \ln P_M^{h-1,h,t}\right)\right]. \qquad (20)$$

The Törnqvist2 index differs from the Törnqvist1 index by an adjustment for the trade imbalance. When imports exceed exports and import prices are falling faster than export prices, this will pull up the adjusted (Törnqvist2) terms-of-trade index relative to a pure (Törnqvist1) terms-of-trade index. This is the case for IT products, where we reported in Tables 1 and 2 that imports grew during the 1990s to exceed exports.

The adjusted terms-of-trade index shown by the Törnqvist2 line in Figure 5 also rises faster than the pure terms-of-trade index shown by the Törnqvist1 line. From Table 3, we see that the Törnqvist2 index rises 9.6 percent over 199612-199912, implying a growth rate of 3.1 percent per year. This growth rate of the Törnqvist2 index exceeds that of the Laspeyres pure terms-of-trade index by 1.7 percent per year, and it exceeds the growth rate of the BLS-based measure by 2.4 percent per year. The difference between the Törnqvist2 index and the ratio of BLS indexes is nearly twice as large as the difference between the Törnqvist1 index and the ratio of BLS indexes. In other words, if imported capital goods could be treated as intermediate inputs, correcting for the trade imbalance effect would have roughly the same impact as correcting the index number formula to use a geometric rather than an arithmetic formula.

5. Effect on Estimates of Productivity Growth

5.1 Output side effects

Our improved price indexes for imports and exports affect estimates of MFP though two channels. First, they affect the output growth component of the MFP and labor productivity calculations by changing the growth rate of aggregate real value added. Second, they affect the inputs growth component of the MFP calculations by changing the capital input.

The Törnqvist terms-of-trade indexes probably differ more from the Laspeyres or BLS-based indexes of the terms of trade than the terms-of-trade indexes implicit in BEA's output measures would because BEA uses a Fisher index number formula. In general, Fisher indexes match Törnqvist indexes quite closely. However, BEA's aggregation process starts with indexes for mid-level aggregates calculated by BLS using a Laspeyres formula. Most of the difference between our Törnqvist terms-of-trade indexes and their Laspeyres or BLS-based counterparts appears to arise at detailed and intermediate levels of aggregation, so our estimates of bias in the terms-of-trade indexes are useful upper bounds for effects on BEA's output measures and on the productivity measures that depend on them.

The output side effect can be measured by the formula in equation (12), but, as is shown in (19'), to use this formula to estimate the difference between "true" and measured productivity, we need to multiply the correction to the adjusted terms-of-trade by the average share of trade in GDP, i.e. by $(s_x^t + s_m^t)/2$. Over 1997-1999, the average GDP share of merchandise trade excluding imports of petroleum and capital goods was 7.5 percent. The Törnqvist1 estimate of the terms-of-trade effect of 1.3 percent per year therefore implies an upward bias in measured real GDP growth of 0.1 percent per year. This is our first calculation of the upward bias in total factor productivity for the U.S. economy due to the output effects of mismeasurement of export and import prices.

Our second calculation of the output side effect focuses more narrowly on the value added of the business sector, which excludes the contributions households, non-profit institutions and government (including government enterprises) to GDP. The broadest measures of US multifactor and labor productivity growth available from BLS use business sector real value added as their measure of output.[14] We make the approximately correct assumption that all imported goods are used by or distributed by the business sector, so that the entire terms-of-trade effect operates on this sector of the economy. The average share of merchandise trade excluding petroleum and capital goods imports relative to business sector value added was 9.5 percent in 1997-1999. Multiplying this by the bias of 1.3 percent per year in the terms-of-trade index, we obtain an upward bias in measured productivity of 0.12 percentage points per year.

If we also exclude the farming sector from both business value added, and agricultural exports from U.S. merchandise exports, then we obtain an average trade share of 9.3 percent over 1996-1999. In that case, the upward bias in productivity for the non-farm business sector is again 0.12 percentage points per year.

5.1 Input side effects

Any bias in the growth rate of output (i.e. real value added) of the business sector or of the nonfarm business sector would imply an identical bias in the BLS estimates of these sectors' labor productivity growth. However, for BLS's MFP estimates, import price mismeasurement

[14] In analyzing multi-factor productivity for any sector, the conceptually correct measure of the sectors' output is its gross sales outside the sector, which should equal the sector's value added plus its purchases of intermediate inputs from outside the sector. The output concept for the business sector therefore ought to equal its value added plus its use of imported intermediate inputs. However, inclusion of these imported intermediate inputs in both output and inputs was found to have a very small effect on the MFP estimates for this sector, so in calculating business sector MFP, BLS measures its output by its real value added. See Gullikson and Harper (1999, p. 50 and fn 29).

also matters on the input side. The log-change in the MFP measures for the two higher-level aggregates (business and nonfarm business) is calculated as the difference between the log-change in an output index and the log-change in an index of inputs of capital and labor. Mismeasurement of import prices will affect MFP through the capital input measure, in addition to its effect on the output side through imported intermediate inputs.

We did a rough calculation of the possible magnitude of the capital input effect. The Törnqvist price index for imported capital equipment drops faster than the corresponding BLS price index by more than 1.5 percent per year in 1995-1999, but by much less before 1995 (see Figure 4). Imported capital items account for about 30 percent of total business sector equipment investment in National Accounts data. Assuming that 30 percent of the indexes used to deflate equipment investment were subject to a upward bias of 1.5 percent per year starting in 1995 and no bias before then, the measurement error in the price of new equipment would be about 0.45 percent per year, beginning with 1995. Because capital stock is estimated by adding new investment to existing capital, which is about seven times greater, this assumption will have only small effects on the stock of equipment in 1995. However, equipment depreciates rapidly (about 13 percent per year during the late 1990s) and the effects would increase each year that the error persisted, eventually approaching the assumed 0.45 percent investment error. For example, by 2002 the capital stock growth rate would be 0.39 percent higher.

We estimate that the capital stock trend, for the entire 1995-2002 period, would increase by about 0.25 percent. In the BLS capital model, the growth rate for capital services inputs is the same as the growth rate for the productive capital stock, and equipment accounts for 15.3 percent of the value of output during the period. Therefore, the input side effect of correcting the import deflators would be to *lower* the MFP trend by 0.038 percent during the period. This small capital effect is in addition to the estimated 0.12 percent per year output-side effect on MFP.

Rather than explicitly modeled the effect of prices of imported capital goods on capital inputs, a simple shortcut might be to treat capital goods as if they were intermediate inputs and adjust for their prices on the output side rather than on the input side. Although the timing of any affects will obviously be distorted forward by this shortcut, in the case of a constant and persistent bias, the timing effect may not matter. This accuracy of this shortcut method is also of interest because researchers studying terms of trade effects have generally failed to exclude capital goods from intermediate inputs.

We can approximate the performance of the shortcut method by the difference between the Törnqvist2 and the Törnqvist1 measures of output effects (although this approximation will be slightly understated, our input effect estimate that we want to compare it to is also conservative.) The growth rate of the Törnqvist2 terms-of-trade index is 2.4 percent per year, 1.1 percent per year faster than the growth rate of the Törnqvist1 terms-of-trade index. Including imports in our average merchandise share calculation raises this share from 9.5 percent to 11.5 percent, so the shortcut method would lead to a bias estimate of 0.28 percent per year. This is 0.16 percent per year higher than our estimate with capital goods excluded from imports. For comparison purposes, in the long run, a constant bias of 0.45 percent per year in equipment investment would lead to a bias of about 0.07 percent per year in the growth of capital services inputs in the MFP calculation. Even in the long run, therefore, treating imported capital equipment as intermediate inputs overstates their effect on business sector MFP growth by a substantial margin.

7. Conclusions

Major trade developments that would be expected to boost nominal GDP growth in the US coincided with the productivity speedup of the late 1990s. Furthermore, although import and export price indexes do not play conspicuous roles in the measurement of productivity, we verify that they are important. Thus, a contribution of trade effects to the measurement of the productivity speedup seems like a real possibility.

An improvement in pure terms of trade, defined as the ratio of the exports price index to the imports price index, affects nominal GDP in much the same way as a gain in productivity. Also, even if export and import prices move together, unless imports equal exports, these prices also affect nominal GDP through a trade imbalance affect. Therefore unmeasured prices increases for exports, or price decreases for imported intermediate inputs, will affect the deflation of the components of nominal GDP in ways that cause an overstatement of real GDP growth. Similar effects will occur in the measurement of real output growth that enters into calculations of labor productivity or multifactor productivity. Finally, for the measurement of multifactor productivity, unmeasured declines in prices of imported capital goods (which must be treated as imports of final goods, not intermediate goods) will lead to an understatement of inputs of capital services, resulting in productivity getting too much of the credit for output growth.

Using a Törnqvist formula to calculate alternative price indexes for imports and exports, we find that both indexes grow more slowly than reported by BLS, but the effect on the imports index is considerably larger. We obtain an effect on the pure terms-of-trade index in 1997-1999 of about 1.3 percent per year, compared to virtually no effect for 199309 to 199512. This alternative index of the terms of trade implies a reduction in the estimate of real GDP growth by

0.1 percent per year in 1997-1999. (Note, however, that this figure does not represent an estimate of a bias in real GDP because it does not take into account BEA's use of a superlative Fisher formula for the top level aggregation, which can be expected to reduce the size of this effect, and because the undercount of nominal exports in US trade data discussed in Bureau of the Census, 1998, might be the source of an offsetting bias.)

The broadest measure of output used in calculating productivity is the real value added of the business sector, not all of GDP. The Törnqvist price indexes for foreign trade imply slightly larger reductions in growth rates for real value added of the business sector than for GDP. Combined with the input effect from the revision of the capital good import price index, the Törnqvist terms-of-trade index implies a reduction in its growth rate of about 0.16 percent per year in the estimate of MFP for the business sector. Again, given the incomplete nature of the analysis to date, this figure is more an indication of what kind of value would be plausible for the trade-related bias than it is an actual estimate.

Although our estimates suggest that trade effects explain only a small portion of the productivity speedup, they demonstrate that foreign trade prices do matter for the measurement of growth and productivity. One topic for future research is additional alternative ways of measuring some of the import and export price indexes, including "counterfactual" indexes that allow estimates of the effect of the ITA agreement. A second topic for future research is to use data from BEA's GDP-by-industry accounts as an additional check on our aggregate level results, and to identify the ways that the trade effects flow through individual industries. Under the assumptions needed to use the aggregate GDP function approach, the industry-level MFP measures that include both imported and nontraded intermediate inputs used by industries imply the same aggregate effect as is obtained from the GDP function.

Appendix A: Growth Accounting with Imported Intermediate Inputs

I. Treatment of Imports and Exports in the Model of the Open Economy

For a closed economy, Hulten (1978) shows that under assumptions of constant returns to scale and perfect competition, the log-change in aggregate productivity measured from the shift in the social production possibility frontier is equal to a linear combination of the log-changes in productivity of individual industries, where the industry level productivity measures include effects of changes in intermediate inputs. The weights on the industry productivity changes in this linear combination are the "Domar weights", which are ratios of industry gross output to aggregate value added and which add up to more than 1. This appendix shows that Hulten's result is preserved when exports and imports are introduced into the model. Effects of changes in import and export prices on GDP growth can therefore be estimated by adding up estimates of their effects on individual industries that use or make traded commodities.

In this appendix commodities are allowed to have different prices in foreign trade markets than they do in domestic markets. To reconcile this seeming violation of the law of one price with the assumptions of perfect competition and profit maximization, the version of a commodity that is traded internationally must be assumed to have different characteristics from the non-traded version, so that it is, in effect, a different commodity. The ratio of the price of the exported variety to the price of its domestically-consumed counterpart can then be viewed as equal to their marginal rate of transformation in the production function where they are joint products. Similarly, we assume that the ratio of the price of the domestically-produced intermediate input to the price of its imported counterpart equals the marginal rate of technical substitution between the two varieties in the production technology.

Distinguishing traded and non-traded versions in this way means that a commodity is too coarse an aggregate for use of the quantity form of the usual expression that derives the domestic production of a final-use commodity by subtraction of net imports from domestic final uses. (This expression is most familiar in aggregated form as the Keynesian expression for GDP of C+I+G+X−M, where C+I+G equals domestic **final** uses, and X and M are **total** uses of exports and imports, with all items expressed as expenditures, not quantities.) Versions of a commodity that have different prices and different marginal costs or marginal products in the production process cannot be viewed as interchangeable in the equations that balance total quantity supplied with total quantity demanded of each commodity. Consequently, we define total uses of quantities of imports of commodity Y_i^M as the (positive) sum of the intermediate uses of imports of commodity i in all industries:

$$Y_i^M = \sum_j X_{ij}^M \tag{A1}$$

For the non-traded version of the commodity, domestic final uses are:

$$Y_i^D = Q_i^D - \sum_j X_{ij}^D \tag{A2}$$

where Q_i^D is gross output of the nontraded version of commodity i, and X_{ij}^D is intermediate uses of the non-traded version of the commodity. Finally, letting Y_i^X denote exports of commodity i and Q_i^X denote industry i's gross output of the exported version of commodity i, for exports we have:

$$Y_i^X = Q_i^X \tag{A3}$$

To keep things simple, we follow Hulten (1978) in assuming that only one industry produces any commodity. The gross revenue of the industry that produces commodity i is denoted by:

$$Q_i^{\$} = p_i^D Q_i^D + p_i^X Q_i^X. \tag{A4}$$

If all commodities i are included in the summation, current-dollar GDP equals:

$$\sum_i Y_i^{\$} \equiv \sum_i [p_i^D Y_i^D + p_i^X Y_i^X - p_i^M Y_i^M] \tag{A5}$$

where $p_i^D Y_i^D$ represents current-dollar expenditures on final uses of the non-traded version of commodity i, $p_i^X Y_i^X$ represents current-dollar revenue from exports of commodity i, and $p_i^M Y_i^M$ represents current-dollar expenditures on intermediate uses of imports of commodity i.

II. Proof of the Identity between Aggregate MFP and the Sum over Industries of Industry MFP

Let T be the log-change in aggregate MFP and J be an index of primary inputs for the economy as a whole. In Hulten's closed-economy model, Y_i is final consumption of commodity i and $F(Y_1,Y_2, \ldots ,J,t) = 0$ defines the social production possibility frontier. Hulten shows that the aggregate measure of productivity change is:

$$\begin{aligned} T &\equiv \frac{\partial F/\partial t}{\sum_i (\partial F/\partial Y_i)Y_i} \\ &= \sum_i [s_i^Y \partial \log Y_i/\partial t] - \partial \log J/\partial t. \end{aligned} \tag{A6}$$

where $s_i^Y \equiv p_i Y_i / \sum_j p_j Y_j$.

For the open economy, we require a different definition for the social production possibilities frontier $F(\cdot)$. In particular, let

$$F(Y_1^D, Y_1^X, Y_1^M, Y_2^D, Y_2^X, Y_2^M, \ldots, Y_N^D, Y_N^X, Y_N^M, J, t) = 0 \qquad \text{(A7)}$$

where $\{Y_i^M; i=1,\ldots, N\}$ and J are inputs, and $\{Y_i^D; i=1,\ldots, N\}$ and $\{Y_i^X; i=1,\ldots, N\}$ are outputs.

Next, define the function $\delta(x)$ as $\partial \log x/\partial t$ if x is positive, or as 0 otherwise. Also, to allow for different kinds of primary inputs without cluttering up the notation with unnecessary detail for this type of input, let the aggregate of primary inputs in industry i have the quantity index J_i, with associated price index w_i scaled so that $w_i J_i$ equals the actual total cost of primary inputs in current prices. Replacing $\partial \log J/\partial t$ by $\sum_i s_i^J \delta(J_i)$, where $s_i^J \equiv w_i J_i / \sum_j w_j J_j$, the open economy generalization of equation (A1) is:

$$T = \sum_i [s_i^{Y^D} \delta(Y_i^D) + s_i^{Y^X} \delta(Y_i^X) - s_i^{Y^M} \delta(Y_i^M) - s_i^J \delta(J_i)]. \qquad \text{(A8)}$$

where $s_i^{Y^D} \equiv p_i^D Y_i^D / \sum_j Y_j^\$$, $s_i^{Y^X} \equiv p_i^X Y_i^X / \sum_j Y_j^\$$, and $s_i^{Y^M} \equiv p_i^M Y_i^M / \sum_j Y_j^\$$. Note that by the assumption of perfect competition, the economy's cost of primary inputs $\sum_i w_i J_i$ equals its aggregate value added $\sum_i Y_i^\$$.

Recalling that $Q_i^\$ = p_i^D Q_i^D + p_i^X Q_i^X$, let $s_i^{Q^D} \equiv p_i^D Q_i^D / Q_i^\$$ and let $s_i^{Q^X} \equiv p_i^X Q_i^X / Q_i^\$$. Also, let the input shares of commodities j in industry i be $s_{ji}^{*D} \equiv p_j^D X_{ji}^D / Q_i^\$$, $s_{ji}^{*M} \equiv p_j^M X_{ji}^M / Q_i^\$$, and $s_i^{*J} \equiv w_i J_i / Q_i^\$$. For a particular industry, say industry i, the production possibility frontier is defined by $F^i(Q_i^D, Q_i^X, X_{1i}^D, X_{1i}^M, X_{2i}^D, X_{2i}^M, \ldots, X_{Ni}^D, X_{Ni}^M, J_i, t) = 0$, where J_i is a vector of primary inputs used by industry i, and t reflects productivity change over time. A measure of productivity change for any industry i that is analogous to equation (A8) is:

$$T^i = s_i^{Q^D} \delta(Q_i^D) + s_i^{Q^X} \delta(Q_i^X) - \sum_j [s_{ji}^{*D} \delta(X_{ji}^D) + s_{ji}^{*M} \delta(X_{ji}^M)] - s_i^{*J} \delta(J_i) \qquad \text{(A9)}$$

where $\delta(F^i)$ is the log-change in the production function of industry i caused by productivity growth. Note that by the assumptions of constant returns to scale and perfect competition, we have $s_i^{Q^D} + s_i^{Q^X} = 1$, and also $s_i^{*J} + \sum_j [s_{ji}^{*D} + s_{ji}^{*M}] = 1$.

Adding together equations (A1), (A2) and (A3), a balance equation for the supply and demand of the commodity i in the open economy is:

$$Q_i^D + Q_i^X = Y_i^D + Y_i^X - Y_i^M + \sum_j [X_{ij}^D + X_{ij}^M] \tag{A10}$$

Differentiating (A10) and multiplying by $p_i^D/Q_i^\$$ gives:

$$\delta(Q_i^D)(p_i^D Q_i^D/Q_i^\$) + \delta(Q_i^X)(p_i^D/p_i^X)(p_i^X Q_i^X/Q_i^\$) = \delta(Y_i^D)(p_i^D Y_i^D/Q_i^\$) + \delta(Y_i^X)(p_i^D/p_i^X)(p_i^X Y_i^X/Q_i^\$)$$
$$- \delta(Y_i^M)(p_i^D/p_i^M)(p_i^M Y_i^M/Q_i^\$) + \sum_j [\delta(X_{ij}^D)(p_i^D X_{ij}^D/Q_i^\$) + \delta(X_{ij}^M)(p_i^D X_{ij}^M/Q_i^\$)] \tag{A11}$$

Define the Domar weight D_i as $Q_i^\$ / \sum_j Y_j^\$$. Then $p_i^D Y_i^D/Q_i^\$ = s_i^{Y^D}/D_i$ and $p_i^X Y_i^X/Q_i^\$ = s_i^{Y^X}/D_i$. Also, define r_i^X as (p_i^D/p_i^X), define r_i^M as (p_i^D/p_i^M) and define Δ_i as $(r_i^X - 1)s_i^{Y^X}\delta(Y_i^X) - (r_i^M - 1)s_i^{Y^M}\delta(Y_i^M)$. Recalling that $s_{ij}^{*D} \equiv p_i^D X_{ij}^D/Q_j^\$$, (A11) becomes:

$$D_i\{s_i^{Q^D}\delta(Q_i^D) + r_i^X s_i^{Q^X}\delta(Q_i^X) - \sum_j (Q_j^\$/Q_i^\$)[s_{ij}^{*D}\delta(X_{ij}^D) + r_i^M s_{ij}^{*M}\delta(X_{ij}^M)]\}$$
$$= s_i^{Y^D}\delta(Y_i^D) + r_i^X s_i^{Y^X}\delta(Y_i^X) - r_i^M s_i^{Y^M}\delta(Y_i^M).$$
$$= [s_i^{Y^D}\delta(Y_i^D) + s_i^{Y^X}\delta(Y_i^X) - s_i^{Y^M}\delta(Y_i^M)] + [(r_i^X - 1)s_i^{Y^X}\delta(Y_i^X) - (r_i^M - 1)s_i^{Y^M}\delta(Y_i^M)].$$
$$= [s_i^{Y^D}\delta(Y_i^D) + s_i^{Y^X}\delta(Y_i^X) - s_i^{Y^M}\delta(Y_i^M)] + \Delta_i. \tag{A12}$$

Rewrite (A12) as:

$$D_i\left\{s_i^{Q^D}\delta(Q_i^D) + r_i^X s_i^{Q^X}\delta(Q_i^X) - \sum_j (Q_j^\$/Q_i^\$)[s_{ij}^{*D}\delta(X_{ij}^D) + r_i^M s_{ij}^{*M}\delta(X_{ij}^M)]\right\} - \Delta_i$$
$$= s_i^{Y^D}\delta(Y_i^D) + s_i^{Y^X}\delta(Y_i^X) - s_i^{Y^M}\delta(Y_i^M) \qquad \text{(A13)}$$

Substituting into (A8) gives:

$$T = \sum_i \left[D_i\left\{s_i^{Q^D}\delta(Q_i^D) + r_i^X s_i^{Q^X}\delta(Q_i^X) - \sum_j (Q_j^\$/Q_i^\$)[s_{ij}^{*D}\delta(X_{ij}^D) + r_i^M s_{ij}^{*M}\delta(X_{ij}^M)]\right\} - \Delta_i - s_i^J\delta(J_i)\right]$$
$$= \sum_i \left[D_i\left\{s_i^{Q^D}\delta(Q_i^D) + r_i^X s_i^{Q^X}\delta(Q_i^X) - \sum_j (Q_j^\$/Q_i^\$)[s_{ij}^{*D}\delta(X_{ij}^D) + r_i^M s_{ij}^{*M}\delta(X_{ij}^M)] - s_i^{*J}\delta(J_i)\right\} - \Delta_i\right]$$
$$\text{(A14)}$$

where the last expression substitutes $D_i s_i^{*J}$ for s_i^J.

Omitting the effect of the deviations of the r_i^M from 1, the sum of intermediate inputs terms in (A14) equals the sum of industry-level intermediate inputs terms in (A9):

$$\sum_i D_i\left[\sum_j (Q_j^\$/Q_i^\$)[s_{ij}^{*D}\delta(X_{ij}^D) + s_{ij}^{*M}\delta(X_{ij}^M)]\right] = \sum_i D_i\left[\sum_j [s_{ji}^{*D}\delta(X_{ji}^D) + s_{ji}^{*M}\delta(X_{ji}^M)]\right] \qquad \text{(A15)}$$

Therefore, using the industry-level productivity equation (A9) to substitute T^i for $s_i^{Q^D}\delta(Q_i^D)$ + $s_i^{Q^X}\delta(Q_i^X) - \sum_j [s_{ji}^{*D}\delta(X_{ji}^D) + s_{ji}^{*M}\delta(X_{ji}^M)] - s_i^{*J}\delta(J_i)$ in (A14), we have:

$$T = \sum_i D_i\left\{T^i + (r_i^X-1)s_i^{Q^X}\delta(Q_i^X) - (r_i^M-1)(Q_j^\$/Q_i^\$)[\textstyle\sum_j s_{ij}^{*M}\delta(X_{ij}^M)]\right\} - \sum_i \Delta_i$$
$$= \sum_i D_i T^i + \sum_i \left[D_i(r_i^X-1)s_i^{Q^X}\delta(Q_i^X) - (r_i^X-1)s_i^{Y^X}\delta(Y_i^X)\right]$$
$$- \sum_i \left[D_i(r_i^M-1)(Q_j^\$/Q_i^\$)[\textstyle\sum_j s_{ij}^{*M}\delta(X_{ij}^M)] - (r_i^M-1)s_i^{Y^M}\delta(Y_i^M)\right] \qquad \text{(A16)}$$

To show that the omitted effects of the deviations of the r_i^X and the r_i^M from 1 equal zero, recall that $s_i^{Q^X} = p_i^X Q_i^X/Q_i^\$$ and $s_i^{Y^X} = p_i^X Y_i^X / \sum_j Y_j^\$$, with $Q_i^X = Y_i^X$. Therefore,

$$D_i\, s_i^{Q^X}\, \delta(Q_i^X) \;=\; s_i^{Y^X}\, \delta(Y_i^X). \tag{A17}$$

As a result,

$$D_i\,(r_i^X - 1)\, s_i^{Q^X}\, \delta(Q_i^X) - (r_i^X - 1)\, s_i^{Y^X}\, \delta(Y_i^X) \;=\; 0. \tag{A18}$$

Similarly, recalling that $s_{ij}^{*M} \equiv p_i^M X_{ij}^M / Q_j^\$$, that $s_i^{Y^M} \equiv p_i^M Y_i^M / \sum_j Y_j^\$$, and that $Y_i^M = \sum_j X_{ij}^M$, we have:

$$D_i\,(r_i^M - 1)(Q_j^\$ / Q_i^\$)\left[\sum_j s_{ij}^{*M} \delta(X_{ij}^M)\right] \;-\; (r_i^M - 1)\, s_i^{Y^M}\, \delta(Y_i^M) \;=\; 0. \tag{A19}$$

Therefore the last two summations in (A16) have values of zero, and (A16) becomes:

$$T \;=\; \sum_i D_i\, T^i\,. \tag{A20}$$

Appendix B: Bias in Weighted Arithmetic Indexes

A Laspeyres index can be written as a weighted average of price relatives where the weights are the expenditure shares from the period furnishing the initial prices, say period t-1. Consider the case where the weights are instead derived from an earlier base period, so the price index takes the weighted arithmetic form:

$$P_A(p^{t-1}, p^t, w^0) \equiv \sum_{i=1}^{N} \left(\frac{p_i^t}{p_i^{t-1}} \right) w_i^0\,, \tag{B1}$$

where w_i^0 are historical weights that remain fixed, with $\sum_{i=1}^N w_i^0 = 1$. It is well known that if the type of index in (1) is chained, it will result in an upward bias. This upward bias is closely related to the problem of formula bias in the CPI, discussed by Reinsdorf (1998). That bias in (B1) is expressed by:

Proposition 1

Suppose prices move from p^0 to p^1 and then back to p^0. Chaining the fixed-weight index in (B1) will result in a value exceeding unity:

$$P_A(p^0, p^1, w^0)\, P_A(p^1, p^0, w^0) \geq 1\ . \qquad \text{(B2)}$$

Proof:

$$P_A(p^0, p^1, w^0)\, P_A(p^1, p^0, w^0) = \sum_{i=1}^{N}\left(\frac{p_i^1}{p_i^0}\right)w_i^0 \ \sum_{i=1}^{N}\left(\frac{p_i^0}{p_i^1}\right)w_i^0$$

$$\geq \sum_{i=1}^{N}\left(\frac{p_i^1}{p_i^0}\right)w_i^0 \left[\sum_{i=1}^{N}\left(\frac{p_i^1}{p_i^0}\right)w_i^0\right]^{-1}$$

$$= 1,$$

where the second line is obtained because the arithmetic mean $\sum_{i=1}^{N}\left(\frac{p_i^1}{p_i^0}\right)w_i^0$ is greater than or equal to the harmonic mean $\left[\sum_{i=1}^{N}\left(\frac{p_i^1}{p_i^0}\right)w_i^0\right]^{-1}$. QED

Because BLS does not collect data on expenditure shares in every period, it can either use the arithmetic index (B1) to measure *long-term* rather than *short-term* price movements – the approach taken in the IPP program – or it can estimate the updated expenditure shares in period t-1 as proportional to the $w_i^0(p_i^{t-1}/p_i^0)$ – the approach taken in the CPI program. Under the IPP approach, when prices change from p^0 to p^1 and then back to $p^2 = p^0$, we can measure the long-term change from period 0 to period 2 as $P_A(p^0, p^2, w^0) = P_A(p^0, p^0, w^0) = 1$. In this case, the short-term change in prices are:

(a) from period 0 to period 1, we just apply equation (B1) to measure $P_A(p^0, p^1, w^0)$;

(b) from period 1 to period 2, we apply equation (B1) to measure $P_A(p^0, p^2, w^0)$, and then define the change in prices from period 1 to period 2 as the ratio:

$$P_A(p^0, p^2, w^0) \,/\, P_A(p^0, p^1, w^0). \qquad \text{(B3)}$$

Chaining the short-term change in prices we obtain:

$$P_A(p^0, p^1, w^0)[P_A(p^0, p^2, w^0) \,/\, P_A(p^0, p^1, w^0)] = P_A(p^0, p^2, w^0) = 1, \text{ when } p^2 = p^0.$$

Thus, by using the ratio shown in (B3) to measure short-term price changes, and chaining to obtain long-term changes, we avoid the upward bias in Proposition 1. This is one justification for the method used by IPP to construct its price indexes.

Now we consider a different type of movement in prices: that of secular drift rather than "bouncing" back to their previous values. This would be the case with IT products, for example. Define the weighted covariance of price ratios as:

$$\operatorname{cov}\left[\left(\frac{p_i^2}{p_i^1}\right),\left(\frac{p_i^1}{p_i^0}\right)\right] \equiv \sum_{j=1}^{N}\left[\left(\frac{p_j^2}{p_j^1}\right) - \sum_{i=1}^{N}\left(\frac{p_i^2}{p_i^1}\right)w_i^0\right]w_j^0\left[\left(\frac{p_j^1}{p_j^0}\right) - \sum_{i=1}^{N}\left(\frac{p_i^1}{p_i^0}\right)w_i^0\right]. \qquad \text{(B4)}$$

The case of prices moving from p^0 to p^1 and then back to $p^2 = p^0$ would have a negative covariance in (B4), but now we want to consider a positive covariance, as with secularly declining (or rising) prices. Then we have the result:

Proposition 2

When the weighted covariance in (B4) positive, then:

$$P_A(p^0, p^2, w^0) > P_A(p^0, p^1, w^0)\, P_A(p^1, p^2, w^0)\ . \qquad \text{(B5)}$$

Proof:

We can write the long-term index from period 0 to period 2 as:

$$P_A(p^0, p^2, w^0) \equiv \sum_{i=1}^{N} \left(\frac{p_i^2}{p_i^0}\right) w_i^0 = \sum_{i=1}^{N} \left(\frac{p_i^2}{p_i^1}\right)\left(\frac{p_i^1}{p_i^0}\right) w_i^0$$

Then re-writing the definition of the covariance in (B4), we have:

$$\operatorname{cov}\left[\left(\frac{p_i^2}{p_i^1}\right),\left(\frac{p_i^1}{p_i^0}\right)\right] = \sum_{j=1}^{N} \left(\frac{p_j^2}{p_j^1}\right)\left(\frac{p_j^1}{p_j^0}\right) w_j^0 - \left[\sum_{i=1}^{N} \left(\frac{p_i^2}{p_i^1}\right) w_i^0\right]\left[\sum_{i=1}^{N} \left(\frac{p_i^1}{p_i^0}\right) w_i^0\right]$$

$$= P_A(p^0, p^2, w^0) - P_A(p^1, p^2, w^0)\, P_A(p^0, p^1, w^0)\ .$$

It follows that if the covariance in positive, then (B5) is obtained. QED

Notice that if the covariance in (B4) is negative, then the inequality in (B5) is also reversed. This was essentially Proposition 1, where $P_A(p^0, p^2, w^0) = 1$ when $p^0 = p^2$ was a lower-bound to the chained short-term indexes. Proposition 2 is the opposite, and shows that the long-term index lies *above* the chained, short-term indexes. This means that when considering an index that includes secularly falling prices, such as for IT products using the long-term ratios can result in an upward bias (as compared to the chained index).

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Table 1: International Trade in the IT Industries Over the 1990s

Industry		1992	1996	2000
Computers & Office Equipment (SIC 357)	Exports	26,060	38,895	45,715
	Imports	32,753	62,820	90,503
	Trade Balance	-6,693	-23,924	-44,788
Of which: Computers (SIC 3571)	Exports	18,790	25,520	29,035
	Imports	14,411	21,555	37,397
	Trade Balance	4,380	3,965	-8,362
Electronic Components (SIC 367)	Exports	17,711	35,880	64,264
	Imports	24,449	51,144	73,166
	Trade Balance	-6,738	-15,264	-8,902
Of which: Semiconductors (SIC 3674)	Exports	11,345	23,952	44,585
	Imports	15,320	36,866	48,057
	Trade Balance	-3,976	-12,914	-3,473
Share of Computers, Office Equipment and Electronic Components in Total Trade	Exports	10.0%	12.2%	14.2%
	Imports	11.8%	15.6%	14.8%

Notes: Trade exports and imports are in millions of current dollars, and trade balance equals exports minus imports.
Source: Trade data for SIC industries comes from Bureau of the Census, 1992-2000. The export and import shares are computed by dividing trade in SIC 357+367 by total U.S. exports and non-petroleum imports, obtained from *Economic Report of the President*, 2004, Table B-104.

Table 2: Trade Intensity of IT Commodities in the 1997 Benchmark I-O Tables

Commodity	**% of Commodity Output Exported**	**% of Commodity Output Imported**	**Trade Balance**
Computer & peripheral equipment	19.2	37.8	–18.7
Semiconductors & Electronic components	36.1	36.6	–0.5
Manufacturing Products	13.8	20.5	–6.7

Source: Calculated from the "Use of Commodities" tables in the U.S. BEA's Input-Output Accounts.

Table 3: Terms-of-trade indexes (1996=100)

Terms-of-trade index	**Value in 199912 (199612 = 100)**	**Difference from Ratio of BLS Indexes**	**Difference from Laspeyres index**
	(1)	(2)	(3)
Ratio of BLS Indexes	102.1		
Laspeyres	104.4	2.3	
Geometric	107.1	5.0	2.7
Törnqvist1	106.1	4.0	1.7
Törnqvist2	109.6	7.5	5.2

Source: Column (1) reports the 199912 values of the indexes shown in Figure 5, relative to 199612 = 100. Column (2) is the difference between each index and a terms-of-trade index for 199912 calculated as the ratio of the export and import price indexes published by BLS. Column (3) is the difference between each index and the 199912 value of the Laspeyres terms-of-trade index.

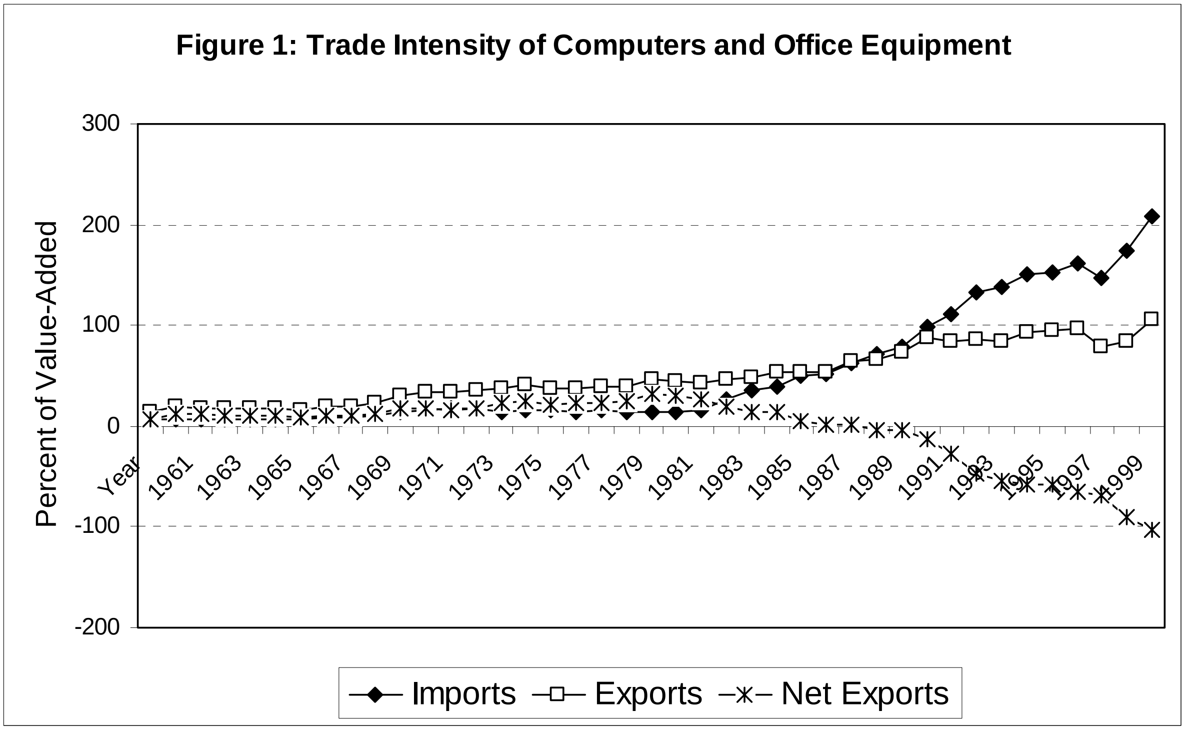


Figure 1: Trade Intensity of Computers and Office Equipment
300
200
100
0
-100
-200
Percent of Value-Added
Year
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
Imports
Exports
Net Exports

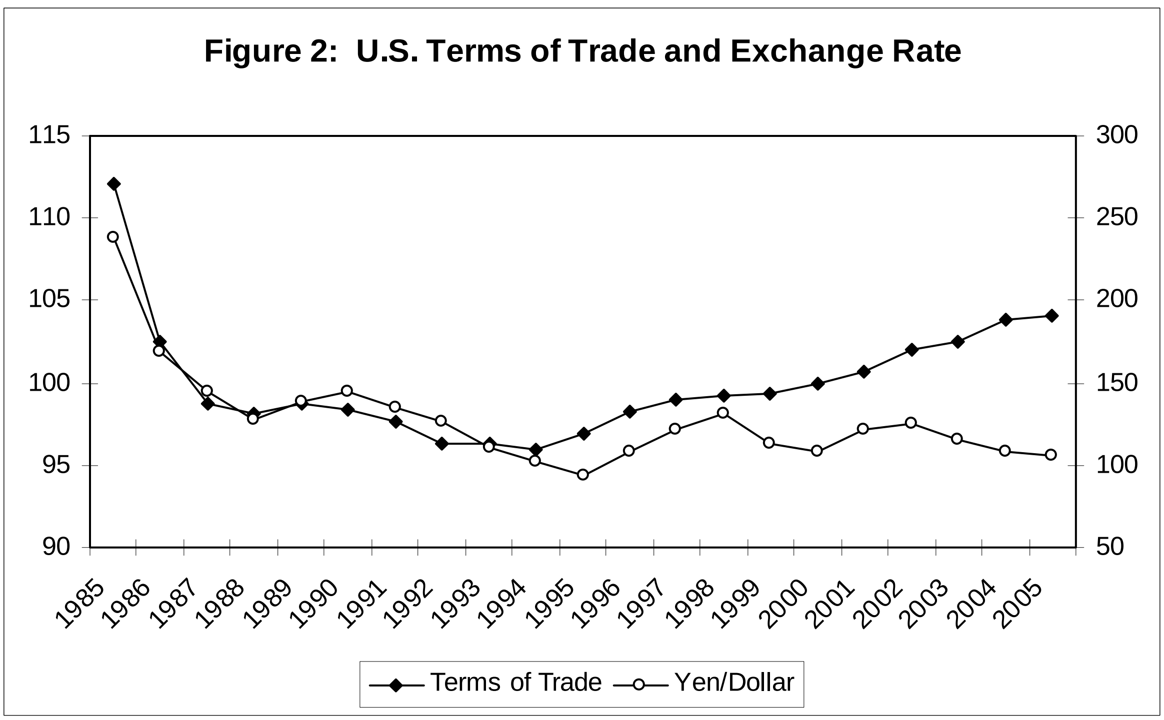


Figure 2: U.S. Terms of Trade and Exchange Rate
115
110
105
100
95
90
300
250
200
150
100
50
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
Terms of Trade
Yen/Dollar

Figure 3: U.S. Export Prices

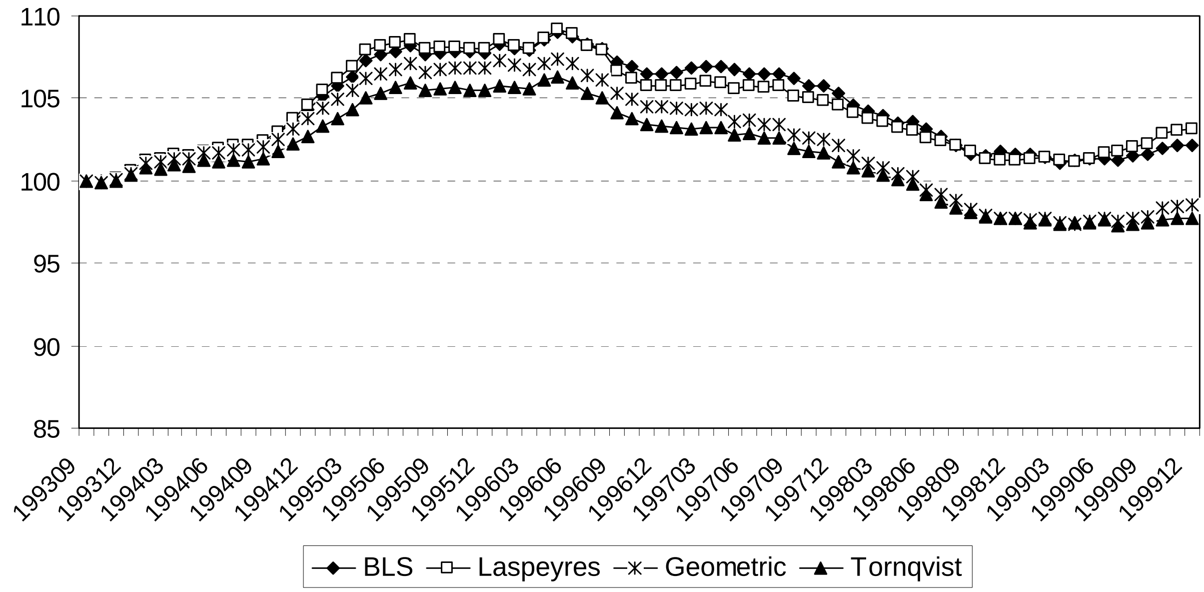
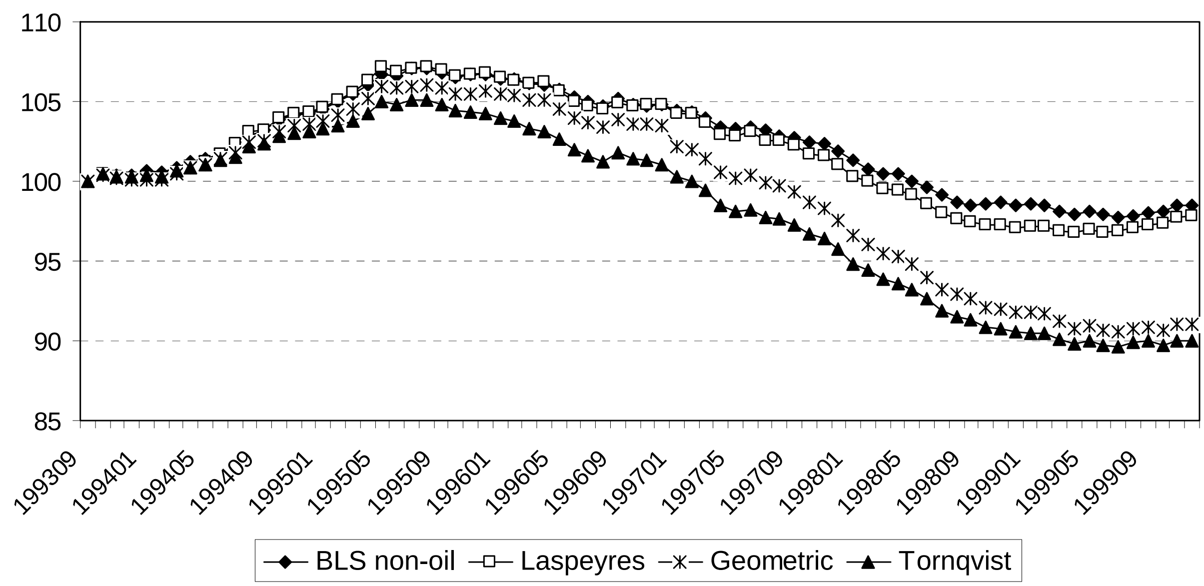


Figure 4: U.S. Import Prices



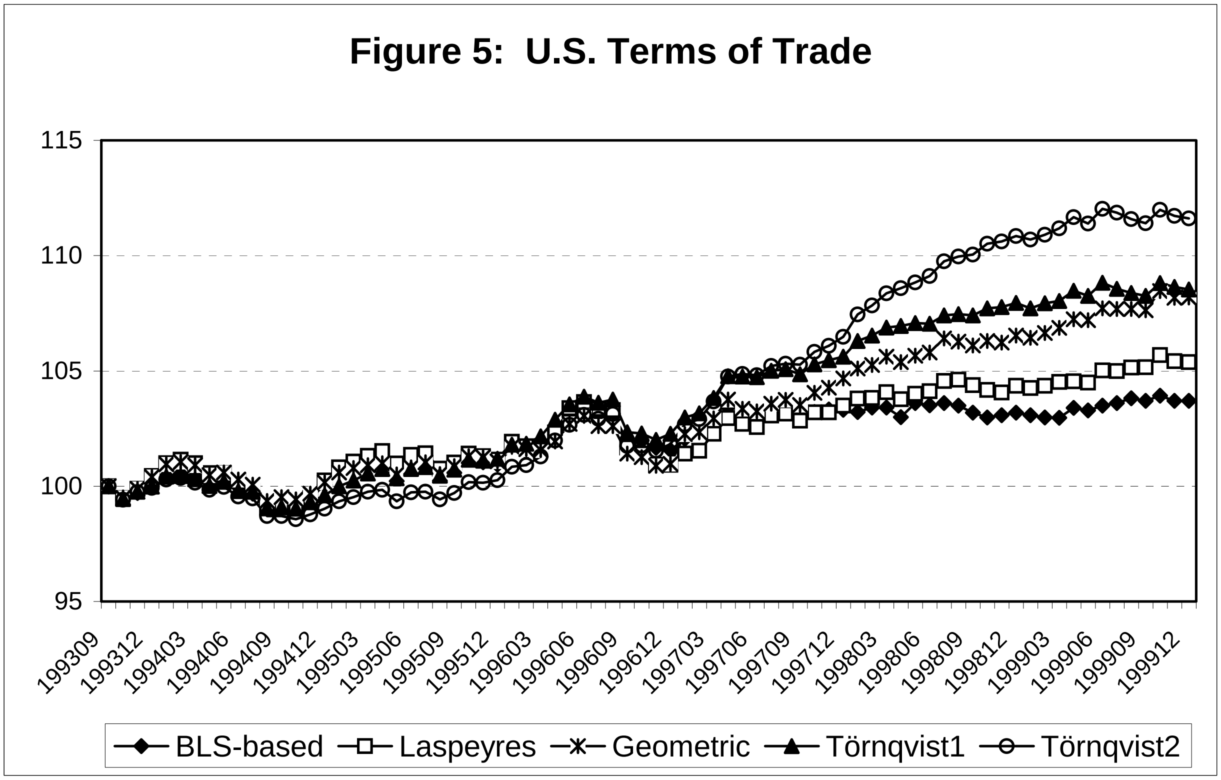


Figure 5: U.S. Terms of Trade
115
110
105
100
95
199309
199312
199403
199406
199409
199412
199503
199506
199509
199512
199603
199606
199609
199612
199703
199706
199709
199712
199803
199806
199809
199812
199903
199906
199909
199912
BLS-based
Laspeyres
Geometric
Törnqvist1
Törnqvist2