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Sector-Specific Technical Change

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Abstract: Economic theory suggests that the economy's response to a technology shock depends on the final-use sector that it affects. We provide a unified framework for measuring innovations to final-goods technology using industry-level innovations and the input-output tables. Our approach enables us to relax and test the assumptions maintained in the literature on investment-specific technical change, which measures relative technologies using relative prices—assumptions that, we find, provide a poor approximation in the short run. We find that the dynamic responses of the economy are, in fact, very different for consumption versus investment shocks. In particular, improvements in investment technology lead to sharp and statistically significant declines in hours worked, investment, consumption and output. Consumption technology improvements lead to an immediate boost to consumption, investment, and output, and little effect on hours worked. These results are robust to adjusting the data to match the Gordon investment deflators (as extended by Cummins and Violante)
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I. Introduction

Economic theory tells us that the composition of technological change, in terms of which final goods production is affected, matters for the dynamics of the economy's response to technology change. For example, we show that a shock to the technology for producing consumption goods has no interesting business-cycle effects in a standard RBC model. All of the dynamics of hours and investment stressed by RBC theory come from shocks to the technology for producing investment goods.[2] In an open economy, terms-of-trade shocks affect the economy's ability to provide consumption and investment goods for final use, even if no domestic producer has had a change in technology.

In this paper, we describe new evidence on the biases of technological change in favor of producing durables goods. Existing evidence in favor of the importance of biased change to growth and business cycles is based primarily on relative movements in the price deflators for investment and consumption goods, an approach pioneered in an important paper by Greenwood, Hercowitz and Krusell (1997; henceforth GHK). Our evidence, in contrast, is based on an augmented growth-accounting approach, where we estimate technology change at a disaggregated industry level and then use the input-output tables to aggregate these changes. Our decomposition clarifies the relationship between estimates in terms of producing industries and estimates in terms of final expenditure "sectors."

Our approach offers several advantages. First, we can relax and, indeed, test many of the assumptions necessary for relative-price movements to correctly measure relative changes in domestic technological change. For example, suppose different producers have different factor

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[2] Greenwood, Hercowitz and Krusell (2000) provide an insightful approach to business-cycle modeling with sector-specific technical change. However, they used a normalization for sector-specific technology that did not have a pure consumption-augmenting shock, and thus did not uncover this neutrality result.

shares or face different input prices; or suppose markups change over time. Then relative prices do not properly measure relative technical change.[3] Second, we discuss extensions to the open economy, where the ability to import and export means that relative investment prices need not measure relative technologies in terms of *domestic* production. Third, we can better assess the reasons why the trend decline in the relative price of durable goods accelerated after the 1970s. We find that two factors played a role in explaining this accelerating trend. First, in addition to some increases in the pace of investment goods total-factor-productivity (TFP) growth, TFP growth also slowed for non-durable consumption goods and services. Second, since the 1970s, an appropriately weighted measure of nominal input prices rose much more quickly in the production of consumption goods than for investment goods.

In conjunction, the theory and empirical work in our paper suggests that we need to revisit several influential empirical literatures using multi-sector economic models. For example, papers in the large literature on the macroeconomic effects of technology shocks typically examine the responses of macroeconomic variables to aggregate measures of technical change.[4] But if consumption- and investment-specific shocks are expected to have different economic effects, aggregating the two into a single measure can introduce significant measurement error in an explanatory variable. (Interestingly, the strong dichotomy between the effects of the two types of shocks typically does not hold in models with sticky prices. Thus, similarities or differences in the economy's response to consumption- and investment-specific shocks may also cast light on the importance of price stickiness in the macroeconomy.)

To take another example, many papers follow the suggestion of Cochrane (1994) and take the consumption-output ratio to be a measure of permanent income relative to current

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[3] We can also test the orthogonality restrictions used in the structural VAR approach of Fisher (2006), who also uses relative price data but with a long-run restriction.

[4] An exception is Fisher (2006).

income. In a general-equilibrium model, the gap is usually due to (expected) changes in productivity. Rotemberg and Woodford (1996) use this interpretation to fashion an empirical critique of RBC models by comparing the expected transitory changes in macroeconomic variables in the data to those predicted by a one-sector RBC model. But the correlation between expected changes in consumption, output and other variables can be quite different depending on whether the shock affects consumption technology, investment technology, or both. Thus, it may be necessary to revisit Rotemberg and Woodford's influential critique by comparing the data to the predictions of multi-sector RBC models.

Our approach to the data also forces us to think about the role of the open economy in economic fluctuations. That is, our approach requires that we take a stand on the "technology" for producing net exports. Thus, we need to decide whether to take a narrow or broad view of technology. The narrow view is to say that "technology" is just something that shifts a domestic production function. We choose to take a broader view, and define technology from the consumption possibilities frontier: At least in a neoclassical model where there are stable preferences and no distortions, technology is anything that changes consumption for given levels of capital, investment and hours worked. Technology thus defined therefore incorporates changes in the terms of trade. It is clear, of course, that terms of trade changes do not shift domestic production functions, and thus are not technology shocks in the narrow sense.[5] But it is also true that domestic technology shocks are not the only sources of changes in consumption and welfare, even in a fully neoclassical model. Understanding the behavior of consumption in both the short and long runs requires us to take an open-economy, multi-sector approach.

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[5] See Kehoe and Ruhl (2006).

.The paper is structured as follows. After this introduction, we demonstrate that simple economic theory suggests that consumption- and investment-specific shocks should have very different economic effects, and thus it would be interesting to obtain separate measures of the two and study their empirical effects. Next we present our method for obtaining disaggregated final-use shocks, with special attention to the role of the terms of trade. We then discuss the data, present results, and draw some preliminary conclusions.

II. Consumption-Technology Neutrality

The character of both growth and business cycles depends on the sectoral distribution of technical change. In the neoclassical growth model, capital accumulation arises only if technical change expands the possibilities for producing capital goods. Indeed, as shown by Kimball (1994), with balanced growth, technology change that affects the consumption-producing sector alone has no impact on employment or capital accumulation at all. Hence, the nature of growth is tightly connected to the sectoral distribution of technical change.

The response of a real business cycle model economy to an exogenous technology shock also depends on the sectors of the economy it affects. Hours and investment responses to a pervasive, sector-neutral, positive technology shock are well understood. They follow from the intertemporal substitution of current leisure and consumption for future consumption. The household is willing to do this because of the high returns to working and saving. These effects are amplified when technical change affects the investment sector alone, because current consumption is even more expensive relative to future consumption in this case (e.g., Fisher, 2005). Consumption-sector shocks have smaller effects on intertemporal substitution and so have much less effect on decision rules. As Fisher (1994, 1997) and Kimball (1994) discuss, if preferences are logarithmic, then the decision rules for investment and hours, as well as the allocation of capital and labor across producing consumption and investment goods, are invariant to the stochastic process of consumption-specific technology. More generally, for preferences that are consistent with balanced growth, hours and investment and factor allocations do not respond to a technology shock, if that shock is permanent, unanticipated, and affects only the consumption sector. So the nature of business cycles is also tied to the sectoral distribution of technical change.

We now present a simple model to illustrate these points. We then discuss other recent macroeconomic work that has focused on the final-goods sector in which technical change occurs. The empirical evidence has been drawn almost exclusively from aggregate data, with heavy reliance on relative prices.

Consider the two-sector closed-economy neoclassical growth model. Suppose one sector produces consumption goods C, the other sector produces investment goods, J (We use J to differentiate investment from the identity matrix, which we use extensively later). Both sectors produce output by combining capital K and labor L with the same function F but separate Hicks-neutral technology parameters, Z_C and Z_J.

In particular, consider the social planner's problem for the following problem, where utility is logarithmic:

$$\begin{aligned} &\max_{N,C,X,I} E_0 \sum_{t=0}^{\infty} \beta^t [\ln(C_t) - v(L_t)] \\ &s.t. \quad C = Z_C \cdot F(K_C, L_C) \\ &\qquad\;\; J = Z_J \cdot F(K_J, L_J) \\ &\qquad\;\; K = K_C + K_J, \quad L = L_C + L_J \\ &\qquad\;\; K_{t+1} = J_t + (1-\delta) K_t \end{aligned} \tag{1}$$

We omit (most) time subscripts for simplicity. This setup appears in the recent literature in various places. For example, this is a two-sector version of the model in Greenwood, Hercowitz, and Krusell (GHK, 1997); Whelan (2000) discusses the mapping to GHK in greater detail. There are various ways to normalize the technology shocks. For example, GHK define Z_J

$= Z_C q$, where $q = Z_J/Z_{C,.}$ GHK label Z_C as "neutral" technology and q as "investment specific," a labeling that has been widely followed since. A shock that raises Z_C but leaves q unchanged is neutral in that both Z_C and Z_J increase equally.

For the purposes of discussing consumption-technology neutrality, a different normalization is more natural. In particular, suppose we define $A = Z_C/Z_J$ as "consumption-specific" technology. Then the problem in (1) can be expressed as a special case of the following problem, where we have expressed the problem with a single aggregate budget constraint:

$$\begin{aligned} &\max_{N,C,X,I} E_0 \sum_{t=0}^{\infty} \beta^t [\ln(C_t) - v(L_t)] \\ &s.t. \quad C_t = A_t X_t \\ &\qquad\; X + J = F(K, L, Z) \\ &\qquad\; K_{t+1} = J_t + (1-\delta) K_t \end{aligned} \tag{2}$$

X is an index of inputs devoted to consumption (in the previous example, it would correspond to the production function $Z_J F(K_C, L_C)$. Since $X=C/A,$ and A corresponds (in the decentralized equilibrium) to the relative price of investment to consumption, we can interpret X as consumption in investment-goods units (i.e., nominal consumption deflated by the investment deflator). This is essentially the same approach taken by GHK, except that given their normalization, they express everything (investment and output, in particular) in consumption units. But given logarithmic utility, we can express this problem as:

$$\begin{aligned} &\max_{N,C,X,I} E_0 \sum_{t=0}^{\infty} \beta^t [\ln(A_t) + \ln(X_t) - v(L_t)] \\ &s.t. \quad X + J = F(K, L, Z) \\ &\qquad\; K_{t+1} = J_t + (1-\delta) K_t \end{aligned} \tag{3}$$

Consumption-technology neutrality follows directly from this expression of the problem. In particular, because *ln(A)* is an additively separable term, *any* stochastic process for A has no effect on the optimal decision rules for *L*, *X,* or *J*. They do not induce capital-deepening or any of the "expected" RBC effects; e.g., employment doesn't change. Consumption jumps up, which immediately moves the economy to its new steady state.[6] They affect only real consumption and the relative price of consumption goods. In contrast, investment-sector technology shocks would have much more interesting dynamics. They induce long-run capital-deepening, and even in the short-run affect labor supply and investment dynamics.

Thus, consumption-sector technology shocks are "neutral." .This consumption-technology neutrality proposition has been implicit in two-sector formulations for a long time; the first explicit references we are aware of are Kimball (1994) and Fisher (1994). Nevertheless, it appears to be a little-known result. One reason is that the seminal work by Greenwood, Hercowitz, and Krusell (1997) used a different normalization, as noted above; they focused on the response of the economy to "investment specific" shocks. A shock to consumption technology alone (leaving investment technology unchanged) would then involve a positive neutral shock, combined with a negative investment-specific shock.[7]

The theoretical motivation for studying sectoral technical change is bolstered by a nascent empirical literature. Most of this literature has followed the GHK normalization of "neutral" and "investment specific" shocks. GHK used data on real equipment prices and argued that investment-specific, not sector-neutral, technical change, is the primary source of economic growth, accounting for as much as 60% of per capita income growth. Cummins and Violante (2000) also find that investment-specific technical change is a major part of growth using more

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[6] Kimball (1994) discusses this case further, as well as the extension to King-Plosser-Rebelo (1988) preferences.

[7] Equivalently, a positive shock to investment-specific technology (with neutral technology unchanged) or a positive shock to neutral technology (leaving investment-specific technology unchanged) would *both* raise investment-technology in the two-sector formulation, and hence would lead to dynamic responses in the frictionless model.

recent data. Several papers also highlight the potential role sector-specific technology shocks in the business cycle. Greenwood, Hercowitz and Huffman (1988) were the first to consider investment-specific shocks in a real business cycle model. Other papers studying investment-specific shocks within the context of fully-specified models are Campbell (1998), Christiano and Fisher (1998), Fisher (1997), and Greenwood, Hercowitz and Krusell (2000). These authors attribute 30-70% of business cycle variation to permanent investment-specific shocks. In the structural VAR literature, Fisher (2006), extending the framework used by Gali (1999) to the case of investment-specific shocks, finds that investment-specific shocks explain 40-60% of the short-run variation in hours and output.[8]

This prior work is based on a "top-down" measurement strategy that relies on investment and consumption deflators (either directly from the BEA, or augmented with equipment deflators from Gordon (1990), and Cummins-Violante (2002). Our paper contributes to the literature by providing new measures of sector-specific technical change that, in principle, are more robust. These new measures of technical change can be used to assess the veracity of the existing literature's findings. The next few sections discuss some of the challenges involved in linking this framework to the disaggregated data. We begin with a conceptual issue of how to treat terms-of-trade effects. We then discuss how we use the input-output tables to create the link between disaggregated productivity and aggregate final-use sectors.

III. Terms of Trade Effects

For an open economy, relative prices capture not just relative technologies, but also terms-of-trade effects. More generally, terms-of-trade shocks affect the ability of an economy to produce consumption and investment goods, since one can export and import these kinds of

[8] Fisher's impulse response functions look similar to the subperiod results in Gali, Lopez-Salido, and Valles (2002), with technology shocks reducing hours worked in the pre-1979 period and raising them thereafter.

goods. As a simple example, suppose we import consumption goods and export investment goods. Then a terms of trade improvement, other things equal, allows us to obtain more consumption goods while producing (and using domestically) the same quantity of investment goods, and with no change in input use. One might, as a more realistic example, consider that if we get a better price for exporting financial services, we can import more (i) machine tools; (ii) consumption goods; and (iii) oil (which, once refined into petroleum products, is an intermediate input into everything).

These examples point out an ambiguity in the meaning of "technology" in the context of final expenditure. In an open economy, terms-of-trade shocks affect the economy's ability to supply consumption and investment goods, even if no production function changes.

The situation is somewhat analogous to a firm that produces a particular product using capital, labor, and intermediates. The firm's ability to convert a given quantity of inputs into that product is not affected by relative prices. But the firm's ability to obtain the output of another firm does depend on relative prices. Similarly, an economy's ability to produce final output depends on its ability to trade with the rest of the world (other producers) and on what terms. In our measurement, we will incorporate these terms-of-trade effects into our estimation of sectoral technologies.

In a productivity context, it is controversial to label terms of trade changes "technology shocks," since they do not shift any production function for domestic output. On the other hand, from the standpoint of thinking about the economy-wide budget constraint, trade clearly matters. Trade is, in effect, just a special (linear) technology: terms of trade changes allow consumers to have more consumption with unchanged labor input or investment. It is particularly useful to interpret terms-of-trade changes as "technology" in the context of sector-specific technical change, because the composition of imports and exports is quite different.

Nevertheless, it is important to keep in mind that this form of technology is a special one. For example, rather than having unbounded trend growth, we expect the trade "technology" to be stationary (at least if purchasing power parity holds in the long run).

Once again, the information in the input-output matrix allows us to keep track of trade flows, and discern the impacts of changes in the terms of trade on different categories of final expenditures.

IV. Sectoral Technical Change from the Bottom Up

A. Preliminaries

The input-output tables allow us to track flows of goods and services, in order to map disaggregated productivity data into aggregated final-use sectors. The tables tell us the uses of each identified commodity, where "commodity" means a category of goods or services. These uses include final uses (consumption, investment, government purchases, and net exports) and intermediate uses (e.g., steel sold as an input into the auto production). Several issues arise in using the input-output and productivity data.[9]

First, the standard use table shows the flows of *commodities* to final uses as well as to intermediate uses in *industry* (not commodity) production. But because of our interest in the sector of final use, we are inherently interested in the production of commodities, not production by industries. Some industries produce multiple commodities. In our two-digit data, the largest deviation between industries and commodities is in printing and publishing: About 62 percent of the production of the printing and publishing industry (in 1977) is the commodity labeled printing and publishing; most of the rest is services (the detailed BEA accounts reported in

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[9] Appendix A discusses the link between the simple dynamic theory presented earlier—with production functions for consumption and investment, and no intermediate inputs—and the complicated, rich, and interrelated data that we manipulate empirically. Later versions of this paper will make these links more explicit.

Lawson et al (2002) indicate that this is advertising services). In this example, the same establishment will often produce both commodities. Hence, as a data issue, the input-output accounts record inputs according to the primary product of the establishment. But the so-called "make" table shows what commodities each industry produces, which allows us to, in effect, produce a commodity-by-commodity use table. (The appendix discusses our specific manipulations. Nevertheless, with a few exceptions, the make table is close enough to diagonal that these manipulations do not make much difference.)

Second, productivity data (such as that obtained from the KLEM dataset of Jorgenson and his collaborators) is also in terms of industries; but final-use sales are in terms of commodities. So we need to convert industry productivity data into commodity productivity data. Again, the make table allows us to do that conversion. Suppose we have a column vector of industry productivity growth rates, dz^I. Conceptually, we interpret this vector of industry productivities as a "garbled" version of the column vector of commodity productivity growth rates, *dz*, that we are interested in, so that a weighted average of commodity technology growth equals industry technology growth, where the make table tells us the output-share weights . In particular, suppose we convert the make table *M* to row-share form, so that element m_{ij} corresponds to the share of output of industry *i* that consists of commodity *j*. Then $M\, dz_t = dz_t^I$. Thus, given the industry productivity-growth vector and the make table, the implied commodity productivity growth vector is $dz_t = M^{-1} dz_t^I$.

Third, the standard use table is in terms of domestically produced commodities and domestic industry production. But we can also import commodities to satisfy either intermediate or final demands; so given a focus on commodity uses, we want a use table that is in terms of total commodity supply and total commodity production. (For example, through imports, we could consume more than the total value of domestically produced consumption.) Total supply is, of course, either domestically produced or imported. The import information is already in the standard use table so, again, we must simply rearrange the information in the table.

We assume that have already incorporated the information from the make table to create a use table that is entirely in terms of commodities. For simplicity of presentation, we assume there are only two commodities in the economy and we ignore government purchases. The extension to more commodities and more final-use categories will be obvious.[10]

In simplified form, the use table (in nominal terms) represents the production and uses of domestically produced goods, and looks like (4) below. Rows represent uses of domestic production; columns (for commodities 1 and 2) represent inputs into domestic production. Row and column totals for the two commodities represent domestic production of the good.

	1	2	C	J	X	M	Row Total
1	$P_1Y_1^1$	$P_1Y_1^2$	$P_1 Y_1^C$	$P_2 Y_1^J$	$P_1^D Y_1^X$	$-P_1^M Y_1^M$	$P_1^D Y_1^D$
2	$P_2Y_2^1$	$P_2Y_2^2$	$P_2 Y_2^C$	$P_2 Y_2^J$	$P_2^D Y_2^X$	$-P_2^M Y_2^M$	$P_2^D Y_2^D$
K	$P_K^1 K^1$	$P_K^2 K^2$	$\dots$	$\dots$	$\dots$	$\dots$	$P_K K$
L	$P_L^1 L^1$	$P_L^2 L^2$	$\dots$	$\dots$	$\dots$	$\dots$	$P_L L$
Column total	$P_1^D Y_1^D$	$P_2^D Y_2^D$	$P_C C$	$P_J J$	$P_X X$	$-P_M M$	

(4)

Note that the domestic commodity price is P_i^D. The imported commodity price is P_i^M. The overall supply price of the commodity (a Divisia index of the domestic and imported prices) is simply P_i. In principle, the supply price of a commodity might differ for use as an intermediate input, consumption, or investment, since the mix of imported and domestic supply might differ. In practice, the data do not allow us to differentiate between uses of domestically

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[10] For the purposes of discussion, we also ignore so-called non-competing imports. When we apply our framework, we aggregate non-competing imports with commodity imports as "trade" inputs into the production of domestic supply; and we consider non-competing consumption, investment, and government goods as the direct contribution of "trade" to these final uses. Our discussion also ignores indirect business taxes, which would be an additional row of "value added" necessary for row and column shares to be equal. On the production side, we will need factor shares in producer's costs, which do not include these taxes.

produced versus imported commodities; so we assume all users face the same composite price. We assume that commodity exports are from domestic producers, with price P_i^D. Reading down a commodity column (1 or 2 in the example above) gives payments to each factor input. Implicitly, any pure profits are attributed to one or more of the factors; most obviously, they have been attributed to capital, whose factor payment is measured as a residual to ensure that the value of output equals the value of inputs. (Note that we have omitted time subscripts for simplicity.)

Total supply of a commodity is the aggregation of domestic production and imports. In nominal terms, the total supply of the commodity (column sums and row sums for commodities 1 and 2) is $P_i Y_i = P_i^D Y_i^D + P_i^M Y_i^M$.

The purpose of exports, of course, is to obtain imports. We can think of the import-export sector (what we'll call the "trade" sector—not to be confused with wholesale and retail trade) as a commodity. Consider the following rearrangement of the information in the use table:

	1	2	Trade goods	C	J	NX	Row Total
1	$P_1Y_1^1$	$P_1Y_1^2$	$P_1^DY_1^X$	$P_1Y_1^C$	$P_1Y_1^J$	…	P_1Y_1
2	$P_2Y_2^1$	$P_2Y_2^2$	$P_2^DY_2^X$	$P_2Y_2^C$	$P_2Y_2^J$	…	P_2Y_2
Trade goods	$P_1^MY_1^M$	$P_2^MY_2^M$	…	…	…	P_XX $-P_MM$	P_XX
K	$P_K^1K^1$	$P_K^2K^2$	…	…	…	…	P_KK
L	$P_L^1L^1$	$P_L^2L^2$	…	…	…	…	P_LL
Column total	P_1Y_1	P_2Y_2	P_XX	P_CC	P_JJ	P_XX $-P_MM$	

(5)

Note that the "final use" columns for consumption and investment don't change. For trade goods, the technology is that we export goods in exchange for imports. We also use the "trade goods" to obtain pieces of paper that represent claims on the future: net exports. So the final-expenditure category for trade goods is net exports; those are conceptually a form of investment. So the inputs into producing trade goods (shown in the "trade goods" column) are exports of commodities 1 and 2. The trade-goods row shows the uses of trade-goods output: we obtain imports of commodities 1 and 2 (which augment domestic production and increase commodity supply) as well as net exports. These commodity imports are then an input into producing a supply of the commodity, as well as being part of the output of the commodity. (This is comparable to the fact that some of the output of commodity 1 is used as an input into commodity 1; so that part of the input-output table already represents commodities that are both inputs and output of the commodity.)[11]

Corresponding to this nominal use table is a real use table. In most cases, the relevant deflator is obvious; and where we aggregate goods (e.g., nominal consumption expenditure), we use Tornquist aggregates that weight growth rates by nominal shares. The one exception to the "obvious" nature of the deflators is the deflator for overall trade-goods output. Nominal trade goods output equals the value of exports; that's the nominal value of the goods we supply to the rest of the world. The real output, though, is the real quantity of imports that we can get from those exports, so we deflate the nominal exports with the deflator for imports. Hence, growth in real trade goods equals growth in real exports *plus* the growth in the terms of trade. This is true for the final-use net-exports column, as well.

We can calculate technology change for each commodity, either using standard growth accounting to obtain a Solow residual or else using augmented growth accounting (as in Basu, Fernald, and Kimball, 2006) to obtain a "cleansed" residual. In any case, we essentially take growth in the real index of commodity supply and subtract growth in real inputs, possibly multiplied by an estimate of returns to scale, and possibly with a correction for utilization. Note that commodity imports are an intermediate input into the production of commodity supply, as

[11] We combine these imports with non-competing imports that are inputs into commodity production in the standard tables, with a row that corresponds to the commodity "non-competing imports." We will thus think about there being q commodities in total, in either the standard or our rearranged tables.

well as being part of the commodity output. (For Divisia indices, which the Tornquist approximates in discrete time, this simply leads to a rescaling of commodity TFP by the ratio of domestic production to total supply, much in the way that standard gross-output TFP is a scaled-down version of value-added TFP.)

For the trade sector, we assume the technology has constant returns to scale. Growth in real trade goods equals growth in exports *plus* the growth in the terms of trade; and growth in real trade inputs equals growth in exports. Hence, trade-commodity technology growth dz_{Trade} (dz_3 in the numbering above) is growth in the terms of trade, $(dp_X - dp_M)$.

Notationally, it will prove useful to transpose the use table and then take row shares. This yields the following:

$$\left[\begin{array}{r|ccc|cc} & 1 & 2 & \begin{array}{c}\text{Trade}\\ \text{goods}\end{array} & K & L \\ \hline 1 & b_{11} & b_{12} & b_{13} & s_{1K} & s_{1L} \\ 2 & b_{21} & b_{22} & b_{23} & s_{2K} & s_{2L} \\ \text{Trade goods} & b_{31} & b_{32} & 0 & \cdots & \cdots \\ \hline C & b_{C1} & b_{C2} & 0 & \cdots & \cdots \\ J & b_{J1} & b_{J2} & 0 & \cdots & \cdots \\ NX & 0 & 0 & 1 & \cdots & \cdots \end{array}\right] = \left[\begin{array}{ccc} & & | \quad | \\ B & & s_K \quad s_L \\ & & | \quad | \\ [\text{—} \quad b_C \quad \text{—}] & & \\ [\text{—} \quad b_J \quad \text{—}] & & \\ [\text{—} \quad b_{NX} \quad \text{—}] & & \end{array}\right] \tag{6}$$

Reading across a row, the shares sum to one. For the net exports row, we simply define the “trade goods” share to be 1, to avoid dividing by zero in the case where net exports are zero. The lines in the vectors on the right show whether we define them as row or column vectors.

B. Aggregation

The examples above used three final-use sectors (C, J, and NX). In our data, we will extend this to consumption of nondurables and services (C), consumer durables (CD), equipment and software investment (JE), structures (JS), government purchases (G), and net exports (NX). For final-use sector f, we define sectoral technology change as:

$$dz_f = b_f (I - B)^{-1} dz \tag{7}$$

Why does this provide a reasonable approach to aggregation? In aggregating up from commodity-level technology growth, it is desirable to have a relatively mechanical aggregation procedure that is not too sensitive to the details of a particular model. The analogy is Domar weighting. However, Domar weighting, because it aims at a comprehensive aggregate, does not need to explicitly address the issue of what a commodity is used for. By contrast, in order to get an aggregate consumption technology measure or an aggregate investment technology measure, one cannot avoid the issue of what a commodity is used for. Here, to avoid strong model sensitivity, we take as our standard the usage shares in which a given commodity is distributed in the steady-state—or in practice, the trend values of the usage shares.

This strategy of "constant-share aggregation" is convenient, because it implies that when the quantity produced of a commodity increases by 1 percent, the amount of the commodity in each use increases by 1 percent. This leads to quite tractable aggregation formulas. In particular, suppose there are q commodities (including the virtual "trade good"). Let ΓC_M be a qxq matrix where the rows give the elasticities of the output of a particular commodity with respect to each of the commodities as an intermediate input. Think of Γ as a qxq diagonal matrix of returns to scale parameters; and think of C_M as a matrix with each row giving the cost shares of the various commodities used as intermediate inputs into producing a given commodity. Under the assumption of zero profits (which we will make in what follows), $C_M = B$. But what follows depends only on ΓC_M being the matrix of elasticities of the output of one commodity with respect to each of the commodities as an input.

Now suppose there are innovations *dz* to the vector of commodity technologies. First, the vector *dz* gives the direct effect of commodity-level innovations on the *q* different commodity outputs. Second, under constant-share aggregation, the extra output of each commodity increases its use proportionately as an intermediate input into other commodities; this second-round effect is $\Gamma C_M dz$. Third, again under constant-share aggregation, these second round effects on the quantity of each commodity yields a third-round effect of $(\Gamma C_M)^2 dz$. In the end, as the technological improvements in the production of each commodity repeatedly work their way through the input-output matrix,there is an "input-output" multiplier of

$$[I + \Gamma C_M + (\Gamma C_M)^2 + (\Gamma C_M)^3 + ...]dz = [I - \Gamma C_M]^{-1} dz \tag{8}$$

In practice, we impose zero profits, which means that elasticities are proportional to the observed share matrix *B*. For the purposes of aggregation, we also set Γ equal to the identity matrix, at least at an initial step. When we use standard TFP—where constant returns is a necessary condition for it to measure technology—setting $\Gamma = I$ is quite natural. When we use Basu, Fernald, and Kimball (2004) residuals as a measure of technology, we could use their estimated Γ matrix. A concern there is that measurement error in estimating Γ is then inverted, so that positive and negative measurement error in Γ are not symmetric (in the way that positive and negative measurement error in the *dz* vector, for example, is symmetric and in the limit cancels out). We plan to revisit this estimation and aggregation issue in later drafts.[12]

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[12] Note that column *j* of $[I-B]^{-1}$ gives the direct and indirect effects of a shock to commodity *j* on the full vector of commodities. Row *j*, in turn, gives the effect on a given commodity *j* of the full vector of shocks. For intuition on what $[I-B]^{-1}$ looks like, recognize that I+B gives much of the weight, where the direct effect of shocks reflects the identity matrix, and the first indirect effect is given by the B matrix which, in turn, gives output elasticities under the assumption of constant returns and perfect competition.

Finally, multiplying by the row vector of final-use shares (e.g., $dz_C = b_C(I-B)^{-1}dz$) arises from the obvious aggregation of the bundles of commodities used to make the final-goods consumption basket and the final-goods investment basket.

C. Relating relative TFP to relative final-demand prices

For the closed economy case where there are no intermediate inputs (i.e., one representative producer uses capital and labor to produce consumption goods; another produces investment goods), our definitions match the two-sector growth model.

In practice, a large literature measures investment-specific technical change by the change in the relative price of consumption to investment. To highlight the conditions necessary for this relative-price/relative-technology relationship to hold, we now consider how our definition of relative TFP corresponds to relative output prices. (Standard TFP, of course, represents technology only under relative strict conditions; we return to this issue below.) In particular, we can write standard industry/commodity TFP in its dual form as growth in share-weighted real factor prices, or[13]

$$dz_i = s_{Ki}dp_{Ki} + s_{Li}dp_{Li} + s_{Ni}dp_{Ni} - dp_i \, . \qquad (9)$$

dp_{Ji} is growth in the input price for factor J in producing commodity I; s_{Ji} is its factor share, and dp_i is the growth in commodity price i (importantly, from the producer's point of view). For the international trade commodity, TFP growth is the terms of trade. In the dual formulation, international trade has capital and labor shares equal to zero (so the first term in

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[13] The equality of the dual and primal representations comes from differentiating the accounting identity that the value of output equals the value of input: $PY = P_L L + P_K K + P_N N$; for the identity to hold, any pure profits are included in the price of capital input. Putting quantity growth terms on the left-hand side and price growth terms on the right hand side $dy - s_L dl - s_K dk - s_N dn = s_L dp_L + s_K dp_K + s_N dp_N - dp$, where dj represents growth in the variable j, and s_J is the factor share for input J. In discrete time, this is not quite an identity, but the standard deviation of the approximation error is typically on the order of thousandths of a percentage point.

brackets is zero). We export in order to import. Hence, the intermediate input share in production is unity and the intermediate input price is the export price; the output price is the import price. With all prices and shares in column-vector form, equations (4) and (9) imply that we can write relative TFP growth as:

$$\begin{aligned} dz_J - dz_C &= (b_J - b_C)(I-B)^{-1} dz \\ &= (b_J - b_C)(I-B)^{-1}[s_K dp_K + s_L dp_L] + (b_J - b_C)(I-B)^{-1}[s_N dp_N - dp] \end{aligned} \quad (10)$$

Consider the final term in brackets. The intermediate-input share for producing commodities, s_N, is the row sum of the B matrix. And the intermediate input prices for producing commodities is the Tornquist index of all the <u>purchaser</u> prices, using the intermediate-input share matrix *B*. Indeed, suppose that there were no sales taxes or distribution margins (so purchaser and producer prices were equal), and that the foreign supply of each commodity had the same price as the overall import price deflator (the final element of the vector *dp*). Then it would exactly be the case that $s_N dp_N = Bdp$. In this special case, we would have:

$$\begin{aligned} dz_J - dz_C &= (b_J - b_C)(I-B)^{-1}[s_K dp_K + s_L dp_L - (I-B)dp] \\ &= (b_J - b_C)(I-B)^{-1}[s_K dp_K + s_L dp_L] + (b_C - b_J)dp \end{aligned}. \quad (11)$$

The first term on the right-hand-side is the difference in growth in share-weighted primary-input prices for capital and labor (after they have been passed through the I-O matrix $[I-B]^{-1}$); the second term is the difference in the growth of the relative price of consumption to investment (using the Divisia price index, which is a very close approximation to the national accounts definition). Suppose all sectors face the same input prices, have the same shares of capital and labor in revenue, and have a similar input-output structure (in particular, suppose the row-sums of $[I-B]^{-1}$ are all equal).[14] Then the first relative-factor-price term is zero—the

[14] Recall that row *j* of $(I-B)^{-1}$ gives the effect on commodity *j* of the vector of shocks hitting the economy, working through the input-outpu tables. For intuition, consider again that $(I-B)^{-1} = I+B+B^2+\ldots$. A shock to share-

consumption and investment sectors implicitly face the same share-weighted prices for capital and labor. In that case—which most macro models implicitly or explicitly assume—relative sectoral TFP shows up one-for-one in relative final-goods prices. This relative-price and relative-TFP decomposition suggests that our definition is a natural extension of the GHK case.

In practice, however, there is no reason to expect share-weighted factor prices to be equal for the consumption and investment sectors. First, equality of factor shares across producers clearly doesn't hold (see, for example, Herrendorf and Valentinyi, 2007). Second, factor prices movements are likely to differ across firms. For example, with adjustment costs/quasi-fixity, neither the ex ante nor the ex post return to capital need not be equated across firms. Moreover, indices for capital and labor input involve aggregating across different types of capital—and the mix of, say, high tech equipment (where prices have been falling rapidly) versus structures (where relative prices have been rising) differs across producers. Thus, even if the input price for an identical machine or an identical worker were equated across producers, the indices of capital or labor input prices could well differ.

More generally, there are two additional channels for changes in relative prices to diverge from relative TFP changes. First, the relevant intermediate-input price for the "use" of international trade is the foreign supply price for that commodity, [15] not the overall import price. If, for example, the price of imported investment goods falls relative to price of imported consumption goods then the consumption price will rise relative to the investment price. Second,

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weighted input prices in commodity *k* has an first-round indirect effect on the marginal cost of commodity *j* of $b_{k,j.}$ As the shock works its way through the I-O tables, there are further indirect effects given by B^2 and so on. Mechanically, suppose that factor shares and factor prices are equated, so that the vector of share-weighted input prices are equal. If the row-sums of $(I\text{-}B)^{-1}$ are also equal, then the consumption and investment share-weighted factor prices are also equal and cancel out—the direct and indirect effects of shocks to primary share-weighted factor prices hits all producers equally.

[15] More accurately, we need to aggregate the prices for foreign supply of the commodity with non-competing imports used in domestic production of the commodity.

the derivation above assumed that there are no changes in the wedges between the prices paid by purchasers versus the prices received by producer. Sales taxes and distribution margins can drive a wedge between these two. If, say, sales taxes rise on consumer goods relative to investment goods, then the consumption price will rise relative to the investment price. For the general case, the appendix derives the following identity:

$$\begin{aligned} dz_J - dz_C &= (b_C - b_J)dp + (b_J - b_C)(I-B)^{-1}[s_K dp_K^C + s_L dp_L^C] \\ &\quad + (b_J - b_C)(I-B)^{-1} b^{\text{Trade-column}} \left(dp^{\text{Commod-import-price}} - dp^M \right) + (b_J - b_C)(I-B)^{-1} \omega^D (dp^{\text{D,Purch}} - dp^{\text{D,Prod}}) \\ &= \text{Relative price + Input prices + Import-prices + sales-tax wedge} \end{aligned} \tag{12}$$

The final two terms capture the effects of relative import prices for investment and consumption goods; and the wedge between purchaser and producer prices.

So far, the decomposition has been a purely accounting one, and does not take a stand on whether standard TFP growth is a good measure of technology change. A substantial body of literature argues that, certainly in the short run, it is not. As is well known, to equate firm-level TFP growth with technology change, one generally needs to assume constant returns, perfect competition, and full observation of all inputs (including factor utilization). Basu, Fernald, and Kimball (2006) find that none of these conditions apply empirically, and suggest a method to control for the non-technological factors that affect measured TFP, such as variations in capital's workweek and labor effort. But in general, markups and variations in markups drive a further wedge between technology and relative prices.

D. An example

For further intuition, consider the 2x2 case where there is only one non-trade commodity. Commodity 2 is the trade-commodity. Then b_{21} equals 1 (only commodity 1 is exported) and b_{22} equals zero (the trade good is not an input into itself). In this case, $(I\text{-}B)^{-1}$ is

$$\left[I-\begin{bmatrix} b_{11} & b_{12} \\ 1 & 0 \end{bmatrix}\right]^{-1} = \begin{bmatrix} 1-b_{11} & -b_{12} \\ -1 & 1 \end{bmatrix}^{-1} = \left(\frac{1}{(1-b_{11}-b_{12})}\right)\begin{bmatrix} 1 & b_{12} \\ 1 & 1-b_{11} \end{bmatrix} \tag{13}$$

The consumption-sector (and, for that matter, investment sector) technology shocks are:

$$\begin{aligned} dz_C &= b_C[I-B]^{-1}dz \\ &= [1 \quad 0]\begin{bmatrix} 1 & b_{12} \\ 1 & 1-b_{11} \end{bmatrix}\begin{bmatrix} dz_1 \\ dz_2 \end{bmatrix}\left(\frac{1}{1-b_{11}-b_{12}}\right) \\ &= (dz_1 + b_{12}dz_2)/(1-b_{11}-b_{12}) \end{aligned} \tag{14}$$

dz_1 is technology growth in the non-trade commodity; dz_2 is the change in the terms of trade $(dp_X - dp_M)$. Hence, the technology for producing consumption goods in the economy can improve if the economy becomes better at producing the commodity; or if the terms-of-trade improve. The terms-of-trade improvement means that by exporting an unchanged quantity of the commodity, the country can increase its consumption because it can import more. In the denominator, the b_{12} term represents imports of commodity 1; they are an "input" into supplying the commodity, and we have already counted them as part of the supply of the commodity. Together, the (1-b_{11}-b_{12}) term represents the standard Domar weight from intermediate goods (in this case, of the commodity itself).

The "trade technology" is:

$$\begin{aligned} dz_{NX} &= b_{NX}(I-B)^{-1}dz \\ &= \begin{bmatrix} 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & b_{12} \\ 1 & 1-b_{11} \end{bmatrix}\begin{bmatrix} dz_1 \\ dz_2 \end{bmatrix}\left(\frac{1}{1-b_{11}-b_{12}}\right) \\ &= (dz_1 + (1-b_{11})dz_2)/(1-b_{11}-b_{12}) \end{aligned} \tag{15}$$

If either sector becomes more productive, then trade technology improves. By getting better at producing commodity 1, you become better at producing intermediate inputs (in this case, exports) that are used to "produce" imports. If the terms of trade improve, then a given quantity of exports now produces more imports.

V. Data

We use input-output data underlying the KLEM dataset produced by Dale Jorgenson and his collaborators.[16] These data, which run 1960-2004, provide consistent industry productivity (output and inputs) as well as commodity final-use data for 35 industries/commodities. (Annual make tables are available beginning in 1977.) We are not aware of any other disaggregated U.S. data set that covers the entire economy and allows productivity analysis for a long time period.

The original data sources for the input-output data and industry gross output data are generally the Bureau of Labor Statistics which has, for a long time, produced annual versions of both nominal and real (chained) I-O tables. (The Jorgenson data link together various vintages of the BLS data.) For the 35 commodities plus non-traded imports, the data include final expenditure on consumer non-durables and services, consumer durables, investment, government, and exports and imports.

Our data do not comprise all of GDP. First, they exclude the service flow from owner-occupied housing. Second, they exclude services produced directly as part of government administration (they do include government enterprises; and they include direct purchases by the government of goods and services produced by non-government businesses). Thus, our output measure corresponds to the output of businesses plus nonprofit institutions serving households.

The Jorgenson data offer several key advantages. First, they provide a unified dataset that allows for productivity analysis by providing annual data on gross output and inputs of capital, labor, and intermediates. Second, the input data incorporate adjustments for quality or composition; e.g., capital services from different types of capital are taken to be proportional to their user cost, as standard first-order-conditions imply, not proportional to their relative

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[16] The dataset updates Jorgenson, Gollop, and Fraumeni (1987). In addition to Dale Jorgenson, we have also discussed the data set with the following collaborators/co-authors: Barbara Fraumeni, Mun Ho, and Kevin Stiroh. Jon Samuels helped tremendously with data availability.

purchase prices. Third, the productivity data are unified with annual input-output data that are measured on a consistent basis.

We have separate prices for domestic commodity production and for commodity imports. For each commodity, we calculate a composite supply price as a Tornquist index, which we apply to (most) uses of the commodity. In essence, we assume that all users of a commodity consume the same composite of domestic and imported supplies of the commodity.[17]

Table 1 shows the shares of the 35 commodities/industries, plus the 36th "international trade" commodity, in each final-use sector. The columns shows the final-use commodity shares—e.g., the vectors b_{Ci}' or b_{JE}', where the elements sum to 100 percent—and the shares after passing them through the input-output tables, e.g., the vector $\left(b_{Ci}[I-B]^{-1}\right)'$.

Note that after incorporating the I-O flows, the column shares sum to much more than 100 percent. Intuitively, suppose a producer increases its gross-output by 1 percent. The firm could sell 1 percent more to, say, consumers, boosting consumption; but they can also boost sales as an intermediate input into other uses, which further boosts overall consumption beyond its initial effect. In the case of international trade, the key second-round "sales" are exports, which are the intermediate input into producing the international-trade commodity.

Note that, in some cases, such as construction, the direct investment effect is similar to the overall effect; in other cases, the overall effect is much larger than the direct effect. In general, sectors that sell primarily to final uses (such as construction) become relatively less important once passed through the I-O structure. This is because there is little "second round"

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[17] Relatively recently, the BEA has begun producing an "import matrix" that shows, for each commodity, the estimated industry uses of imports. But they create this table using the "assumption that each industry uses imports of a commodity in the same proportion as imports-to-domestic supply of the same commodity,",(http://www.bea.gov/industry/xls/1997import_matrix.xls, 'readme' tab) rather than using separate data on where imports flow. So the BEA makes the same assumption we do.

(and further) effect on the production of investment goods, coming from the use of construction goods, say, as an intermediate input. In contrast, sectors that produce a lot of intermediates (such as chemicals, finance, or services) become relatively more important when these second-round effects are taken into account.

Note that the Jorgenson data (and the BLS source data that underlie it) do not always match the BEA data. For example, the input-output data often differ, sometimes substantially, from the quinqennial benchmark BEA I-O tables, for example; and the final-use data are not always benchmarked to aggregate BEA totals. One place this shows up is in relative prices of consumption to investment. In particular, the top panel of Table 2 compares the growth in the price of nondurables and services consumption relative to the price for equipment investment. In the BEA data, this relative price rises sharply, especially over (roughly) the past two decades. The Jorgenson data shows a qualitatively very similar pattern, with an acceleration of roughly two percentage points in the relative price in the post-1982 period compared with the pre-1983 period.

Of course, the magnitude of the relative price movements are notably smaller in the Jorgenson data for both subsamples. In part, the differences appear to reflect fewer hedonic adjustments in the Jorgenson data (and, presumably, in the underlying BLS data). In addition, there are likely to be some aggregation errors. In particular, for all commodities, we follow Jorgenson and apply the “average” commodity supply price for all uses, whether consumption or investment. This average might provide a poor approximation to the actual purchase price paid for the investment component of these commodities (e.g., in retail, the actual margins on investment goods). Similarly, business services (such as computer installation services) are likely to have very different deflators than other services. In contrast, the BEA final-expenditure data are more likely to capture the actual transactions prices.

Much of the macroeconomics literature on investment-specific technical change has used alternative deflators for investment goods, following Gordon (1983) and its extension by Cummins and Violante (2002). We have incorporated these deflators in our work. First, we re-estimated industry capital-input measures; we modify the real equipment investment from the BEA's detailed investment-by-industry dataset, and then estimate perpetual inventory measures. This yields alternative asset-specific capital stocks, which we aggregate to an industry capital-input measure using estimated user-cost weights. Second, we modify commodity and industry output measures to account for the production of equipment goods. For example, if the extended Gordon deflators suggest an adjustment to, say, special industrial machinery, we modify the deflators for the Jorgenson commodity/industry "non-electrical equipment" to take account of this modification. The necessary modifications are fairly complex; details are available from the authors. In general, these modifications affect the means of the data (raising equipment technology growth and reducing consumption technology growth, for example), but regression coefficients discussed below are not much affected.

We also update the estimated industry technology residuals from Basu, Fernald, and Kimball (BFK, 2006). In particular, we estimate the following regressions at the level of each industry, using oil price increases, government defense spending, and a measure of monetary innovations (from a VAR) as instruments:

$$dy_i = c_i + \gamma_i dx_i + \beta dh_i + \varepsilon_i \,,$$

where *dy* is output growth, *dx* is share-weighted input growth, and *dh* is hours-per-worker growth (as a proxy for utilization). These estimates control for variations in factor utilization and deviations from constant returns to scale, both of which can drive a wedge between technology and measured TFP. For each industry, technology is measured as $c_i + \varepsilon_i$. See BFK (2006) or Appendix D of this paper for further details.

VI. Results

We now consider implications of our approach for various issues of relevance for macroeconomists. Unless indicated otherwise, all of our measures of TFP growth or technology change are based on the Jorgenson data adjusted with Gordon-Cummins-Violante deflators.

We first examine the long-run properties of the data. Figure 1A shows the estimated levels of final-use-sector TFP that we estimate from our data. Equipment investment TFP rises about as much as consumer-durables TFP, and much faster than non-durables-and-services TFP or government-purchases TFP. Structures TFP is fairly flat over the sample—indeed, its peak level is in the 1960s. Finally, final-use trade (net exports) technology shows a sharp decline in the 1970s—reflecting terms of trade shocks associated with oil price shocks and the breakdown of Bretton Woods—but then rises fairly strongly thereafter. The strength of the resurgence does not reflect terms-of-trade shocks (the level of the terms of trade moves relatively little after the early 1980s), but rather the indirect effects of other technology shocks. In particular, other sectors matter primarily through their effect on exports (since they are the intermediate input into producing trade goods, i.e., imports), and export-oriented sectors have tended to have faster-than-average TFP growth

Figure 1B shows the corresponding BFK measures. The figure suggests that, as one would expect, over longer periods of time, the BFK measures are qualitatively similar to uncorrected TFP measures. BFK, of course, focused on the differences in the properties of the technology residuals at higher frequency. Their corrections should (and do) have less effect at lower frequencies.

Next, we ask whether relative final-use output prices provide a good approximation to relative final-use TFP. Table 2.B shows the decomposition of relative final-use output prices for consumption (non-durables and services, plus government) to equipment (and software) investment based on equation (12). For all time periods shown, relative TFP in line (1) is qualitatively similar to relative price growth in line (2)—but quantitatively different. For example, line (3) shows that factor prices for capital and labor in equipment production have been consistently falling relative to factor prices in consumption production. One might think that this happens because equipment production has a larger capital share, and the price of capital has been falling relative to wages. Interestingly, and perhaps contrary to intuition, the capital share in equipment production is actually lower than the capital share in consumption production. However, the capital used in equipment production has a larger share of equipment, while more of the capital in consumption good production is structures. Equipment prices fall faster than the prices of structures. As a result, the factor price for equipment production falls faster, despite its lower overall capital share.

Line (4) shows that import prices for equipment have been falling relative to import prices for consumer goods. Not surprisingly, this effect is quantitatively more important in the past two decades.

Line (5) shows that the wedge between purchaser and producer prices, reflecting primarily sales taxes, contributed substantially to the wedge between consumption and equipment prices in the pre-1983 period. (The reason turns out to be rising sales taxes on consumer goods, which worked to raise consumer prices; the effect of this wedge on investment prices alone is relatively small.)

Looking at the final column, relative prices accelerated about 2 percentage points in the second half of our sample; but relative TFP accelerated only about 1.6 percentage points. Hence, the typical macroeconomic shortcut of focusing on relative prices substantially overstates the differences in relative TFP.

Does the acceleration in *relative* TFP and technology reflect an actual acceleration in investment-sector technology? Such an interpretation is implicit or explicit in GHK and much of the subsequent literature that focuses on "investment-specific technical change." But such a relative increase could also reflect a decline in consumption TFP growth.

Table 3.A shows average estimated final-use technology, using standard TFP. Panel B uses the BFK technology measures. In both cases, consumption TFP growth shows a modest uptick in the more recent sample period. (Reassuringly, the BFK measure shows that the growth rate in consumption TFP was positive, albeit small, over the full sample and in both sub-periods.) In contrast, the acceleration in investment-technology is much sharper, close to 1.5 percentage points by either measure.[18] Almost all of that is due to acceleration in equipment technology. Structures stubbornly show negative TFP growth in all sample periods and by any measure. This might happen if, despite our best efforts, we fail to fully correct the labor input measure for composition changes in the labor force (for example, if structures manufacturing generally uses less experienced and educated workers than we believe based on our data).

Government TFP is more similar to consumption than to equipment investment TFP, as one would expect, though it does show a more noticeable acceleration. Note that our "government TFP" is *not* the TFP in the production of services by government workers, which is set to zero by assumption in the National Accounts. We do not use the government production data at all in our calculations, since our underlying technical change data come exclusively from private industries. Our measure of government TFP growth is just the improvement in the technology of production of the goods that the government buys from private industries.

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[18] In earlier data, we found that TFP in both sectors slowed down. Marquis and Trehan (check reference) argued that faster relative investment-sector TFP reflected primarily a sharper slowdown in consumption-sector, consistent with the earlier data.

Table 4 shows selected correlations of sectoral and relative TFP. The sectoral shocks themselves are very highly correlated. This is not too surprising: In addition to any "common" shocks, the final-sector shocks are weighted averages of the same vector of underlying commodity shocks, albeit with quite different weights. However, the correlations are lower using the corrected BFK residuals, as one would expect: The BFK method was designed to eliminate the common mismeasurement coming from variations in factor utilization over the business cycle.

Our procedure allows us to test the orthogonality assumptions typically used in the preceding empirical literature. In particular, GHK and Fisher (2006) explicitly assume orthogonality of what they label "neutral" and (equipment) "investment-specific" productivity innovations. In our two-sector framework, these labels correspond to the consumption-sector productivity shock and the *relative* equipment-investment-consumption shock. Tables 4A and 4B show correlations, for standard TFP and BFK technology, respectively. In all cases, the final-sector technology shocks are highly correlated, as one would expect – they are mixtures of the same vector of shocks, after all. Line 3 shows the more important correlation between consumption TFP/technology and the relative (investment-specific) shock.

A priori, there seems little reason to expect orthogonality, given that these shocks are different mixtures of the same underlying productivity residuals. But the orthogonality assumption works surprisingly well in the data. For both standard TFP and for the BFK technology series, the correlation that the orthogonality assumption says should be zero are never statistically significant. (Note that Fisher (2006) does not assume that observed, standard TFP measures technology, so the BFK result is probably more relevant.) Note also that orthogonality with consumption TFP is a much better approximation than is orthogonality with investment TFP, as shown in line 4.[19]

Finally, what are the dynamic effects of exogenous shocks to different types of technology? Table 5 shows dynamic responses of GDP and its components to different final-use technology shocks, with all the dependent variables entered in growth rates.[20] We use as regressors the current and three lags of the growth in technology for producing equipment, non-durables and services consumption, and net exports. We selected these as the key components of disaggregated technology. We could add other shocks (e.g., to the production of consumer durables, or structures), but with more shocks multicollinearity starts to become a serious problem. Table 6 shows the same regressions for other interesting macroeconomic variables: hours, wages, a variety of prices, interest rates, and the stock market (Tobin's q). Most of the left-hand-side variables are entered in log differences, and the regressions include separate dummies for each decade.

We face a problem in interpreting "export technology"—the terms of trade—as exogenous. First, the terms of trade should change with changes in domestic consumption and investment technology, if these goods are exported. Second and more importantly, the terms of trade may change for reasons that are clearly not exogenous. For example, monetary policy can change the terms of trade if prices are sticky. Monetary policy may also react to changes in output or hours worked due to non-technology shocks, thus creating an endogeneity problem.

[19] The correlations for the entire period are not the averages of the correlations for the subperiods, because the standard deviations over the entire period exceed the average of the standard deviations for the subperiods. An interesting question that we have not yet pursued is what orthogonality of relative TFP and consumption TFP implies about the input-output structure of the economy.

[20] The GDP and investment data are taken directly from published BEA tables. They have not been adjusted using the Gordon investment deflators.

We address this problem by constructing a second set of measures of technology that we *do* think are exogenous, using only industry technology shocks based on the purified BFK residuals. Operationally, we set to zero changes in the terms of trade as well as changes in the TFP of sectors 1-5 and 35 as defined in Table 1 (the natural resource industries and government). We then use this group of rigorously exogenous measures as instruments for the various types of technology change in Table 5.

Focusing first on the effects of investment-specific shocks, we find results similar to those documented by Gali (1999) and BFK (2006), which are puzzling from the standpoint of a simple one- or two-sector RBC model with flexible prices. Aggregate GDP, non-durables consumption, purchases of consumer durables, residential investment and imports all fall significantly after a positive shock to equipment technology. Most puzzlingly, equipment and software investment falls for two years after a positive shock to the technology for producing investment goods, and the decline is highly significant in the first year. This last finding is especially striking if one considers the likelihood of measurement error in our measures of investment output. Since we are regressing investment output on the TFP of investment-goods-producing industries, measurement error in output would create a positive bias in the coefficient. Adjusting for measurement error, the true coefficients are likely to be even more negative than our estimates. (There is little autocorrelation in the investment technology growth series, so this result doesn't seem to reflect predictability that equipment technology will be even better in the future. In some models, news of a future technology improvement will cause demand to contract until the improvement is actually realized.)

Table 6 shows that hours worked fall significantly when investment technology improves, and do not recover their pre-shock value even after two years. Note that this is a decline in *total* hours worked in response to a *positive* technology shock to a sector that produces less than 10 percent of GDP! Although not shown, the updated BFK results show a distinct and significant negative contemporaneous correlation between hours growth and aggregated BFK technology. The negative effect is more pronounced with the original BFK industries (excluding agriculture, mining, and government enterprises).

As expected, an investment technology improvement significantly lowers equipment prices, albeit with a lag of two years (Table 6, line 6). The relative price of equipment goods to non-durables consumption also falls significantly with a lag of two years (line 4), with another decline that is significant at the 10 percent level the year after.

Surprisingly, *lagged* investment-technology improvements significantly raise Tobin's q. In general, we expect current shocks to affect current stock values—not old information. (We used end-of-period measures of stock prices to construct Tobin's q, in order to ensure that there are no issues of time aggregation.)

Next we examine the effects of consumption-technology shocks. Here again we find results at odds with simple RBC models which, as we noted, generally predict consumption technology neutrality. We see that consumption-technology shocks increase GDP and non-durables consumption significantly, but also increase both categories of business investment, consumer durables consumption and residential housing, with at least one statistically significant impact in each category. Imports rise significantly, and net exports fall. Table 6 shows that hours also increase, with the change significant at one lag. As expected, the relative price of consumption to equipment falls. Interestingly, this result is driven mostly by an increase in the nominal price of equipment. Consumption technology shocks have no significant effect on Tobin's q.

Our simple model of Section II predicts that business investment should not change in response to a consumption technology improvement. The model did not include residential investment and consumer durables. We conjecture that if the model is extended to allow for durable goods to provide services that directly enter the utility function, and incorporates non-separability between non-durables consumption and durables services, it would predict roughly the results that we find, at least qualitatively. It is less clear what changes to the model are necessary to reproduce the strong positive effects of consumption technology improvements on business investment.

Taken together, these results suggest that the earlier findings of Gali (1999) and BFK (2006) about the contractionary effects of technology improvements are driven primarily by the effects of investment technology shocks. They also raise an interesting question: Does any fairly standard model predict that consumption technology improvements should be expansionary, but investment technology improvements should not? We believe that a simple two-sector model with sticky prices in both sectors and a standard Taylor rule for monetary policy can reproduce most of the results we find. We are pursuing this approach to explaining our findings in current research.

Considering the two sets of results jointly, we find strong evidence that we cannot summarize technology shocks using a single aggregate index. Aggregation would hold either if (1) all final-use technology shocks were perfectly correlated or (2) if the different shocks had identical economic effects. Unfortunately, neither condition is satisfied, since Table 4B shows that the relevant correlation is between 0.64 and 0.75, and we can statistically reject the hypothesis that all the coefficients of investment- and consumption-technology shocks in Tables 5 and 6 are identical at all lags. Hence, it appears important to use multi-sector models to investigate economic fluctuations due to technology shocks.

The effects for the “trade technology shocks” are also interesting. Trade technology shocks improvements have significant positive effects on equipment investment, consumer durables, and even residential structures, with either one or two lags. Interestingly, the estimated effects on non-durables consumption are all close to zero, with small standard errors. An improvement in trade technology increases imports. There is a statistically significant effect on hours worked, but the size of the effect is small. As expected, a trade technology improvement leads to a large and significant improvement in the terms of trade, which can be measured by taking the difference of the total impact on the export and import prices in lines 8 and 9 of Table 6. Recall that our IV procedure guarantees that these effects on the terms of trade are being driven by changes in production technology in the United States and not, for example, by monetary policy either at home or abroad.

VII. Conclusions

Theory suggests that the final-use sector in which technology shocks occur matters for the dynamic response of those shocks. We make this point with the example of consumption-technology neutrality in the real-business-cycle model. Consistent with the predictions of the model, our empirical results show that consumption- and investment-specific shocks do indeed have significantly different economic effects, and the differences persist for at least several years.

The details of the results present several puzzles. The results for investment-sector shocks show that hours decline when investment technology improves, GDP declines sharply and, most surprisingly, investment itself declines strongly. These results are consistent with the findings of Gali (1999) and BFK (2006), who interpret them as evidence in favor of nominal price rigidities. Our findings for consumption shocks are quite different, however: they show significant increases in GDP and in the consumption of both non-durables and durable goods, including housing. Whether these results taken together can be explained by richer or differently-parameterized flexible-price or sticky-price models with multiple sectors is at this point an open question, although we find two-sector sticky price models promising in this regard.

A novel contribution of this paper is a new method to measure sector-specific technologies that does not rely simply on relative price changes, as frequently used in the macro literature. In special cases, the relative-price measures are appropriate; but in general, they are not. We show that the conditions necessary for relative prices to measure relative technologies do not hold in the data. Since our method allows us to test hypotheses that are identifying assumptions in other works, it is a robust, albeit data-intensive, way of checking whether these assumptions hold in any situation where their validity is in doubt.

Appendix A: The Optimal Mode of Production

In the theory of Section II, there are production functions for consumption and investment, which are each functions of the capital and labor dedicated to that that sector as well as the sector-specific technology level. But in the data, there are many sectors that use not only capital and labor, but use intermediate inputs from a large number of other sectors.

How do the theory and the data correspond? We now discuss a benchmark conceptualization of the data that allows us to map it into the dynamic theory. For now, we assume the economy is closed to international trade, and assume there are constant returns everywhere. Then, conceptually, we can think about there being a stream of production, using capital and labor dedicated to each specific final good, that eventually culminates in the given final good.

Unfortunately, we don't observe the stream of dedicated factors of production. More concretely, suppose each final good is produced on a separate island, using only the capital and labor that is on that island. Of course, if the final good is "shoes", then some of the capital and labor is used to produce leather, some to produce rubber, some to produce natural gas to generate electricity, some to drive trucks to transport goods from one factory to another, and so forth. The available data don't directly tell us how much capital and labor is used to produce shoes. Instead, the data tell us how much capital and labor and intermediate inputs of various sorts are used to produce rubber; or how much are used to produce trucking services; and so forth. So the challenge is to present a theoretically sound method to disentangle the data at hand.

We do so by showing, conceptually, what the production function looks like for a given element of the final good vector (cars, say, or shoes, or turbines). If there is then an aggregator function (e.g., a Cobb-Douglas consumption aggregator), then the resulting final-goods-sector technology maps exactly to what we use in the paper. One can then insert this aggregator into a simple dynamic model, such as the one used in the paper.

To begin, define net output of a commodity as the quantity produced that is used in the *direct* production of final goods—that is, the amount *not* used in the production of intermediate goods. Gross output of a commodity is the *total* amount of the commodity produced for all purposes.

Let R be the rental rate for capital K, W the wage for labor N, and Z a vector of multiplicative technology shifters. Consider the cost minimizing plan for making one unit of net output of commodity i available for use in producing final goods:

$$P_i(R,W,Z) = \min_{\hat{K}_{ij},\hat{N}_{ij},\hat{X}_{ij},\hat{M}_{ij\ell}} R\sum_j \hat{K}_{ij} + W\sum_j \hat{N}_{ij}$$

(1.1)

$$\begin{aligned} s.t.\quad & \hat{X}_{ii} = 1 + \sum_\chi \hat{M}_{i\chi i} \\ & \hat{X}_{ij} = \sum_\chi \hat{M}_{i\chi j} \quad (\forall j \neq i) \\ & \ln(\hat{X}_{ij}) = \ln(Z_j) + a_{jK}\ln(\hat{K}_{ij}) + a_{jN}\ln(\hat{N}_{ij}) + \sum_\ell b_{j\ell}\ln(\hat{M}_{ij\ell}) \quad (\forall j), \end{aligned}$$

The i subscript refers throughout to the fact that the program is intended to produce *net* output of commodity i. The hats on key variables are a reminder that the program is for *one* net unit of commodity i. $P_i(R,W,Z)$ is the minimum average (and marginal) cost of producing commodity *i*. $\hat{K}_{ij}$ is the amount of capital used directly to produce commodity *j* in order to produce one net unit of commodity *i*. $\hat{N}_{ij}$ is the amount of labor used directly to produce commodity *j* in order to produce one net unit of commodity *i*. $\hat{X}_{ij}$ is the *total gross amount* of commodity *j* used to produce one net unit of commodity *i*. $\hat{M}_{ij\ell}$ is the amount of commodity ℓ used directly to produce commodity *j* in order to produce one net unit of commodity *i*. Z_j is the multiplicative technology shifter for producing commodity *j*. a_{jK} is capital's share in the direct inputs to commodity *j*. a_{jN} is labor's share in the direct inputs to commodity *j*. Finally, $b_{j\ell}$ is the share of commodity ℓ in the direct inputs to commodity *j*.

Our objective in this appendix is to find the boiled down production function for net output of commodity *i* as a function of the technology vector and the total capital and labor inputs used directly or indirectly to produce net output of commodity *i*. We will use Shephard's Lemma (also called the derivative principle) to find capital's share α_i and labor's share $1-\alpha_i$, and the corresponding method to find the elasticity ξ_{ij} of net output with respect to each component Z_j of the technology vector *Z*. To be specific, by Shephard's Lemma, capital's share in the boiled-down net output production function is given by

$$\alpha_i = \frac{R}{P_i(R,W,Z)}\frac{\partial P_i(R,W,Z)}{\partial R}, \tag{1.2}$$

labor's share in the net output production function is given by

$$1-\alpha_i = \frac{W}{P_i(R,W,Z)}\frac{\partial P_i(R,W,Z)}{\partial W}, \tag{1.3}$$

and the elasticity of the net output production function with respect to Z_j is equal in magnitude but opposite in sign to the elasticity of the unit cost function with respect to Z_j

$$\xi_{ij} = -\frac{Z_j}{P_i(R,W,Z)}\frac{\partial P_i(R,W,Z)}{\partial Z_j}. \tag{1.4}$$

These elasticities of the unit cost function can be found by using the Envelope Theorem. First, write the Lagrangian for (1.1) as

$$\begin{aligned} L_i &= R\sum_j \hat{K}_{ij} + W\sum_j \hat{N}_{ij} \\ &+\sum_j \lambda_{ij}\left[\ln(\hat{X}_{ij}) - \ln(Z_j) - a_{jK}\ln(\hat{K}_{ij}) - a_{jN}\ln(\hat{N}_{ij}) - \sum_\ell b_{j\ell}\ln(\hat{M}_{ij\ell})\right] \\ &+\zeta_{ii} + \sum_j \zeta_{ij}\left[\left(\sum_\chi \hat{M}_{i\chi j}\right) - \hat{X}_{ij}\right]. \end{aligned} \tag{1.5}$$

The first order conditions with respect to $\hat{K}_{ij}$ and $\hat{N}_{ij}$ yield this pair of equations:

$$R\hat{K}_{ij}(R,W,Z) = a_{jK}\lambda_{ij}(R,W,Z) \tag{1.6}$$

$$W\hat{N}_{ij}(R,W,Z) = a_{jN}\lambda_{ij}(R,W,Z). \tag{1.7}$$

where we have made explicit the dependence of quantities and Lagrange multipliers coming out of the optimal program on *R*, *W*, and *Z*. By the definition of a_{jK} as the share of capital in direct production,

(1.8) $$R\hat{K}_{ij}(R,W,Z) = a_{jK}P_j(R,W,Z)\hat{X}_{ij}(R,W,Z).$$

Together, Equations (1.6) and (1.8) imply that

(1.9) $$\lambda_{ij}(R,W,Z) = P_j(R,W,Z)\hat{X}_{ij}(R,W,Z).$$

To get more insight into λ_{ij} define θ_{ij} as the total gross nominal output of commodity *j* used to produce $\frac{1}{P_i(R,W)}$ net units of commodity *i*. That is,

(1.10) $$\theta_{ij}(R,W,Z) = \frac{P_j(R,W,Z)}{P_i(R,W,Z)}\hat{X}_{ij}(R,W,Z),$$

Using Equation (1.10), Equation (1.9) can be written as

(1.11) $$\lambda_{ij}(R,W,Z) = \theta_{ij}(R,W,Z)P_i(R,W,Z).$$

To find θ_{ij}, consider the relationship between the net output production functions and the direct production functions. Because of the properties of Cobb-Douglas production functions, the value of the commodity *j* used *directly* to produce 1 net unit of commodity *i* is b_{ij}. In turn, obtaining b_{ij} net units of commodity *j* for direct use in the production of commodity *i* requires, in turn, the overall production of a value $b_{ij}\theta_{j\ell}$ of commodity ℓ. Overall, the total value of commodity ℓ produced must be $\theta_{i\ell} = \sum_j b_{ij}\theta_{j\ell}$, except that when $\ell = i$, $\theta_{ii} = 1 + \sum_j b_{ij}\theta_{ji}$, since one must account for the original unit value of commodity *i* that is to be produced. In matrix form,

(1.12) $$\Theta = I + B\Theta,$$

where $\Theta = [\theta_{ij}]$, $\mathrm{B} = [b_{ij}]$, and *I* is the identity matrix. Solving for Θ,

(1.13) $$\Theta = (I - B)^{-1}.$$

Note that for the Cobb-Douglas case, the matrix Θ is a constant.

Now return to the problem of finding the parameters of the boiled-down, net output production function. By the Envelope Theorem,

(1.14) $$\alpha_i = \frac{R}{P_i}\frac{\partial P_i}{\partial R} = \frac{R}{P_i}\frac{\partial L_i}{\partial R} = \frac{R\sum_j \hat{K}_{ij}}{P_i} = \frac{\sum_j \lambda_{ij}a_{jK}}{P_i} = \frac{\sum_j \theta_{ij}P_i a_{jK}}{P_i} = \sum_j \theta_{ij}a_{jK}.$$

Note that P_i, $\hat{K}_{ij}$, λ_{ij}, and a_{jK} are all functions of *R*, *W*, and *Z*, since the optimal program for producing one unit of net output of commodity *i* depends on *R*, *W*, and *Z*. (L_i is a function of almost everything in sight.) Similarly,

(1.15) $$1 - \alpha_i = \sum_j \theta_{ij}a_{jN}.$$

In vector form,

(1.16) $$\alpha = \Theta a_K$$

and

(1.17) $$1-\alpha=\Theta a_N.$$

where 1 in Equation (1.17) represents a vector of 1's. These are all constants in the Cobb-Douglas case. Finally, the elasticity of output with respect to component *j* of the technology vector is

(1.18) $$\xi_{ij}=-\frac{Z_j}{P_i}\frac{\partial P_i}{\partial Z_j}=-\frac{Z_j}{P_i}\frac{\partial L_i}{\partial Z_j}=\frac{\lambda_{ij}}{P_i}==\theta_{ij}.$$

Since all the elasticities of the boiled-down net output production function are constant, it must be given by

(1.19) $$Y_i=\text{constant }\cdot K_i^{\alpha_i}N_i^{1-\alpha_i}\prod_j Z_j^{\xi_{ij}}=\text{constant }\cdot K_i^{\sum_j\theta_{ij}a_{jN}}N_i^{1-\sum_j\theta_{ij}a_{jN}}\prod_j Z_j^{\theta_{ij}},$$

where Y_i represents *net* output of commodity *i*.

Now suppose we calculate the TFP residual, dz_i^f, for net (**f**inal) output Y_i. In its natural growth-rate form, this is:

$$dz_i^f=\sum_j\theta_{ij}dz_j$$

In vector terms, we can write this as:

$$dz^f=\Theta dz=(I-B)^{-1}dz$$

Now suppose there is a Cobb-Douglas consumption aggregator (reflecting the form of the utility function). Growth in this aggregate is thus equal to share-weighted growth in its components. Hence: $dc=b_C dy_i$, where b_C is a row vector of nominal shares in consumption. If we now calculate TFP for this aggregate *dc*, we find:

$$dz_C=b_C(I-B)^{-1}dz$$

This expression exactly matches what we used in the text. Of course, the Cobb-Douglas assumption is not restrictive—we could, instead, use a translog index, which provides a second-order approximation to any aggregator. The same expression holds with a translog, except that the shares would be time-varying, not constant.

A similar logic obviously applies to other final expenditure categories. Thus, we can think of there being a production function (implicit, perhaps not explicit) for consumption as a function of capital and labor and consumption-technology; and a corresponding production function for investment. We can then embed these functions into our dynamic macroeconomic model.

Appendix B: Further Details on I-O Manipulations

This appendix provides further details on how we combine the use and make tables to produce a commodity-by-commodity use table and commodity technology change measures. As in the text, we omit time subscripts for notational convenience.

As noted in the text, the standard use table shows the flows of *commodities* to final uses as well as to intermediate uses in *industry* (not commodity) production. We use the information in the make table to produce a commodity-by-commodity use table as follows. Each row of the make table corresponds to an industry; the columns correspond to commodities. So a row tells what commodities are produced by each industry. Consider the make table *M* in row-share form, so that element m_{ij} corresponds to the share of output of industry *i* that consists of commodity *j*.

From the standard use table, we know the shares of each input (the q commodities plus capital and labor) in industry production; define that commodity-by-industry use matrix as U^I, where columns correspond to industries and each row corresponds to a separate input into that industry. (One of these input commodities is so-called non-competing imports.) Conceptually, this commodity-by-industry use table is a "garbled" version of the commodity-by-commodity use table, which we denote by U. The make table tells us the garbling: $UM' = U^I$.

For example, suppose there are two industries, which produce using inputs of two commodities and one primary input, labor. These matrices have the following form:

$$UM' = \begin{pmatrix} u_{11} & u_{12} \\ u_{21} & u_{22} \\ u_{L1} & u_{L2} \end{pmatrix} \begin{pmatrix} m_{11} & m_{21} \\ m_{12} & m_{22} \end{pmatrix} = \begin{pmatrix} u_{11}m_{11} + u_{12}m_{12} & u_{11}m_{21} + u_{12}m_{22} \\ u_{21}m_{11} + u_{22}m_{12} & u_{21}m_{21} + u_{22}m_{22} \\ u_{L1}m_{11} + u_{L2}m_{12} & u_{L1}m_{21} + u_{L2}m_{22} \end{pmatrix} = U^I \tag{20}$$

The columns of U sum to one, and give the factor shares in producing each commodity. On the right hand side, the elements are industry factor shares, which are weighted averages of the commodity factor shares, where the weights are the shares of industry output accounted for by each commodity. For example, consider the upper left element, $u_{11}m_{11} + u_{12}m_{12}$. $u_{11}m_{11}$ is the factor share of commodity one in the production of commodity one, u_{11}, multiplied by the share of the output of industry one that consists of commodity one; $u_{12}m_{12}$ is the factor share of commodity one in the production of commodity two, multiplied by the share of industry one that consists of the output of commodity two. Under the assumption that the commodity factor shares are equal—regardless of which industry produces the commodity—the sum of these two pieces tells us the factor share of commodity one in the production of the composite output of industry one. More generally, the factor shares in each observed industry equal the weighted average of the factor shares in producing each of the underlying commodities that the industry produces. It follows from this discussion that we can obtain the underlying commodity-by-commodity factor shares using the relationship: $U = U^I M'^{-1}$.

Second, we want a vector of disaggregated productivity innovations in terms of commodities rather than industries. Suppose we have a column vector of industry productivity growth rates, dz^I. We again interpret this as a garbled version of the column vector of commodity productivity growth rates, dz, that we are interested in; the make table again tells us the garbling: $M\,dz_t = dz_t^I$. In the two-commodity example:

$$\begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} dz_{1,t} \\ dz_{2,t} \end{pmatrix} = \begin{pmatrix} m_{11}dz_{1,t} + m_{12}dz_{2,t} \\ m_{21}dz_{1,t} + m_{22}dz_{2,t} \end{pmatrix} = \begin{pmatrix} dz_{1,t}^I \\ dz_{2,t}^I \end{pmatrix} \tag{21}$$

The industry productivity growth rates are a share-weighted average of the commodity productivity growth rates, where the weights depend on what commodities the industry produces. Hence, given the industry productivity-growth vector and the make table, the relationship $dz_t = M^{-1}dz_t^I$ gives us the underlying commodity productivity growth vector.

Appendix C: Relative Prices and Relative TFP

To begin, let's review the link between observed domestic industry TFP and overall commodity supply TFP. First, we have assumed that domestic industry TFP growth, dz_t^I is "garbled" domestic commodity TFP growth, dz_t^D where the make table tells us the garbling: $M\,dz_t^D = dz_t^I$. Hence, $dz_t^D = M^{-1}dz_t^I$.

Second, we need to rescale commodity TFP by the domestic-supply share. To see this, observe that "supply" output is the aggregate of domestic production and imported supply; it is produced using domestic imports and, as an additional intermediate input, the imported supply of the commodity. In particular, we can write supply TFP as follows:

$$\begin{aligned} dz_i &= dy_i - s_{Ki}dk_i - s_{Li}dl_i - s_{Ni}dn_i \\ &= [\omega_i^D dy_i^D + (1-\omega_i^D)dy_i^F] - \omega_i^D \tilde{s}_{Ki}dk_i - \omega_i^D \tilde{s}_{Li}dl_i - [\omega_i^D \tilde{s}_{Ni}d\tilde{n}_i + (1-\omega_i^D)dy_i^F] \\ &= \omega_i^D (dy_i^D - \tilde{s}_{Ki}dk - \tilde{s}_{Li}dl_i - \tilde{s}_{Ni}d\tilde{n}_i) \\ &= \omega_i^D dz_i^D \end{aligned}$$

In this expression, tildes over a variable represent domestic production values. (Note that for capital and labor, the domestic and total inputs are the same, so that no tilde is necessary.) We have also used the fact that, for example,

$s_{Li} = \left(W_i L_i / P_i Y_i\right) = \left(P_i^D Y_i^D / (P_i^D Y_i^D + P_i^F Y_i^F)\right)\left(W_i L_i / P_i^D Y_i^D\right) = \omega_i^D \tilde{s}_{Li}$.

Combining these two pieces, we have that $dz_i = \omega_i^D M^{-1} dz_t^I$. Inserting the dual measure of TFP, we have:

$$\begin{aligned} dz_i &= \omega_i^D M^{-1}(\tilde{s}_K^{Ind} dp_K + \tilde{s}_L^{Ind} dp_L + \tilde{s}_N^{Ind} d\tilde{p}_N - dp^P) \\ &= \omega_i^D M^{-1}\tilde{s}_K^{Ind} dp_K + \omega_i^D M^{-1}\tilde{s}_L^{Ind} dp_L + \left(\omega_i^D M^{-1}\tilde{s}_N^{Ind} d\tilde{p}_N + (1-\omega_i^D)dp_i^F\right) - \left(\omega_i^D M^{-1} dp^P + (1-\omega_i^D)dp_i^F\right) \\ &\equiv s_K dp_K^C + s_L dp_L^C + s_N dp_N^C - dp^{P,C}. \end{aligned}$$

Note that, in the last line, we have the share matrices from our manipulations of the use and make tables. The commodity input prices are defined implicitly in order to make the identity hold; in essence, this approach weights industry prices by both the (inverse) make table and by the industry factor shares. (This weighting captures the intuition with Divisia indices of weighting by relative factor shares.)[21] We have included the foreign supply price in intermediate inputs as well as in the producer commodity supply price.

We can now seek to understand the relationship between relative TFP and relative output prices. In particular, the equation we want to understand is:

$$\begin{aligned} dz_J - dz_C &= (b_J - b_C)(I-B)^{-1} dz \\ &= (b_J - b_C)(I-B)^{-1}[s_K dp_K^C + s_L dp_L^C + s_N dp_N^C - dp^{P,C}.] \\ &= (b_J - b_C)(I-B)^{-1}[s_K dp_K^C + s_L dp_L^C] + (b_J - b_C)(I-B)^{-1}[s_N dp_N^C - dp^{P,C}] \end{aligned}$$

Consider the final piece in brackets for the case of two domestic commodities, plus the international trade commodity:

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[21] For example, in Matlab, one can calculate $dp_K^C = \omega_i^D M^{-1}\tilde{s}_K dp_K ./ s_K$, where "./", or dot-division, does element-by-element division.

$$s_N dp_N^C - dp^{P,C} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \\ b_{X,1} & b_{X,2} \end{bmatrix} \begin{bmatrix} dp_1^Z \\ dp_2^Z \end{bmatrix} + \begin{bmatrix} \omega_1^D \tilde{s}_{13} dp_1^{NC} + (1-\omega_1^D) dp_1^F \\ \omega_2^D \tilde{s}_{23} dp_2^{NC} + (1-\omega_2^D) dp_2^F \\ 0 \end{bmatrix} - \begin{bmatrix} dp_1^{P,C} \\ dp_2^{P,C} \\ dp^M \end{bmatrix}$$

$$= \begin{bmatrix} b_{11} & b_{12} & \omega_1^D \tilde{s}_{13} + (1-\omega_1^D) \\ b_{12} & b_{22} & \omega_2^D \tilde{s}_{23} + (1-\omega_2^D) \\ b_{X,1} & b_{X,2} & 0 \end{bmatrix} \begin{bmatrix} dp_1^Z \\ dp_2^Z \\ dp^M \end{bmatrix}$$

$$+ \begin{bmatrix} \omega_1^D s_{13} dp_1^{NC} + (1-\omega_1^D) dp_1^F - \left(\omega_1^D \tilde{s}_{13} + (1-\omega_1^D)\right) dp^M \\ \omega_2^D s_{23} dp_2^{NC} + (1-\omega_2^D) dp_2^F - \left(\omega_2^D \tilde{s}_{23} + (1-\omega_2^D)\right) dp^M \\ 0 \end{bmatrix} - \begin{bmatrix} dp_1^{P,C} \\ dp_2^{P,C} \\ dp^M \end{bmatrix}$$

$$= \left[Bdp - dp\right] + \begin{bmatrix} b_{13}\left(dp_1^{\text{Import}} - dp^M\right) \\ b_{23}\left(dp_2^{\text{Import}} - dp^M\right) \\ 0 \end{bmatrix} + \begin{bmatrix} \omega_1^D (dp_1^{\text{D,Purch}} - dp_1^{D,P}) \\ \omega_2^D (dp_2^{\text{D,Purch}} - dp_2^{D,P}) \\ 0 \end{bmatrix}$$

(Notation might need to be cleaned up, especially with the difference between the domestic purchase price (as measured in dpz) and the domestic producer price (rearranged producer price)—but the identity is correct and holds in our data.)

. Note that $b_{13} = \left(\omega_1^D s_{13} + (1-\omega_1^D)\right)$ is the final column of the B matrix. The first term in brackets is the relationship we have used in the text. The second term is the difference between the commodity-specific import price and the aggregate import price. The final term is the difference between the price paid by a user of a commodity price (what's relevant for the supply price), and the price received by a domestic producer. This final term can be nonzero because of taxes that drive a wedge between producer and purchaser prices, or because of discrepancies in the data between producer-side data and commodity-use data.

We now substitute into the full expression:

$$dz_J - dz_C = (b_J - b_C)(I-B)^{-1}[s_K dp_K^C + s_L dp_L^C] + (b_J - b_C)(I-B)^{-1}[s_N dp_N^C - dp^{P,C}]$$

$$= (b_C - b_J)dp + (b_J - b_C)(I-B)^{-1}[s_K dp_K^C + s_L dp_L^C]$$

$$+ (b_J - b_C)(I-B)^{-1} \begin{bmatrix} b_{13}\left(dp_1^{\text{Import}} - dp^M\right) \\ b_{23}\left(dp_2^{\text{Import}} - dp^M\right) \\ 0 \end{bmatrix} + (b_J - b_C)(I-B)^{-1} \begin{bmatrix} \omega_1^D (dp_1^{\text{D,Purch}} - dp_1^{D,P}) \\ \omega_2^D (dp_2^{\text{D,Purch}} - dp_2^{D,P}) \\ 0 \end{bmatrix}$$

= Relative price + Input prices + Import-prices + sales-tax wedge

The first term is the Divisia index of the relative price of consumption to investment; the second is relative share-weighted input prices. The third reflects relative import prices: It is negative if, over time, import prices for investment goods have fallen relative to import prices for consumption goods. The final term reflects (primarily?) indirect business taxes, such as sales taxes, that drive a wedge between producer and purchaser prices. It is negative if taxes on investment goods have been falling relative to taxes on consumption goods.

In the text, we write this expression in a more notationally compact manner as:

$$dz_J - dz_C = (b_C - b_J)dp + (b_J - b_C)(I-B)^{-1}[s_K dp_K^C + s_L dp_L^C]$$
$$+ (b_J - b_C)(I-B)^{-1} b^{\text{Trade-column}} \left(dp^{\text{Commod-import-price}} - dp^M \right) + (b_J - b_C)(I-B)^{-1} \omega^D (dp^{\text{D,Purch}} - dp^{\text{D,Prod}})$$

= Relative price + Input prices + Import-prices + sales-tax wedge

Appendix D: Updating Basu, Fernald, and Kimball (2004) Industry Residuals

With our new dataset, we update the estimated industry technology series produced in Basu, Fernald, and Kimball (2006). The approach uses a Hall (1990)-style regression, which allows for non-constant returns to scale and imperfect competition; BFK add hours-per-worker to the regression as a proxy for unobserved variations in labor effort and capital's workweek. The basic idea behind the utilization proxy is that a cost-minimizing firm operates on all margins simultaneously, both observed and unobserved. As a result, changes in observed margins can proxy for unobserved utilization changes. If labor is particularly valuable, for example, firms will work existing employees both longer (observed hours per worker rise) and harder (unobserved effort rises).

More specifically, let industries have the following gross-output production function:

(22) $$Y_i = F^i \left(A_i K_i, E_i H_i N_i, M_i, Z_i \right).$$

The industry produces gross output, Y_i, using the capital stock K_i, employees N_i, and intermediate inputs of energy and materials M_i. The capital stock and number of employees are quasi-fixed, so their levels cannot be changed costlessly. But industries may vary the intensity with which they use these quasi-fixed inputs: H_i is hours worked per employee; E_i is the effort of each worker; and A_i is the capital utilization rate (that is, capital's workweek). Total labor input, L_i, is the product $E_iH_iN_i$. The production function F^i is (locally) homogeneous of γ_i in total inputs. γ_i exceeding one implies increasing returns to scale, reflecting overhead costs, decreasing marginal cost, or both. Z_i indexes technology.

With cost minimization, the standard first-order conditions give the output elasticities, which we use to weight growth of each input. Let dx_i be observed input growth, and du_i be unobserved growth in utilization. (For any variable *J*, we define *dj* as its logarithmic growth rate $\ln(J_t / J_{t-1})$.) This yields:

(23) $$dy_i = \gamma_i (dx_i + du_i) + dz_i ,$$

where

(24) $$dx_i = s_{Ki} dk_i + s_{Li}(dn_i + dh_i) + s_{Mi} dm_i ,$$
$$du_i = s_{Ki} da_i + s_{Li} de_i ,$$

and s_{Ji} is the ratio of payments to input *J* in total cost.

The challenge is to derive a suitable proxy for unobserved output utilization variation, du_i.. Suppose firms seek to minimize the present discounted value of costs for any given path of output. There is a convex costs of adjusting the quasi-fixed factors (*K* and *N*). Total compensation per worker is $WG(H,E)V(A)$, where *W* is the base wage; the function *G* specifies how the hourly wage depends on effort, *E*, and the length of the workday, *H*; and *V*(*A*) captures a shift premium associated with varying capital's workweek. (This true shadow wage might be implicit, and not observed in the data at high frequency.) Thus, firms must pay a higher wage to get workers to work longer (on a given shift), or to work harder, or to work at night. In this environment, BFK show that, as a first-order approximation, the following expression holds:

$$dy_i = \gamma_i \, dx_i + \beta_i dh_i + dz_i .$$

The coefficient β_i, which can be estimated, relates observed hours growth to unobserved variations in labor effort and capital's workweek. That coefficient incorporates various elasticities including, in particular, the elasticity of unobserved effort with respect to hours, from the implicit function relating them (which came out of optimization).

We estimate these equations using instrumental variables, in order to control for correlation between technology shocks and input growth. As described in BFK, we use updated versions of two of the Hall-Ramey instruments: oil prices and growth in real government defense spending. For oil, we use increases in the U.S. refiner acquisition price. We also use, as a third instrument, an updated estimate of Burnside's (1996) quarterly Federal Reserve "monetary shocks" from an identified VAR. In all cases, we have quarterly instruments; we sum the four year *t-1* quarterly shocks as instruments for year *t*.[22]

Specific regression results will be available in a later version of the paper. Relative to the BFK estimates, parameters are often somewhat different (reflecting both data revisions and some differences in data definitions), but qualitatively, results appear consistent with the earlier estimates. In particular, when we use the old and new data, constrained to the common sample period of 1961-1996, the correlation between the resulting Domar-aggregated BFK technology shocks (restricted to the BFK industry sample, which is the non-farm, non-mining private economy) is about 0.7.

We need residuals for all commodities (industries) that are used as intermediate inputs or that use intermediate inputs. BFK did not estimate residuals for agriculture (commodity 1, in Jorgenson's mnemonics), mining (2-5), or government enterprises (35). TFP is highly volatile, and the instruments have no explanatory power. In the updated Jorgenson dataset, the instruments also have very low explanatory power for inputs into petroleum refining (16), finance, insurance, and real estate (33), and services (34). These are large sectors but, at least for FIRE and services, are relatively uncorrelated with developments in the overall economy. For agriculture, mining, and government enterprises (1-5, 35), we simply use the uncorrected TFP residuals as our measure of BFK technology—i.e., we make no correction for utilization or non-constant returns to scale. For petroleum refining, FIRE, and services, we constrain returns to scale to equal one, but allow for utilization effects. (The first-stage fit was extremely poor for overall inputs; the estimated returns to scale coefficients were implausibly small and imprecisely estimated. However, these constraints had little qualitative effect on the properties of the resulting residuals.)

To conserve parameters, we restrict the utilization coefficient within three groups: durables manufacturing (11 industries); non-durables manufacturing (10); and non-manufacturing (8).

For trade-goods technology (commodity 36), we use the terms of trade directly in this version of the paper. It is, of course, likely to have an important endogenous component, responding to a wide range of other shocks (e.g., demand shocks at home and abroad). Thus, a

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[22] BFK find that results are robust to different combinations and lags of the instruments; results are not driven by any one of these instruments. They also discuss the small sample properties of instrumental variables.

reduced-form shock to, say, hours worked (e.g., a labor supply shock, or a monetary shock) could affect the terms of trade and thereby affect our measures of technology. As a result, we also experiment with simply zeroing out the terms of trade shock. These results will be included in a later draft of the paper.

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Table 1. Commodities final-goods shares, 1961-2004 average (percent)

		Investment in Equipment		Investment in Structures		NDS Consumption		Durables Consumption		Government		Trade	
		Final-use share, b_{JEi}	I-O Share, $b_{JEi}[I-B]^{-1}$	Final-use share, b_{JSi}	I-O Share, $b_{JSi}[I-B]^{-1}$	Final-use share, b_{Ci}	I-O Share, $b_{Ci}[I-B]^{-1}$	Final-use share, b_{CDi}	I-O Share, $b_{CDi}[I-B]^{-1}$	Final-use share, b_{Gi}	I-O Share, $b_{Gi}[I-B]^{-1}$	Final-use share, b_{Ti}	I-O Share, $b_{Ti}[I-B]^{-1}$
1	Agriculture	-0.68	2.75	0.00	2.95	1.23	9.92	0.00	3.95	0.03	3.81	0.00	13.72
2	Metal mining	0.00	0.65	0.00	0.42	0.00	0.15	0.00	0.56	-0.03	0.42	0.00	0.85
3	Coal mining	0.00	0.60	0.00	0.41	0.01	0.65	0.00	0.60	0.04	0.81	0.00	1.53
4	Oil and gas extraction	0.00	2.29	0.00	2.29	0.00	4.31	0.00	2.17	-0.03	4.10	0.00	4.78
5	Non-metallic mining	0.00	0.23	0.00	1.29	0.00	0.19	0.00	0.26	0.02	0.68	0.00	0.61
6	Construction	0.00	1.37	93.73	94.75	0.85	2.82	0.00	1.53	36.92	38.37	0.00	1.60
7	Food and kindred product	0.56	3.60	0.00	1.48	10.17	15.56	0.00	4.28	1.99	4.30	0.00	8.58
8	Tobacco	-0.06	0.14	0.00	0.08	0.91	1.19	0.00	0.20	0.00	0.14	0.00	1.24
9	Textile mill products	0.86	2.40	0.00	0.86	0.26	2.07	0.00	3.26	0.08	1.09	0.00	2.17
10	Apparel	0.09	0.65	0.00	0.19	3.45	4.02	0.00	1.07	0.47	0.80	0.00	1.28
11	Lumber and wood	1.43	3.20	0.00	7.49	0.01	0.82	0.00	2.02	0.05	3.69	0.00	2.30
12	Furniture and fixtures	3.18	3.69	0.00	0.45	0.00	0.08	0.00	5.73	0.52	0.86	0.00	0.58
13	Paper and allied	0.59	3.16	0.00	1.66	0.53	3.14	0.00	3.29	0.77	3.50	0.00	4.45
14	Printing, publishing and	0.20	0.98	0.00	0.50	0.63	1.84	0.00	2.90	1.86	2.85	0.00	1.32
15	Chemicals	0.86	7.33	0.00	4.77	2.23	7.15	0.00	7.21	1.48	7.14	0.00	14.57
16	Petroleum and coal products	0.46	2.56	0.00	3.01	2.67	5.00	0.00	2.27	2.71	5.70	0.00	4.54
17	Rubber and misc plastics	0.43	3.58	0.00	2.32	0.16	1.59	0.00	5.62	0.38	2.66	0.00	3.47
18	Leather	0.02	0.12	0.00	0.04	0.69	0.90	0.00	0.23	0.03	0.11	0.00	0.36
19	Stone, clay, glass	0.09	1.38	0.00	6.52	0.03	0.87	0.00	2.18	0.11	3.34	0.00	1.74
20	Primary metal	-0.23	12.39	0.00	8.49	0.00	2.15	0.00	9.98	0.22	8.41	0.00	10.97
21	Fabricated metal	2.08	8.84	0.00	9.60	0.08	2.24	0.00	7.82	1.61	8.08	0.00	7.09
22	Machinery, non-electrical	26.85	35.90	0.00	4.79	0.01	2.45	0.00	7.75	2.65	7.99	0.00	18.01
23	Electrical machinery	8.19	16.27	0.00	5.04	0.14	2.24	0.00	15.75	2.97	8.30	0.00	12.19
24	Motor vehicles	16.77	22.47	0.00	1.08	0.00	1.38	0.00	33.07	1.90	3.94	0.00	10.33
25	Transportation equipment	3.68	6.30	0.00	0.82	0.00	0.93	0.00	5.13	11.40	15.35	0.00	10.13
26	Instruments	8.40	10.10	0.00	0.83	0.12	0.91	0.00	3.00	4.29	5.82	0.00	4.79
27	Misc. manufacturing	1.03	1.41	0.00	0.42	0.52	0.86	0.00	4.70	0.32	0.68	0.00	1.23
28	Transportation	1.05	7.72	0.00	6.25	2.83	7.89	0.00	8.57	3.67	10.45	0.00	15.85
29	Communications	1.10	3.15	0.00	1.62	2.53	5.13	0.00	2.04	1.79	3.82	0.00	2.74
30	Electric utilities	0.00	2.54	0.00	1.87	2.89	5.14	0.00	2.80	2.92	5.06	0.00	2.94
31	Gas utilities	-0.02	1.41	0.00	1.20	1.11	3.02	0.00	1.46	0.27	1.99	0.00	1.95
32	Wholesale and Retail Trade	13.53	25.91	0.00	12.90	22.23	29.42	0.00	48.70	2.07	13.05	0.00	21.37
33	Finance Insurance and Real Est.	0.00	8.45	6.27	13.52	14.08	25.62	0.00	9.60	4.63	12.78	0.00	16.28
34	Services	9.54	23.37	0.00	15.27	27.97	43.24	0.00	15.77	9.48	23.37	0.00	17.24
35	Government enterprises	0.00	0.78	0.00	0.62	0.80	1.87	0.00	0.85	0.48	1.20	0.00	0.81
36	International Trade	0.01	20.46	0.00	7.46	0.86	8.68	0.00	19.19	1.91	13.69	100.00	116.93
	COLUMN TOTALS	100.00	248.13	100.00	223.27	100.00	205.45	0.00	245.51	100.00	228.34	100.00	340.56

Notes:

Table 2. Relative output prices, relative input prices, and relative sectoral TFP
(percent change, annual rate)

A. Prices of nondurable and services consumption relative to price of equipment investment, BEA and Jorgenson datasets

	1960-2004	1960-1982	1982-2004
BEA	2.66	1.58	3.70
Jorgenson	1.48	.68	2.28
Jorgenson – adjusted with Gordon deflators	2.54	1.57	3.52

Notes: Price index for consumption of non-durables and services is calculated as a chained-price index. In Jorgenson, equipment investment is all investment less construction investment. Services of owner-occupied housing are excluded from both the Jorgenson data, and from the BEA calculation.

B. Jorgenson data (adjusted with Gordon deflators):
Relative prices and relative sectoral TFPs

	Full Sample (1)	**1960-1982 (2)**	**1982-2004 (3)**	**Acceleration ((3) – (2))**
(1) Relative TFP (Equip. invest. relative to NDS consump.)	2.42	1.60	3.24	1.65
(2) Relative price (NDS consump. relative to equip. investment)	2.54	1.57	3.52	1.95
(3) Relative primary input prices (equip relative to NDS cons.)	0.19	0.09	0.29	0.20
(4) Relative import prices (equip. relative to NDS cons.)	-0.43	-0.27	-0.59	-0.32
(5) Relative sales tax wedge (equip. relative to NDS cons.)	0.11	0.21	0.02	-0.19

Notes: Terms are defined in the text. NDS consumption is non-durables and services.

Table 3. Sample average growth rates of sector-specific technologies
(Standard TFP and BFK estimates)

A. Final-goods sector TFP growth
(percent change, annual rate)

	1960-2004	1960-1982	1982-2004
(1) Consumption TFP, dz_C	-0.22	-0.24	-0.21
(2) Durables Consumption, TFP dz_{CD}	1.44	0.85	2.08
(3) Investment TFP, dz_J	0.80	0.20	1.46
3a. Equipment dz_{JE}	2.20	1.40	3.06
3b. Structures dz_{JS}	-0.63	-0.67	-0.59
(4) Government TFP, dz_G	0.90	0.53	1.31
(5) Trade TFP, dz_{Trade}	0.29	-1.39	2.13

B. Final-goods sector technology, using Basu, Fernald, Kimball industry shocks
(percent change, annual rate)

	1960-2004	1960-1982	1982-2004
(1) Consumption TFP, dz_C	0.10	0.08	0.12
(2) Durables Consumption, TFP dz_{CD}	1.67	0.99	2.42
(3) Investment TFP, dz_J	0.94	0.31	1.62
3a. Equipment dz_{JE}	2.23	1.42	3.11
3b. Structures dz_{JS}	-0.36	-0.47	-0.24
(4) Government TFP, dz_G	1.08	0.64	1.56
(5) Trade TFP, dz_{Trade}	0.37	-1.36	2.26

Notes: TFP is calculated for domestic production in the 35 industries in the Jorgenson dataset, converted to a commodity-supply basis, and aggregated to final-use sectors as described in the text. The bottom panel uses industry residuals estimated following Basu, Fernald, and Kimball (2006). BFK do not have estimates for agriculture, mining, and government enterprises; for those industries, technology is taken to be standard TFP.

Table 4. Correlations of sector-specific residuals

A. Selected correlations of sectoral TFP

	1960-2004	1960-1982	1982-2004
(1) Corr(dz_J, dz_C)	0.83	0.90	0.75
(2) Corr(dz_{JE}, dz_C)	0.74	0.82	0.67
(3) Corr(dz_{JE} - dz_C, dz_C)	0.18	0.27	-0.02
(4) Corr(dz_{JE}- dz_C, dz_J)	0.61	0.58	0.54

B. Selected correlations of sectoral BFK technology

	1960-2004	1960-1982	1982-2004
(1) Corr(dz_J, dz_C)	0.70	0.73	0.75
(2) Corr(dz_{JE}, dz_C)	0.45	0.43	0.60
(3) Corr(dz_{JE} - dz_C, dz_{CG})	-0.06	-0.09	-0.01
(4) Corr(dz_{JE}- dz_C, dz_J)	0.59	0.53	0.57

Notes: dz_J is TFP or technology for overall investment; $dz_{J,E}$ is for equipment and software; dz_C is for non-durables and services consumption. With 44 observations, a correlation of 0.25 is significant at the 10 percent level and 0.30 is significant at the 5 percent level; with 22 observations, a correlation of 0.36 is significant at the 10 percent level and 0.43 is significant at the 5 percent level. See also notes to Table 3.

Table 5 Regression results for GDP Components

	Technology shocks												
	Equipment and consumer durables				Consumption (nondurables and services)				Net Exports				
	dzjecd	dzjecd(-1)	dzjecd(-2)	dzjecd(-3)	dzc	dzc(-1)	dzc(-2)	dzc(-3)	dznx	dznx(-1)	dznx(-2)	dznx(-3)	R^2
1 GDP	-0.62	-0.37	0.12	-0.05	0.65	0.57	0.00	0.10	-0.06	0.17	0.04	0.10	0.58
	(0.16)	*(0.13)*	*(0.14)*	*(0.11)*	*(0.19)*	*(0.22)*	*(0.39)*	*(0.22)*	*(0.1)*	*(0.06)*	*(0.09)*	*(0.04)*	
2 Investment	-1.98	-2.12	0.10	0.26	1.77	2.24	-0.41	-0.65	-0.36	0.40	0.40	0.32	0.59
(equipment and software)	*(0.51)*	*(0.54)*	*(0.38)*	*(0.28)*	*(0.63)*	*(0.76)*	*(1)*	*(0.93)*	*(0.27)*	*(0.21)*	*(0.19)*	*(0.11)*	
3 Consumer durables	-0.76	-0.43	0.45	-0.32	1.49	1.57	-0.79	0.05	-0.10	0.63	-0.11	0.19	0.52
	(0.43)	*(0.36)*	*(0.43)*	*(0.32)*	*(0.47)*	*(0.76)*	*(1.29)*	*(0.53)*	*(0.29)*	*(0.19)*	*(0.19)*	*(0.12)*	
4 Consumption	-0.30	-0.15	-0.06	-0.04	0.33	0.37	0.32	0.16	0.07	0.07	0.01	0.03	0.55
(Nondur+serv)	*(0.06)*	*(0.08)*	*(0.08)*	*(0.06)*	*(0.07)*	*(0.1)*	*(0.19)*	*(0.1)*	*(0.05)*	*(0.04)*	*(0.03)*	*(0.02)*	
5 Investment	-1.93	-2.67	-0.49	0.19	1.64	1.89	1.19	-0.85	-0.08	-0.28	0.31	0.51	0.38
(nonresidential structures)	*(0.74)*	*(0.76)*	*(0.43)*	*(0.28)*	*(1)*	*(1.01)*	*(1.56)*	*(1)*	*(0.33)*	*(0.3)*	*(0.24)*	*(0.22)*	
6 Investment	-2.04	0.19	0.14	-1.17	2.96	0.88	-0.62	0.57	0.19	1.66	0.06	-0.01	0.60
(residential structures)	*(0.77)*	*(0.84)*	*(0.65)*	*(0.64)*	*(0.75)*	*(1.72)*	*(2.41)*	*(1.66)*	*(0.59)*	*(0.67)*	*(0.36)*	*(0.33)*	
7 Exports	-1.25	-0.90	0.13	0.18	0.75	-0.39	0.52	0.12	-0.13	0.15	0.28	0.47	0.37
	(0.44)	*(0.5)*	*(0.51)*	*(0.36)*	*(0.63)*	*(0.79)*	*(1.61)*	*(1.06)*	*(0.28)*	*(0.22)*	*(0.19)*	*(0.15)*	
8 Imports	-1.84	-1.10	0.08	-0.44	1.73	0.06	1.18	0.63	0.45	0.55	0.23	0.14	0.57
	(0.47)	*(0.33)*	*(0.27)*	*(0.22)*	*(0.75)*	*(0.81)*	*(1.21)*	*(0.58)*	*(0.28)*	*(0.2)*	*(0.2)*	*(0.12)*	

Notes: Instrumental variables regressions from 1963-2004. All variables are in annual growth rates. Dependent variables are shown in the left column. Regressors are current and lagged values of BFK final-use-sector technology shocks shown, along with a constant term (not shown). Instruments are corresponding variables where the terms of trade and technology in agriculture, mining, and government enterprises are zeroed out before aggregation. Heteroskedastic and auto-correlation robust standard errors in parentheses

Table 6 Regression results for other variables

	Technology shocks												
	Equipment and consumer durables				Consumption (nondurables and services)				Net Exports				
	dzjecd	dzjecd(-1)	dzjecd(-2)	dzjecd(-3)	dzc	dzc(-1)	dzc(-2)	dzc(-3)	dznx	dznx(-1)	dznx(-2)	dznx(-3)	R^2
1 Hours	-0.61	-0.61	0.07	0.06	0.12	0.58	-0.05	-0.09	-0.04	0.14	0.11	0.11	0.50
	(0.17)	(0.18)	(0.18)	(0.13)	(0.19)	(0.23)	(0.4)	(0.27)	(0.11)	(0.06)	(0.08)	(0.05)	
2 Wage	-0.01	-0.20	-0.29	-0.25	0.44	0.11	0.54	0.30	-0.04	-0.09	-0.14	-0.05	0.62
(Jorgenson)	(0.15)	(0.14)	(0.17)	(0.11)	(0.18)	(0.25)	(0.53)	(0.21)	(0.11)	(0.09)	(0.06)	(0.05)	
3 GDP deflator	-0.24	-0.24	-0.32	-0.08	-0.05	0.10	0.34	-0.03	-0.07	-0.15	-0.02	-0.03	0.89
(Jorgenson, GCV-adj.)	(0.09)	(0.1)	(0.12)	(0.08)	(0.11)	(0.16)	(0.28)	(0.16)	(0.04)	(0.06)	(0.03)	(0.03)	
4 Rel price: CNDS to Equip	0.15	-0.12	0.27	0.20	-0.39	0.04	-0.57	-0.40	-0.19	0.21	0.07	0.09	0.60
(Jorgenson, GCV-adj.)	(0.17)	(0.18)	(0.09)	(0.11)	(0.2)	(0.26)	(0.33)	(0.34)	(0.11)	(0.09)	(0.09)	(0.04)	
5 Con. price	-0.13	-0.29	-0.23	-0.05	-0.13	0.11	0.13	-0.03	-0.20	-0.08	-0.03	0.00	0.87
(Jorgenson, GCV-adj.)	(0.1)	(0.11)	(0.11)	(0.09)	(0.13)	(0.17)	(0.28)	(0.16)	(0.05)	(0.05)	(0.04)	(0.03)	
6 Equip price	-0.28	-0.17	-0.50	-0.24	0.26	0.06	0.70	0.37	-0.01	-0.30	-0.10	-0.09	0.90
(Jorgenson, GCV-adj.)	(0.12)	(0.13)	(0.12)	(0.09)	(0.17)	(0.29)	(0.34)	(0.3)	(0.08)	(0.09)	(0.07)	(0.03)	
7 Structures price	-0.10	-0.24	-0.32	-0.13	-0.21	0.23	0.54	0.01	-0.12	-0.12	0.04	0.00	0.81
(Jorgenson, GCV-adj.)	(0.13)	(0.13)	(0.17)	(0.11)	(0.29)	(0.27)	(0.47)	(0.24)	(0.08)	(0.1)	(0.06)	(0.04)	
8 Export price	-0.34	-0.27	-0.39	-0.05	0.24	0.14	0.71	-0.06	-0.15	-0.27	0.00	-0.05	0.90
(Jorgenson, GCV-adj.)	(0.14)	(0.12)	(0.17)	(0.11)	(0.16)	(0.28)	(0.51)	(0.24)	(0.1)	(0.09)	(0.05)	(0.05)	
9 Import price	0.54	-0.10	-0.38	-0.12	0.31	-0.05	0.86	0.08	-0.93	-0.28	-0.05	-0.07	0.97
(Jorgenson, GCV-adj.)	(0.14)	(0.15)	(0.17)	(0.1)	(0.15)	(0.32)	(0.58)	(0.24)	(0.13)	(0.11)	(0.06)	(0.05)	
10 Fed Funds Rate	-0.10	-0.86	-0.42	-0.35	-0.36	0.45	-0.29	0.27	-0.26	0.05	-0.12	0.13	0.77
	(0.17)	(0.23)	(0.12)	(0.08)	(0.26)	(0.4)	(0.56)	(0.39)	(0.16)	(0.11)	(0.08)	(0.07)	
11 10-year Treasury	-0.20	-0.45	-0.31	-0.23	0.02	-0.19	-0.06	-0.12	-0.03	0.01	-0.02	0.08	0.92
	(0.06)	(0.1)	(0.05)	(0.05)	(0.1)	(0.19)	(0.21)	(0.12)	(0.06)	(0.04)	(0.03)	(0.03)	
12 Tobin's q	0.12	2.90			-0.66	-1.63			2.07	-1.04			0.31
	(1.29)	(1.08)			(2.57)	(1.42)			(0.42)	(0.37)			

Notes: Instrumental variables regressions from 1963-2004. All variables except interest rates are in annual growth rates; interest rates are entered in levels. Dependent variables are shown in the left column. Regressors are current and lagged values of BFK final-use-sector technology shocks shown, along with a constant term (not shown). Regressions with prices or the wage also include decade dummies for the 1970s and 1980s. Instruments are corresponding variables where the terms of trade and technology in agriculture, mining, and government enterprises are zeroed out before aggregation. Heteroskedastic and auto-correlation robust standard errors in parentheses .

Figure 1.A. Cumulated Sectoral TFP Series

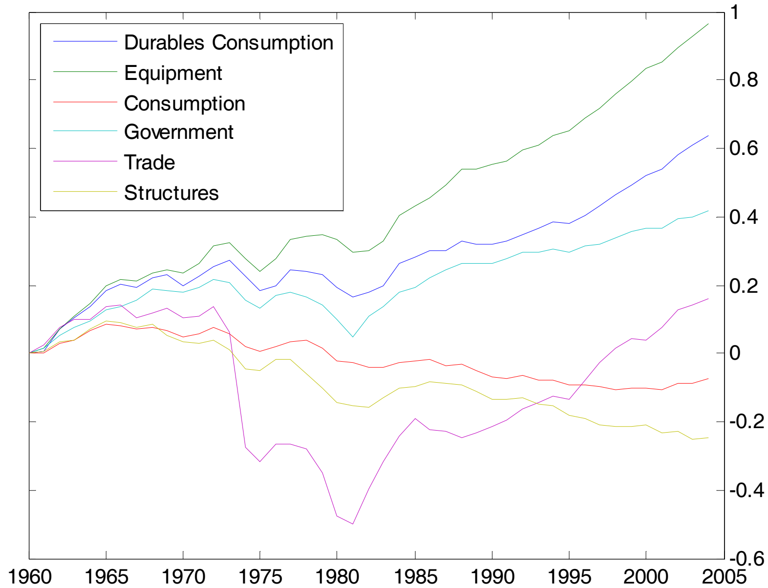
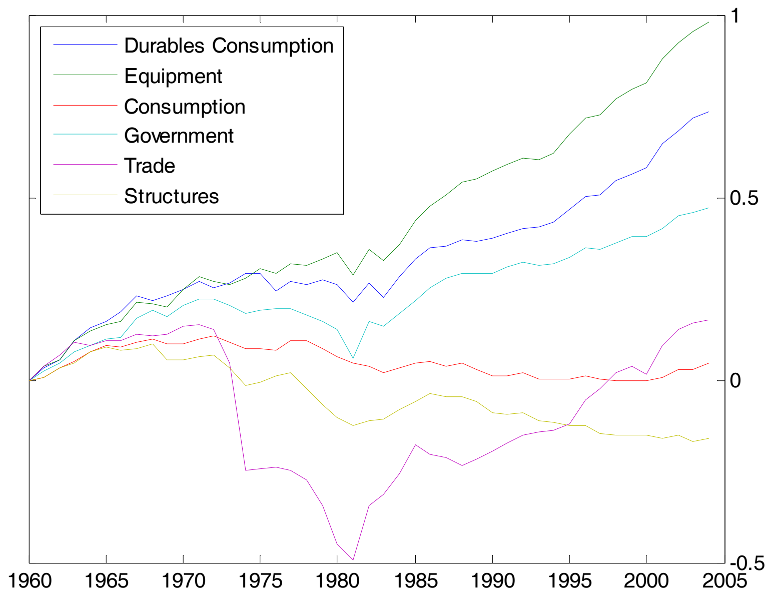


Figure 1.B. Cumulated BFK Technology Series



Note: All series are calculated by cumulating log changes from 1961-2004. The value for 1960 is normalized to zero.