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## The Next Generation of the Penn World Table<sup>†</sup>

By ROBERT C. FEENSTRA, ROBERT INKLAAR, AND MARCEL P. TIMMER\*

*We describe the theory and practice of real GDP comparisons across countries and over time. Version 8 of the Penn World Table expands on previous versions in three respects. First, in addition to comparisons of living standards using components of real GDP on the expenditure side, we provide a measure of productive capacity, called real GDP on the output side. Second, growth rates are benchmarked to multiple years of cross-country price data so they are less sensitive to new benchmark data. Third, data on capital stocks and productivity are (re)introduced. Applications including the Balassa-Samuelson effect and development accounting are discussed. (JEL C43, C82, E01, E23, I31, O47)*

For over four decades, the Penn World Table (PWT) has been a standard source of data on real GDP across countries. Making use of prices collected across countries in benchmark years by the International Comparisons Program (ICP), and using these prices to construct purchasing-power-parity (PPP) exchange rates, PWT converts gross domestic product (GDP) at national prices to a common currency—US dollars—making them comparable across countries. Previous versions of PWT, each based on a newer ICP benchmark, were described extensively by their originators (Summers and Heston 1988, 1991; Heston and Summers 1996). From version 8 onward, development has moved to the University of California, Davis and the University of Groningen, while retaining the PWT initials and with continued input from Alan Heston at the University of Pennsylvania.<sup>1</sup> In this paper we describe the main changes to the measurement of real GDP that have been introduced in this “next generation” of PWT.

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<sup>1</sup>PWT version 7 is based on the 2005 ICP prices. PWT version 8.1 is still based on the 2005 benchmark but has new features described in this paper, and is available online at: <http://www.rug.nl/research/ggdc/data/pwt/>. Version 9 will be based on the new ICP 2011 benchmark that became available in 2014.

Most importantly, we distinguish whether real GDP is intended to measure the standard of living across countries or to measure productive capacity. As argued by Feenstra et al. (2009), real GDP in previous versions of PWT, or its components such as consumption or domestic absorption, was intended to measure the standard of living across countries. They refer to this concept as “real GDP on the expenditure side,” or real GDP<sup>e</sup>. This variable was close to what is called “command-basis GDP” in the United States. We contrast this concept with “real GDP on the output-side,” or real GDP<sup>o</sup>, which is intended to measure the productive capacity of an economy. Countries that have strong terms of trade—meaning higher than average prices for exports or lower than average prices for imports—will have higher real GDP<sup>e</sup> than real GDP<sup>o</sup> as a result. We have incorporated a new dataset of quality-adjusted prices of exports and imports so that both real GDP variables are now reported in PWT8.

Second, to hold prices constant over time, past versions of PWT relied upon real GDP growth from the national accounts for each country. That is, the level of real GDP across countries was constructed for the most recent ICP benchmark and then projected backward and forward in time by using national accounts growth rates for each country. That approach meant that past years of ICP data were discarded. In PWT8 we likewise include a variable that uses real GDP growth from the national accounts, but we further introduce measures of real GDP that correct for changing prices over time and use ICP benchmarks from *multiple years*. All of these measures of real GDP in PWT8 resolve the problem noted by Johnson et al. (2013) that, in past versions, growth rates were dependent on the benchmark year of ICP data used in PWT.

Third, we reintroduce measures of the capital stock across countries based on data of investment by type. They are used in conjunction with measures of human capital to provide, for the first time, measures of total factor productivity across countries. New data on labor income shares in GDP allow factor substitution elasticities to differ across countries and over time. This opens the possibility of analyzing the proximate sources of differences in productivity and living standards across countries.

The paper is organized as follows. In Section I we provide a guided tour to the new PWT, highlighting the main sets of variables, briefly discussing their construction and indicating areas of research where they can be useful. Compared to previous PWT versions, PWT8 allows us to forge a much closer link between the variables in PWT and the theoretical concepts of welfare and production in the literature. In Sections II–IV we describe this theory behind real GDP comparisons. We use a familiar model with traded and nontraded goods, whereby more technologically developed countries have higher prices for nontraded goods: this is the Balassa-Samuelson effect (Balassa 1964, Samuelson 1964), or “Penn effect” (Samuelson 1994). In this context, we argue that it is highly misleading to use a single good—even a traded good—as numeraire to measure “real” GDP. If the law of one price holds, then that approach is equivalent to deflating GDP across countries using their *nominal* exchange rates, and will give a biased measure of the standard of living or productive capacity across countries. Instead, real GDP must be measured by holding the entire vector of prices constant across countries and over time, and we discuss practical ways to achieve that end. In Section II we discuss comparisons of real

expenditure, while Section III covers measurement of real output across countries and over time. In Section IV we outline the measurement of total factor productivity.

In Section V we discuss computational issues within PWT8 and show how the concepts discussed in the theoretical sections are empirically implemented. It reviews our approach of dealing with multiple ICP benchmarks and how we incorporate quality-adjusted prices of exports and imports from Feenstra and Romalis (2014), needed to compute real GDP<sup>o</sup>. Core details on the construction of capital stock and productivity measures are provided. To illustrate potential uses of the new PWT data, three applications are presented in Section VI. We show the differences between real GDP<sup>e</sup> and real GDP<sup>o</sup> and explain this gap based on familiar relationships in the literature. We also document how the new measures of factor inputs and productivity can explain more of the cross-country variation in real GDP per capita than standard approaches in the literature. Finally, we show that our use of multiple ICP benchmarks has important implications for estimating the Balassa-Samuelson effect, the positive relationship between a country's relative price level and its income per capita. Section VII concludes and the (online) Appendix contains the proofs of our theorems and further details on the calculation of variables in PWT8.

### I. A Guided Tour of PWT8

What is “real” GDP? In macroeconomics, this concept means GDP evaluated at constant prices over time. Likewise, for international comparisons research, real GDP means GDP that is evaluated at constant prices across countries. It is not enough to hold just one price constant across countries (i.e., to have a numeraire such as a traded good), but it is essential to hold *all* prices for goods and services constant across countries when evaluating real GDP. This is the basic approach taken in the PWT since its inception. Up to version 7, PWT used information on relative prices of consumption and investment from ICP that allowed for the measurement of relative standards-of-living across countries. For PWT8, we have developed new data that allow us to also provide measures on relative productive capacity across countries. Combined with new data on capital and labor input, cross-country comparisons of productivity can be made as well. In this section we outline the main variables in PWT and their uses, and provide pointers to more detailed discussions in the remainder of the paper.

An important distinction is between GDP measured from the expenditure side and the production side. Traditionally, PWT measured GDP from the expenditure side, and in earlier versions this was the *only* measure of real GDP. It was constructed as nominal GDP, deflated by the relative price level for domestic absorption.<sup>2</sup> To achieve this, the ICP would collect detailed data on consumer expenditures as well as the prices for those expenditure categories, and by dividing expenditures by prices it obtained the consumption quantities relevant to the standard of living. In conjunction with the prices and quantities of investment goods and government expenditures, also collected by the ICP, real GDP from the expenditure side was

<sup>2</sup>In the US National Income and Product Accounts, a comparable measure is referred to as “command-basis GDP.” Command-basis GDP is obtained by deflating nominal GDP by the price index for gross domestic purchases. See equation (16) for the comparable definition of expenditure-side real GDP in PWT.

computed. In PWT8 we refer to this real GDP concept as  $GDP^e$  to distinguish it from real GDP measured from the production side. This emphasis is important because PWT8, for the first time, includes output-based real GDP, or real  $GDP^o$ .

Output-based real GDP was previously not feasible because its computation requires not only relative prices of consumption and investment, but also of export and imports. Incorporating such data is challenging as there is no cross-country survey that collects prices for traded goods of comparable quality across countries, as the ICP does for consumption and investment products. Instead, we are forced to start with the unit values of traded goods. A recent body of research in international trade shows how to correct these unit values for quality, thereby obtaining quality-adjusted prices across countries, as in Feenstra and Romalis (2014).<sup>3</sup> Dividing export and import values by these prices we obtain quality-adjusted quantities, which are treated as outputs and inputs, respectively, to production and to the construction of output-based real GDP. Real  $GDP^o$  can be used to compare the productive capacity across countries in a given year and will typically be different from real  $GDP^e$  as countries face differing terms of trade; see Feenstra et al. (2009) and Section V for more.

A second important distinction between various sets of variables in PWT is whether they are constructed holding prices for goods and services constant across countries *as well as over time*, or not. This distinction leads to the following two definitions of real GDP as appear in PWT8: real GDP using prices that are constant across countries but depend on the *current year* (variables  $CGDP^e$  and  $CGDP^o$ ); and real GDP using prices that are constant across countries and are also *constant over time* ( $RGDP^e$  and  $RGDP^o$ ). We prefix the first concept by *C* because it uses prices in the *current year*: this concept is sometimes called “current-price” real GDP in the literature on international comparisons. It is straightforward to correct this concept for inflation in the United States, but it is not purely real since the vector of (reference) prices at which GDP is evaluated can change over time. Accordingly, the *C* variables are best-suited for comparisons across countries in a particular year. We prefix the second concept by *R* because it also holds prices constant over time and therefore corresponds to what economists normally think of as “real”: this concept is sometimes called “constant-price” real GDP. The *R* variables are well-suited for comparisons across countries and over time, e.g., the productive capacity of China’s economy today as compared to the US economy at some point in the past. By construction these two sets of variables are equal in the benchmark year 2005 ( $RGDP^o = CGDP^o$  and  $RGDP^e = CGDP^e$ ), but otherwise differ because the *C* variables are evaluated at different prices in other years. Sections II, III, and V provide more detailed discussions.

The key variables in PWT8.1 are shown in Table 1, where part A lists the “current-price” or *C* variables and part B lists the “constant-price” or *R* variables.<sup>4</sup> Focusing first on part A, the variable  $CGDP^e$  and its components (consumption, investment, and government expenditures) play an important role in measures of

<sup>3</sup>The starting point of this literature is that a good that is imported in high quantity but without having a low unit value must be of high quality: see Khandelwal (2010) and Hallak and Schott (2011). Feenstra and Romalis (2014) extend this demand-side measurement by also building in a supply side, as discussed in Section V.

<sup>4</sup>The variables *CCON*, *CDA*, and *CWTF* were not included in PWT8.0, but are newly added in PWT8.1.

TABLE 1—KEY VARIABLES IN PWT VERSION 8.1 AND THEIR USES

Acronym	Name	Units	Useful for comparing	See also
<i>Panel A. Based on prices that are constant across countries in a given year</i>				
<i>CGDP<sup>e</sup></i>	Expenditure-side real GDP, using prices for final goods that are constant across countries	Millions of 2005 US \$	Living standards across countries in each year	Section V
<i>CGDP<sup>o</sup></i>	Output-side real GDP, using prices for final goods, exports, and imports that are constant across countries	Millions of 2005 US \$	Productive capacity across countries in each year	Section III, V
<i>CCON</i>	Real consumption of households and government, using prices that are constant across countries	Millions of 2005 US \$	Living standards across countries in each year	Section II, V
<i>CDA</i>	Real domestic absorption, computed as real consumption ( <i>CCON</i> ) plus real investment	Millions of 2005 US \$	Living standards across countries in each year	Section II, V
<i>CK</i>	Capital stock using prices for structures and equipment that are constant across countries	Millions of 2005 US \$	Capital stock across countries in each year	Section IV, V
<i>CTFP</i>	TFP level, computed with <i>CGDP<sup>o</sup></i> , <i>CK</i> , labor input data, and <i>LABSH</i>	USA value = 1 in all years	Productivity level across countries in each year	Section IV, V
<i>CWTFP</i>	Welfare-relevant TFP level, computed with <i>CDA</i> , <i>CK</i> , labor input data, and <i>LABSH</i>	USA value = 1 in all years	Living standards across countries in each year	Section IV, V
<i>Panel B. Based on prices that are constant across countries and over time</i>				
<i>RGDP<sup>e</sup></i>	Expenditure-side real GDP, using prices for final goods that are constant across countries and over time	Millions of 2005 US \$, $RGDP^e = CGDP^e$ in 2005	Living standards across countries and across years	Section III, V
<i>RGDP<sup>o</sup></i>	Output-side real GDP, using prices for final goods exports and imports that are constant across countries and over time	Millions of 2005 US \$, $RGDP^o = CGDP^o$ in 2005	Productive capacity across countries and across years	Section III, V
<i>Panel C. Based on national prices that are constant over time</i>				
<i>RGDP<sup>NA</sup></i>	Real GDP at constant national prices, obtained from national accounts data for each country	Millions of 2005 US \$, $RGDP^{NA} = CGDP^o$ in 2005	Growth of GDP over time in each country	
<i>RCON<sup>NA</sup></i>	Real household and government consumption at constant national prices	Millions of 2005 US \$, $RCON^{NA} = CCON$ in 2005	Growth of consumption over time in one country	
<i>RDA<sup>NA</sup></i>	Real domestic absorption at constant national prices	Millions of 2005 US \$, $RDA^{NA} = CDA$ in 2005	Growth of domestic absorption over time in each country	
<i>RK<sup>NA</sup></i>	Capital stock at constant national prices, based on investment and prices of structures and equipment	Millions of 2005 US \$, $RK^{NA} = CK$ in 2005	Growth of the capital stock over time in each country	Section V
<i>RTFP<sup>NA</sup></i>	TFP index, computed with $RGDP^{NA}$ , $RK^{NA}$ , labor input data, and <i>LABSH</i>	2005 value = 1 for all countries	Growth of productivity over time in each country	Section V
<i>RWTFP<sup>NA</sup></i>	Welfare-relevant TFP index, computed with $RGDP^{NA}$ , $RK^{NA}$ , labor input data, and <i>LABSH</i>	2005 value = 1 for all countries	Growth of welfare-relevant productivity over time in each country	Section V

(Continued)

TABLE 1—KEY VARIABLES IN PWT VERSION 8.1 AND THEIR USES (*Continued*)

Acronym	Name	Units	Useful for comparing	See also
<i>Panel D. Other variables</i>				
<i>PL_CON</i>	Price level of <i>CCON</i> , equal to the PPP (ratio of nominal <i>CON</i> to <i>CCON</i> ) divided by the nominal exchange rate	USA value = 1 in 2005	How consumption price levels differ across countries	Section V
<i>PL_DA</i>	Price level of <i>CDA</i> and <i>CGDP<sup>e</sup></i> , equal to the PPP (ratio of nominal <i>DA</i> to <i>CDA</i> ) divided by the nominal exchange rate	USA value = 1 in 2005	How expenditure price levels differ across countries	Section V
<i>PL_GDP<sup>o</sup></i>	Price level of <i>CGDP<sup>o</sup></i> , equal to the PPP (ratio of nominal <i>GDP</i> to <i>CGDP<sup>o</sup></i> ) divided by the nominal exchange rate	USA value = 1 in 2005	How output price levels differ across countries	Section V
<i>LABSH</i>	The share of labor income of employees and self-employed workers in GDP	Fraction of nominal GDP	Total inputs across countries or over time	Section V

comparative living standards. PWT8 provides a number of alternatives. Jones and Klenow (2011) ask by how much consumption of a random person in the United States would have to be adjusted to make this person indifferent between living for a year in the United States or in another country. This involves taking into account differences between the two countries in the real level of consumption, but also in life expectancy, leisure, and income inequality. The relevant building block for such a “consumption-equivalent” welfare measure from PWT8 is real consumption, the sum of real household and government consumption, denoted by *CCON*.<sup>5</sup> Starting with this variable, we can add real investment to obtain *CDA*, and likewise adding the real trade balance we get back to *CGDP<sup>e</sup>* (the details of this calculation are in Section V). From the point of view of the representative consumer, *CGDP<sup>e</sup>* essentially treats the trade balance as an income transfer that is then deflated by the local prices, including prices for nontraded goods. *CGDP<sup>e</sup>* can be viewed as a measure of the standard of living, but extended to incorporate the real trade balance.

The new measure of productive capacity of an economy (variable *CGDP<sup>o</sup>*) is particularly relevant in studies that account for the proximate determinants of GDP levels, also known as development accounting, as in Hall and Jones (1999); Caselli (2005); and Hsieh and Klenow (2010). Its construction is discussed in detail in Sections III and V. PWT8 also provides new information on real inputs that enables one to compare total factor productivity (TFP) across countries. Measures of the capital stock are cumulated from series on investment in buildings and different types of machinery and converted with relative prices for structures and equipment that are constant across countries (variable *CK*).<sup>6</sup> New measures of labor input are provided as well, corrected for differences in schooling. In addition, we expand upon the work of Gollin (2002) and estimate the share of labor income in GDP that varies over time and across countries (variable *LABSH*, in part D of Table 1). Combining this with (more standard) measures of human capital, one can compare the *level* of

<sup>5</sup>As also argued in Jones and Klenow (2011), the dividing line between household and government consumption is very country-specific and based on the institutional details of how the education and healthcare systems are organized. A total consumption measure is thus the most relevant.

<sup>6</sup>Some earlier versions of PWT had also included capital stock information, but the current data have been newly developed for PWT8; see Section V and online Appendix C.

productivity across countries at a point in time (variable  $CTFP$ , with  $CTFP = 1$  for the United States). The new data on real inputs are relevant in accounting for productivity differences, as in Caselli (2005), but can also be used in constructing welfare-relevant TFP measures along the lines of Basu et al. (2014). They show that the welfare of a country's infinitely lived representative consumer is summarized, to a first order, by total factor productivity and by the capital stock per capita. To calculate this welfare-relevant TFP, they argue that a measure of real domestic absorption is needed which includes consumption as well as investment. This measure is called  $CDA$  in PWT8 and the TFP measure based on this is called  $CWTFP$ . Details are provided in Sections IV, V, and online Appendix C.

In past versions of PWT the growth rate of RGDP was computed solely based on the growth rate of real GDP—or its components—obtained from national accounts (NA) data.<sup>7</sup> In the PWT8 the measures of  $RGDP^e$  and  $RGDP^o$ , listed in part B of Table 1, are based on growth rates that are tied to *multiple* ICP benchmarks and correct for changing prices between these benchmarks. Because we interpolate between multiple ICP benchmarks, there is no guarantee that the growth rate of real GDP so obtained will necessarily be close to the NA growth rate.<sup>8</sup> We now indicate the real series with national-accounts growth rates with the superscript  $NA$ , so that  $RGDP^{NA}$  in PWT8 is based on those growth rates. We normalize it such that  $RGDP^{NA} = CGDP^o$  in the benchmark year 2005.<sup>9</sup> In all of our measures of real GDP, the growth rates will not change in between existing benchmark years as new benchmarks become available, unless the underlying nominal GDP data from the national accounts are revised.<sup>10</sup> This “invariance of growth rates between benchmarks” was not previously a feature of PWT—as discussed by Johnson et al. (2013)—which meant that ICP benchmarks often led to considerable changes in real GDP growth rates for all prior years. That deficiency is no longer the case in PWT8.

In addition we provide two new variables also based on national accounts growth rates. To measure capital stocks *over time* we include  $RK^{NA}$ , which is also computed based on cumulated investment in structures and equipment, but deflated with national prices that allow for a comparison over time. It is set equal to  $CK$  in 2005. The corresponding measure of productivity,  $RTFP^{NA}$ , is computed using the growth rate of real GDP from national-accounts data,  $RGDP^{NA}$ , in conjunction with the growth rates of  $RK^{NA}$  and the labor force, to obtain productivity growth rates for each country.  $RTFP^{NA}$  is normalized to 1 in 2005 for all countries; see Section V.

Finally, PWT8 provides various relative price levels, which equal the PPP exchange rate divided by the nominal exchange rate. These variables show how

<sup>7</sup>Up to version 6.1, the variable “rgdpl” in PWT relied upon a weighted average of the NA growth rates of the *components* of GDP, i.e.,  $C$ ,  $I$ ,  $G$ ,  $X$ , and  $M$ . The weights used depended on the ICP benchmark being used, leading to the criticism of Johnson et al. (2013). Beginning in version 6.2, a second real GDP variable “rgdpl2” was introduced that relied instead on the NA growth rate of total absorption, and therefore was not subject to that criticism.

<sup>8</sup>India, for example, is found to have a higher standard of living in its 1975 ICP benchmark than predicted from the 1985 benchmark and back-casting using the growth of national accounts prices. It follows that the change in real GDP from 1975 onward is correspondingly reduced.

<sup>9</sup> $RGDP^{NA}$  is similar to the series “rgdpl2” that was used in PWT6.2 and v7 except that: (i) “rgdpl2” used the real growth of absorption from the national accounts of each country rather than the real growth of GDP; (ii) “rgdpl2” was normalized to equal expenditure-side  $CGDP^e$  in the relevant ICP benchmark year, whereas  $RGDP^{NA}$  is normalized to equal the output-side measure  $CGDP^o$  in 2005.

<sup>10</sup>These changes can be large. For example, Jerven (2013) discusses Ghana's upward revision of nominal GDP by 60 percent in 2012. More recently, Nigeria announced an upward revision of almost 100 percent.



prices differ across countries when converted at the nominal exchange rate. The ratio of nominal GDP in local currency to  $CGDP^o$  equals that country's PPP exchange rate relative to the US dollar ( $PL\_GDP^o$ ). The price levels of  $CON$  and  $DA$  in a country are given by  $PL\_CCON$  and  $PL\_DA$ . Price level concepts are discussed in Section V.

To summarize, PWT8 includes a range of measures useful for comparing living standards and productive capacity across countries and over time, including five different measures of real GDP. Many of these measures, with the  $C$ -prefix, are best-suited when comparing levels across countries in the current year. The variables with the  $R$ -prefix are best-suited for comparisons over time, though only  $RGDP^e$  and  $RGDP^o$  are simultaneously suitable for over time and cross-country comparisons. The  $CGDP$  and  $RGDP$  series, on both the expenditure and on the output sides, are tied to *multiple* ICP benchmarks whenever price data for a country have been collected multiple times. If the sole object is to compare the growth performance of economies, we would recommend using the  $RGDP^{NA}$  series (and this is closest to earlier versions of PWT). In the remainder of this paper, we provide a more detailed discussion of the concepts, definitions, and measurement of the PWT variables.

## II. Measurement of Real Expenditure

To illustrate the challenges to constructing “real” GDP, we use a familiar model with traded and nontraded goods. Let  $\mathbf{q}_{Nj}$  be a vector of consumption of nontraded goods in country  $j$ , with prices  $\mathbf{p}_{Nj}$ , and  $\mathbf{q}_{Tj}$  be a vector of consumption of traded goods in country  $j$ , with prices  $\mathbf{p}_{Tj}$ . We suppose that there is a representative consumer in each country with expenditure function denoted by  $E_j(\mathbf{p}_{Nj}, \mathbf{p}_{Tj}, u_j)$ , where  $u_j$  is utility in country  $j$ . Consider a simplified version of this model as discussed in Obstfeld and Rogoff (1996, ch. 4) and Végh (2014, ch. 4 and 6), with a single traded and a single nontraded good. In the monetary version of the model with prices quoted in national currencies (Végh 2014, ch. 6), we might initially assume that the law of one price holds,

$$(1) \quad p_{Tj} = \mathcal{E}_j p_{T0},$$

where  $\mathcal{E}_j$  is the nominal exchange rate in units of country  $j$  currency per unit of country 0 currency. Then this model can readily yield the prediction that the relative price of the nontraded good is higher in a country that is more productive in the traded good sector. The reason, of course, is that increased productivity of the traded good leads to higher wages, which in turn increases the relative price of the nontraded good,  $p_{Nj}/p_{Tj}$ ; this is the celebrated Balassa-Samuelson hypothesis.

The problem that international comparisons seek to solve is how to compare real GDP across countries when their prices differ, as nontraded prices surely do. The “solution” to this problem will depend on what we want real GDP to measure. Throughout this section we maintain that real GDP should measure the standard of living across countries, to be contrasted with real GDP as a measure of productive capacity as outlined in the next section. In order to measure the standard of living—or the cost of obtaining the actual level of utility—it is not enough to just choose

a common numeraire: comparing GDP across countries with a common numeraire will give a misleading idea of how the standard of living differs across countries. To show this, let us choose the single traded good as the numeraire and suppose that (1) holds. Then allowing for a vector of nontraded goods, “real” expenditure in each country is measured as

$$(2) \quad \frac{E_j(\mathbf{p}_{Nj}, p_{Tj}, u_j)}{p_{Tj}} = E_j(\mathbf{p}_{Nj}/p_{Tj}, 1, u_j),$$

where the equality follows because the expenditure function is homogeneous of degree 1 in prices. Compare this to *nominal* expenditure measured in terms of the currency of country 0:

$$(3) \quad \frac{E_j(\mathbf{p}_{Nj}, p_{Tj}, u_j)}{\mathcal{E}_j} = \frac{p_{Tj} E_j(\mathbf{p}_{Nj}/p_{Tj}, 1, u_j)}{\mathcal{E}_j} = p_{T0} E_j(\mathbf{p}_{Nj}/p_{Tj}, 1, u_j),$$

where we again make use of homogeneity of degree 1 of the expenditure function, and (1). It is evident that nominal expenditure in a common currency in (3) differs from “real” expenditure in (2) by just the traded good price,  $p_{T0}$ . So the ratio of (2) across countries will be identical to the ratio of equation (3). But it is well known that expenditure converted at the nominal exchange rate—which is what we are measuring in equation (3)—gives a highly misleading measure of the standard of living. The reason is that in (3) we are still using the high prices of nontraded goods in more productive countries, leading to higher nominal expenditure and also higher “real” expenditure in (2) when measured in terms of the traded goods price. Conversely, the poor countries will look even poorer when their expenditure is converted to the currency of a rich country, as in (3), if we do not also recognize that their nontraded prices are low. To demonstrate this point in our model, choose country 0 as the United States or a European country with high relative nontraded prices, so that  $\mathbf{p}_{Nj}/p_{Tj} < \mathbf{p}_{N0}/p_{T0}$ . Then because the expenditure function is increasing in prices it follows that  $E_j(\mathbf{p}_{Nj}/p_{Tj}, 1, u) < E_j(\mathbf{p}_{N0}/p_{T0}, 1, u)$ , so we obtain

$$(4) \quad \frac{E_j(\mathbf{p}_{Nj}/p_{Tj}, 1, u_j)}{E_0(\mathbf{p}_{N0}/p_{T0}, 1, u_0)} < \frac{E_j(\mathbf{p}_{N0}/p_{T0}, 1, u_j)}{E_0(\mathbf{p}_{N0}/p_{T0}, 1, u_0)} \text{ and}$$

$$\frac{E_j(\mathbf{p}_{Nj}/p_{Tj}, 1, u_j)}{E_0(\mathbf{p}_{N0}/p_{T0}, 1, u_0)} < \frac{E_j(\mathbf{p}_{Nj}/p_{Tj}, 1, u_j)}{E_0(\mathbf{p}_{Nj}/p_{Tj}, 1, u_0)}.$$

The expressions appearing on the right of the inequality signs in (4) both measure the cost of obtaining the utility levels in each country at *common* relative prices  $\mathbf{p}_{N0}/p_{T0}$  or  $\mathbf{p}_{Nj}/p_{Tj}$ . Regardless of which prices are chosen, the relative standard of living on the right of (4) is *higher* than the ratio of “real” or nominal expenditure from (2) or (3), respectively, that appear on the left of (4). This finding demonstrates that low-income countries (with lower relative prices of nontraded goods) will look poorer if we simply convert their expenditures at the nominal exchange rate. To give just one example from PWT8.1, the GDP of China in 2011 when converted at its

nominal exchange rate is \$5,439 per capita. That is 11.3 percent of nominal GDP per capita in the United States. We will later measure real GDP per capita in China at 20.5 percent of that in the US in 2011, so that converting at the nominal exchange rate understates its value by nearly one-half.<sup>11</sup> Part of this understatement could come from an undervalued exchange rate, so that the law of one price in (1) does not hold for traded goods, but the deeper problem is that the *nontraded* goods are cheaper in China than in the United States when converted at the official exchange rate.

To resolve this problem and obtain an accurate measure of the standard of living or real GDP, one approach would be to collect the price data across countries and estimate expenditure functions as on the right of the inequality signs in (4). The collection of data for comparable goods across countries is undertaken by the International Comparisons Program (ICP)—a joint project of the United Nations, the World Bank, and other international agencies. But these statistical agencies do not like to rely on econometrically estimated expenditure functions to obtain the standard of living, preferring index-number methods that we discuss below. Of course, researchers can estimate expenditure functions and a leading example is Neary (2004), who estimated an AIDS expenditure function across countries to measure the standard of living. Neary pooled data across countries so that there is a single representative consumer with nonhomothetic tastes. Likewise, we shall drop the country subscript from the expenditure function, and now use  $E(\mathbf{p}_{Nj}, \mathbf{p}_{Tj}, u_j)$ . Note that if tastes are homothetic then the expenditure function is written as  $E(\mathbf{p}_{Nj}, \mathbf{p}_{Tj}, u_j) = e(\mathbf{p}_{Nj}, \mathbf{p}_{Tj})u_j$ , in which case the right-hand side of (4) simply becomes the ratio of utilities,  $u_j/u_0$ .

Short of estimating the expenditure function, the approach that is taken by statistical agencies and PWT is to evaluate the expenditures that appear on the right of the inequality signs in (4) using the *observed* consumption vectors in each country. Let  $\mathbf{q}_j = (\mathbf{q}_{Nj}, \mathbf{q}_{Tj})$  be the vector of consumption goods (traded and nontraded) in country  $j$ , with  $\mathbf{p}_j = (\mathbf{p}_{Nj}, \mathbf{p}_{Tj})$  denote the country  $j$  prices. Then we consider evaluating the two ratios

$$(5) \quad \frac{\mathbf{p}'_0 \mathbf{q}_j}{\mathbf{p}'_0 \mathbf{q}_0} \quad \text{and} \quad \frac{\mathbf{p}'_j \mathbf{q}_j}{\mathbf{p}'_j \mathbf{q}_0}.$$

Let us return to the case of a single nontraded good and a single traded good. If country 0 is a rich, productive country then it will have a higher relative price of the nontraded good  $p_{N0}/p_{T0} > p_{Nj}/p_{Tj}$ . With substitution in consumption we would then expect that  $q_{N0}/q_{T0} < q_{Nj}/q_{Tj}$ . Using these inequalities in (5) and dividing both expressions by  $(q_{Tj}/q_{T0})$ , we obtain

$$\frac{\mathbf{p}'_0 \mathbf{q}_j / q_{Tj}}{\mathbf{p}'_0 \mathbf{q}_0 / q_{T0}} = \frac{(p_{N0}/p_{T0})(q_{Nj}/q_{Tj}) + 1}{(p_{N0}/p_{T0})(q_{N0}/q_{T0}) + 1} > \frac{(p_{Nj}/p_{Tj})(q_{Nj}/q_{Tj}) + 1}{(p_{Nj}/p_{Tj})(q_{N0}/q_{T0}) + 1} = \frac{\mathbf{p}'_j \mathbf{q}_j / q_{Tj}}{\mathbf{p}'_j \mathbf{q}_0 / q_{T0}}.$$

<sup>11</sup>The difference between nominal and real GDP per capita is even greater for lower income countries: Cambodia, for example, has nominal (real) GDP per capita that is 1.9 percent (5.9 percent) of the United States in 2011.

The inequality above is obtained because the higher relative price  $p_{N0}/p_{T0} > p_{Nj}/p_{Tj}$  is applied on the left-hand side to relative quantities  $q_{Nj}/q_{Tj} > q_{N0}/q_{T0}$  that are higher in the numerator than in the denominator. In words, this expression says that real consumption in one country relative to another is higher when evaluated at the prices of the *other* country, or to put it most simply, “the grass is greener on the other side.” This result shows that the assessing the standard of living by evaluating the consumption quantities at a particular country’s prices will be quite sensitive to *which* country’s prices are used.

We stress that the above inequality does not depend on having just two goods, and also does not depend on having higher prices of nontraded goods in richer countries, but holds quite generally for any price differences across countries that are consistent with demand-side substitution. Since the country 0 quantity is in the denominator in (5), the first ratio is a Laspeyres quantity index and the second is a Paasche quantity index, and the former exceeds the latter provided that there is negative correlation between the price and quantity differences between countries.<sup>12</sup>

These indexes differ from the ratio of expenditures on the right of (4) because in  $E_j(p_{N0}/p_{T0}, 1, u_j)$ , for example, we use country 0 prices but would allow the consumption quantities in country  $j$  to be *optimal* at those prices; in contrast, in (5) we hold the consumption quantities fixed at their *observed* levels and are not allowing for substitution in response to prices. Under certain conditions, this limitation can be corrected by taking the geometric mean of the Laspeyres and Paasche indexes in (5), obtaining the Fisher ideal quantity index:

$$(6) \quad Q_{j0}^F \equiv \left[ \left( \frac{\mathbf{p}'_0 \mathbf{q}_j}{\mathbf{p}'_0 \mathbf{q}_0} \right) \left( \frac{\mathbf{p}'_j \mathbf{q}_j}{\mathbf{p}'_j \mathbf{q}_0} \right) \right]^{\frac{1}{2}}.$$

For a bilateral comparison with only two countries, it is known that if the representative consumer’s utility function has a homothetic, quadratic functional form, then the Fisher ideal quantity index in (6) will exactly measure the ratio of utilities  $u_j/u_0$  (Diewert 1976). So in that case, the Fisher ideal quantity index is the “right” way to measure the standard of living across countries. When there are many countries, however, then the comparison is more difficult. Computing (6) for two countries  $j$  compared with  $h$ , and then again for  $h$  compared with  $k$ , and multiplying these, we do not necessarily get the same result as directly comparing real expenditure in  $j$  with  $k$ . To overcome this lack of transitivity, we compare country  $j$  with  $k$  by indirectly comparing them via all other countries  $h = 1, \dots, C$ :

$$(7) \quad Q_{jk}^{GEKS} = \prod_{h=1}^C (Q_{jh}^F Q_{hk}^F)^{\frac{1}{C}}, \text{ with } Q_{hh}^F \equiv 1.$$

<sup>12</sup>More precisely if the price and quantity differences between countries, weighted by values, are negatively correlated, then the Laspeyres index exceeds the Paasche index. See Balk (2008, p. 64).

This so-called GEKS index is transitive by construction and is an accepted method for making multilateral comparisons.<sup>13, 14</sup>

We have introduced the reader to these index number comparisons of real expenditure because they play a role in PWT8. Specifically, we shall use a two-stage aggregation procedure that first aggregates the prices of items collected by the ICP *within* the categories of consumption  $C$ , investment  $I$ , and government expenditures  $G$ . Prices within these categories are collected by the ICP in each benchmark year and are aggregated using a GEKS approach, i.e., using Fisher-Ideal price indexes that are made transitive across countries using a formula like (7). Besides the desirable property of transitivity, there is a very practical reason for aggregating the categories of  $C$ ,  $I$ , and  $G$ : in this way, prices *outside* the benchmark years of the ICP can be interpolated or extrapolated using the time-series data on consumption, investment and government price indexes for each country from their national accounts, as described in Section V.

Having thus obtained a complete time-series and cross-country dataset on the prices of  $C$ ,  $I$ , and  $G$  relative to a base country (the US), the second stage is to aggregate to total expenditure. In this second stage we *do not* again use a GEKS procedure to aggregate the prices of  $C$ ,  $I$ , and  $G$  in each year, and in this respect we differ from the World Bank who construct the ICP purchasing-power-parity (PPP) price deflators (or real exchange rates) in this way: real GDP is then obtained as nominal GDP divided by the PPPs. As we shall explain in the next section, such an approach severely limits the ability to compare real GDP both across countries and also *over time*. In order to obtain a time-series and cross-section comparison, we believe that it is essential to adopt another approach to the measurement of real GDP, which will involve using *reference prices*.

In general, the reference-price approach to measuring real expenditure means that a vector  $\pi$  of reference price is used to evaluate real expenditure across countries as

$$\frac{\pi' \mathbf{q}_j}{\pi' \mathbf{q}_0}.$$

In the specific application to PWT8, we are starting with price indexes and hence relative quantities of  $C$ ,  $I$ , and  $G$  obtained from the first-stage GEKS aggregation, so these three components of GDP are multiplied by reference prices and summed in the second stage of aggregation (which is extended to include exports and imports, as discussed below). The question is: what reference prices are used? The most common procedure to use is the *quantity-weighted average over countries of the prices of each good*. This particular choice of reference prices is called the Geary-Khamis (GK) approach.<sup>15</sup> The GK approach satisfies the desirable axiomatic property that

<sup>13</sup> After Gini, Eltetö, Köves, and Szulc. A modern treatment and references are provided by Balk (2008); see also online Appendix B. An alternative approach based on “minimum spanning trees” is presented in Hill (1999). In this method, pairs of countries are compared, either directly or indirectly through a sequence of chained bilateral comparisons involving other countries, with the sequence of countries chosen so that the resulting multilateral indices are least sensitive to the bilateral formula that is used.

<sup>14</sup> Neary (2004) questions whether the GEKS index can accurately reflect the standard of living across countries when preferences are nonhomothetic, however, so this research area is far from resolved. Feenstra, Ma, and Prasada Rao (2009) discuss transitive comparisons with AIDS and nonhomothetic translog expenditure functions.

<sup>15</sup> Due to Geary and Khamis. A modern treatment is provided by Balk (2008) and is described in Section V.

it maintains additivity, so that the components of GDP at reference prices sum to overall real GDP.<sup>16</sup> We now justify the reference-price approach more carefully in the context of measuring real output across countries.

### III. Measurement of Real Output across Countries and over Time

GDP measured from the expenditure side ( $GDP^e$ ) and its components such as consumption and investment play an important role in measures of comparative living standards. We contrast this concept with “real GDP on the output-side,” or real  $GDP^o$ , which is intended to measure the productive capacity of an economy. In order to measure real output we need to hold the entire vector of prices constant across countries and use those prices to evaluate the *production* quantities rather than the consumption quantities. If there were only final goods, one could simply compute production as the difference between consumption and net exports. However, with intermediate goods, the mapping from consumption to production is not straightforward and one approach would be to calculate the value-added components of consumption categories (Herrendorf, Rogerson, and Valentinyi 2013). The data to do so is not widely available. So we take another, indirect approach of specifying the entire production vector for the economy as  $\mathbf{y}_j \equiv (\mathbf{q}_j, \mathbf{x}_j, -\mathbf{m}_j)$ , where  $\mathbf{q}_j$  is the quantity of final goods as before,  $\mathbf{x}_j$  is the quantity of exports and  $-\mathbf{m}_j$  is minus the quantity of imports. Domestic prices for the exports and imports are denoted by  $\mathbf{p}_j^x$  and  $\mathbf{p}_j^m$ , and the vector of prices is  $\mathbf{P}_j = (\mathbf{p}_j, \mathbf{p}_j^x, \mathbf{p}_j^m)$ . We are treating all final goods as nontraded in the sense that some retail services at least have been added, whereas all imports are intermediate inputs into the production process, possibly only into retailing.

To evaluate output we use the revenue or GDP function for the economy,

$$(8) \quad r_j(\mathbf{P}_j, \mathbf{v}_j) = \max_{\mathbf{q}_j, \mathbf{x}_j, \mathbf{m}_j \geq 0} \{ \mathbf{P}_j' \mathbf{y}_j \mid F_j(\mathbf{y}_j, \mathbf{v}_j) = 1 \},$$

where  $F_j(\mathbf{y}_j, \mathbf{v}_j)$  is a transformation function for each country, which depends on the vector  $\mathbf{v}_j$  of primary factor endowments and has an index for country  $j$  due to technological differences across countries. Let us denote a vector of reference prices by  $\mathbf{\Pi} = (\boldsymbol{\pi}, \boldsymbol{\pi}^x, \boldsymbol{\pi}^m)$ . Then real output can be compared across countries using the ratio of revenue functions evaluated at these reference prices:

$$(9) \quad \frac{r_j(\mathbf{\Pi}, \mathbf{v}_j)}{r_0(\mathbf{\Pi}, \mathbf{v}_0)}$$

One approach to measuring real output would be to estimate the revenue functions in (9). But estimating revenue functions across all countries is even harder than estimating the expenditure function—as Neary (2004) does—because the revenue functions are indexed by country  $j$ , indicating technological differences between

<sup>16</sup>This additivity property does not hold, however, when the GEKS approach alone is used to measure real GDP.

them. For this reason, we must rely on indexes that can be used to approximate the ratio of revenue functions in (9).

As in the previous section, the most obvious choice of prices for evaluating the output vectors of two countries is the prices in either country. We have already discussed the inequality that arises from substitution in demand, with the real consumption of one country versus another being higher when evaluated at the other country’s prices. The same inequality holds when evaluating the real output of two countries, despite the fact that this comparison is being made using production data rather than consumption data:

$$(10) \quad \left( \frac{\mathbf{P}'_j \mathbf{y}_j}{\mathbf{P}'_j \mathbf{y}_0} \right) < \left( \frac{\mathbf{P}'_0 \mathbf{y}_j}{\mathbf{P}'_0 \mathbf{y}_0} \right).$$

This inequality can be interpreted by noting that the right-hand side of (10) is the Laspeyres quantity index, which exceeds the Paasche quantity index on the left due to substitution in demand. According to production theory, however, the inequality should be reversed, since those goods whose prices have raised the most will have the greatest quantity increase. Nevertheless, various studies confirm that the “demand-side bias” in (10) holds in empirical work, and this inequality is known as the Gerschenkron effect. Gerschenkron (1951) was the first to provide evidence that the relative GDP of a country was higher when evaluated at another country’s prices. Indeed, for the 146 countries in the 2005 ICP comparison, we find that this inequality holds for more than 98 percent of country pairs.

By taking a geometric mean of the Paasche and Laspeyres indexes, we obtain the Fisher quantity index of real output. The question is how this index-number approach will compare to a reference-price approach as in (9). We can establish a rather tight relationship between these two approaches with the following result, proved in online Appendix A:

**THEOREM 1:** *Suppose that the outputs are revenue-maximizing and that the inequality in (10) holds. Then there exists a reference price vector  $\mathbf{\Pi}$  between  $\mathbf{P}_j$  and  $\mathbf{P}_k$  such that*

$$\frac{r_j(\mathbf{\Pi}, \mathbf{v}_j)}{r_k(\mathbf{\Pi}, \mathbf{v}_k)} = \left[ \left( \frac{\mathbf{P}'_j \mathbf{y}_j}{\mathbf{P}'_j \mathbf{y}_k} \right) \left( \frac{\mathbf{P}'_k \mathbf{y}_j}{\mathbf{P}'_k \mathbf{y}_k} \right) \right]^{\frac{1}{2}}.$$

This new result says that computing a Fisher ideal quantity index of production between the countries is a valid comparison of real output between them, in the sense that it is equivalent to using some reference price vector. Remarkably, it does not depend on the functional form of the revenue function but only on optimizing behavior. This theoretical result suggests that there may not be a substantial difference between using the Fisher ideal index of real output—or its generalization, the GEKS approach in (7)—as compared to a reference price approach. We have confirmed that this result holds in PWT8 in a *single* year: whether we are measuring real output or real expenditure, the results from using a GEKS approach do not differ that much from using reference prices constructed as the weighted average of prices across countries.

But this similarity between the index number (GEKS) and reference price (GK) approaches breaks down when we also make comparisons *across time*. In that case we need to recognize that the reference price vector  $\Pi$  established by Theorem 1 is only implicit, and it depends on the level of prices  $\mathbf{P}_j$  and  $\mathbf{P}_k$ . While this enables us to obtain a valid comparison of real output between two countries in each year, we would not be able to compare those real outputs across time because we do not know how the implicit reference price vector is changing over time, and therefore cannot make a “constant price” comparison that we normally expect in “real” variables.

It turns out, however, that we can readily extend Theorem 1 to obtain a consistent comparison of real GDP across countries and simultaneously over time (such variables in PWT8 are indicated by a prefix  $R$ ). Let the subscript  $t$  on all variables indicate time. Suppose that we start in a situation where we have two reference price vectors at two points in time,  $\Pi_\tau = (\pi_\tau, \pi_\tau^x, \pi_\tau^m)$ ,  $\tau = t - 1, t$ , using the reference prices for all final goods plus exports and imports. In order to also compare real output over time, it would be desirable to use a single vector  $\Pi$  and compute the ratios

$$\frac{r_{jt}(\Pi, \mathbf{v}_{jt})}{r_{jt-1}(\Pi, \mathbf{v}_{jt-1})}, j = 1, \dots, C,$$

for each country. Notice that the endowments in this comparison can change over time, as well as the revenue function itself due to technological change, but the reference prices are held constant.

We can apply Theorem 1 by treating the bilateral comparison there as between country  $j$  using reference prices  $\Pi_{t-1}$  and  $\Pi_t$  in the two periods. The optimal outputs at these prices are denoted by  $y_{j\tau}^* \equiv \partial r_{j\tau}(\Pi_\tau, \mathbf{v}_{j\tau}) / \partial \Pi_\tau$ ,  $\tau = t - 1, t$ . We assume that the time-series analogue of (10) holds, which states that for country  $j$

$$(11) \quad \left( \frac{\Pi_t' \mathbf{y}_{jt}^*}{\Pi_t' \mathbf{y}_{jt-1}^*} \right) < \left( \frac{\Pi_{t-1}' \mathbf{y}_{jt}^*}{\Pi_{t-1}' \mathbf{y}_{jt-1}^*} \right).$$

Again, we interpret (11) as stating that the Laspeyres quantity index (on the right) exceeds the Paasche quantity index (on the left). This inequality is another illustration of the Gerschenkron effect.<sup>17</sup> Then an immediate corollary of the earlier theorem is obtained by changing the notation to compare time periods rather than countries, as follows:

**COROLLARY 1:** *Suppose that the outputs are revenue-maximizing and the Gerschenkron effect in (11) holds. Then there exists a reference price vector  $\Pi$  between  $\Pi_{t-1}$  and  $\Pi_t$  such that*

$$(12) \quad \frac{r_{jt}(\Pi, \mathbf{v}_{jt})}{r_{jt-1}(\Pi, \mathbf{v}_{jt-1})} = \left[ \left( \frac{\Pi_t' \mathbf{y}_{jt}^*}{\Pi_t' \mathbf{y}_{jt-1}^*} \right) \left( \frac{\Pi_{t-1}' \mathbf{y}_{jt}^*}{\Pi_{t-1}' \mathbf{y}_{jt-1}^*} \right) \right]^{\frac{1}{2}}.$$

<sup>17</sup>Evidence for US exports and imports comes from Alterman, Diewert, and Feenstra (1999). They find that the Laspeyres price or quantity indexes for imported goods over time exceed the Paasche price or quantity indexes, consistent with demand-side substitution in the United States. The same inequality holds for many exported goods, too, which must reflect foreign demand-side substitution rather than US supply-side substitution.



To understand how this result is applied in PWT8, recall that we start with a set of prices for  $C$ ,  $I$ , and  $G$ , constructed across countries (relative to a base country, the United States) and over time, constructed from the GEKS method described in (7). To these we add relative prices for exports  $X$  and imports  $M$ , as described in Section V. That is the first stage of aggregation. In the second stage, we use the GK method to construct reference price for each of  $C$ ,  $I$ ,  $G$ ,  $X$ , and  $M$  as the weighted average of these prices (relative to the US) across countries: those are the reference prices  $\Pi_t$  in each year. Then the right-hand side of formula (12) can be used to obtain a *constant reference-price growth rate* of real output. In practice, instead of using the optimal quantities as on the right of (12) we instead use observed quantities (see Section V). In this way, we obtain data for real GDP across countries that are consistent with the reference prices established for each year and also correct for *changing* reference prices when making comparisons across time. These variables are denoted in PWT8 by  $RGDP^e$  (using only prices for  $C$ ,  $I$ , and  $G$ ) and  $RGDP^o$  (also using prices for  $X$  and  $M$ ). We believe that they offer the best cross-country and time-series comparisons of real GDP. As we mentioned at the end of Section I, however, for research questions that can be answered with the growth rate of real GDP from the national accounts, that growth rate is used to construct  $RGDP^{NA}$  and this variable is the closest to real GDP as reported in past versions of PWT.<sup>18</sup>

#### IV. Total Factor Productivity

Having obtained the comparison of real GDP across countries and over time, we now show how total factor productivity can be computed. We rely heavily on our earlier results and on Caves, Christensen, and Diewert (1982a,b)—henceforth, CCD—and Diewert and Morrison (1986)—henceforth, DM. We drop the time subscript and return to the ratio of revenue functions given in (9),  $r_j(\Pi, \mathbf{v}_j) / r_k(\Pi, \mathbf{v}_k)$ , which measures real output in country  $j$  relative to  $k$ . Real output can vary due to differing factor endowments, as indicated by  $v_{lj}$  and  $v_{lk}$  for factors  $l = 1, \dots, L$ , or due to differing technologies, as indicated by the country subscript  $j$  and  $k$  on the revenue function. We can isolate the effect of productivity differences by considering two alternative ratios

$$A_j \equiv \frac{r_j(\Pi, \mathbf{v}_j)}{r_k(\Pi, \mathbf{v}_j)}, \quad \text{and} \quad A_k \equiv \frac{r_j(\Pi, \mathbf{v}_k)}{r_k(\Pi, \mathbf{v}_k)}.$$

Both of these ratios measure the overall productivity of country  $j$  to country  $k$ , holding fixed the level of factor endowments. Neither ratio can be measured directly from the data, however, because the numerator or the denominator involves a revenue function that is evaluated with the productivity of one country but the endowments of the other. But the results of CCD and DM tell us that if the revenue function has a translog functional form, then we can precisely measure the geometric mean of these two ratios:

<sup>18</sup>See footnotes 7 and 9.

**THEOREM 2:** *Assume that the revenue functions  $r_j(\mathbf{\Pi}, \mathbf{v}_j)$  and  $r_k(\mathbf{\Pi}, \mathbf{v}_k)$  are both translog functions that are homogeneous of degree 1 in  $\mathbf{v}$  and have the same second-order parameters on factor endowments, but may have different parameters on prices and on interaction terms due to technological differences between countries. Then the overall productivity of country  $j$  relative to  $k$  can be measured by*

$$(13) \quad (A_j A_k)^{\frac{1}{2}} = \frac{r_j(\mathbf{\Pi}, \mathbf{v}_j)}{r_k(\mathbf{\Pi}, \mathbf{v}_k)} / Q_T(\mathbf{v}_j, \mathbf{v}_k, \mathbf{w}_j^*, \mathbf{w}_k^*),$$

where  $Q_T(\mathbf{v}_j, \mathbf{v}_k, \mathbf{w}_j^*, \mathbf{w}_k^*)$  is the Törnqvist quantity index of factor endowments, defined by

$$(14) \quad \ln Q_T(\mathbf{v}_j, \mathbf{v}_k, \mathbf{w}_j^*, \mathbf{w}_k^*) = \sum_{l=1}^L \frac{1}{2} \left( \frac{w_{lj}^* v_{lj}}{\sum_m w_{mj}^* v_{mj}} + \frac{w_{lk}^* v_{lk}}{\sum_m w_{mk}^* v_{mk}} \right) \ln \left( \frac{v_{lj}}{v_{lk}} \right),$$

and where  $w_{ij}^* = \partial r_j(\mathbf{\Pi}, \mathbf{v}_j) / \partial v_{ij}$ ,  $w_{ik}^* = \partial r_k(\mathbf{\Pi}, \mathbf{v}_k) / \partial v_{ik}$  are the factor prices using reference prices  $\mathbf{\Pi}$ .

CCD establish a result like Theorem 2 using the translog distance and transformation functions, whereas DM establish an analogous result using a time-series rather than cross-country comparison. For completeness, we include a proof in online Appendix A, where we explain that the restriction that the second-order parameters of the factor endowments restricts the technology differences across countries to be of the Harrod-neutral type on factors, or to apply to sectors. The GDP ratio  $r_j(\mathbf{\Pi}, \mathbf{v}_j) / r_k(\mathbf{\Pi}, \mathbf{v}_k)$  in (13) is measured as in Theorem 1, while the Törnqvist quantity index is measured as in (14) but using *observed* factor prices (and therefore observed factor shares) rather than factor prices evaluated at the reference prices, as discussed in the next section.

Theorem 2 tells us that by dividing the observed difference in real  $GDP^o$  by the Törnqvist quantity index of factor endowments, we obtain a meaningful measure of the productivity difference between the countries. This result, like the GDP function in (8) and Theorem 1, relies on strict neoclassical assumptions and in particular on perfect competition in product and factor markets. Then with the added assumptions on the translog function described in Theorem 2, the productivity measure in (13)–(14) reflects cross-country differences in aggregate technology.

We recognize that the requirement of perfect competition in product and factor markets, needed for Theorems 1 and 2, is strong. Recent literature has incorporated imperfect competition into the measurement of productivity: e.g., de Loecker (2009) for a single firm or industry, and Basu et al. (2014) for the entire economy. While we expect that our results could be extended to incorporate imperfect competition, such an extension is beyond the scope of the present paper. Burstein and Cravino (2015) relate empirical productivity measures (using procedures of statistical agencies that are similar to ours) to aggregate productivity and welfare changes in international trade models featuring monopolistic competition, and find that those empirical productivity measures are well-grounded. Likewise, Basu et al. (2014) argue that even with imperfect competition in product markets, TFP calculations based

on aggregate consumption (rather than output) still provide valid welfare comparisons across countries. Specifically, they show that welfare can be measured through the present value of future relative TFP and the relative current capital stock (per capita). Most important, this result does not rely on assumptions regarding market structure and technology, but follows only from assuming a price-taking, optimizing representative consumer. Furthermore, they show that in an open economy, this welfare-relevant measure of TFP should be computed based on real domestic absorption.<sup>19</sup> For these various reasons, we expect that the methods used to construct PWT8, as outlined in the next section, while derived from perfectly competitive behavior as in Theorems 1 and 2, may well apply more generally.

## V. Implementation in PWT

Measures of real GDP in PWT8 are built up from detailed price data on consumption,  $C$  and  $G$ ; investment,  $I$ ; exports and imports,  $X$  and  $M$ ; as well as nominal expenditures and trade. This is done in a two-step aggregation procedure: using the GEKS price indexes (7) to compute aggregates *within* the major categories of GDP; and then using reference prices *for each* of these major categories computed as the world average prices with the Geary-Khamis (GK) approach. We first outline the measurement of GDP from the expenditure side, then from the output side, and finally discuss productivity.

Within each category  $C$ ,  $I$ , and  $G$ , we first aggregate the ICP prices using GEKS price indexes.<sup>20</sup> ICP prices are available for the benchmark years 1970, 1975, 1980, 1985, 1996, and 2005. There is an expanded set of countries available from the ICP in each benchmark, and in total 167 countries are used in one benchmark or another. That is the set of countries included in PWT8 (this set will expand as more countries are included in future benchmarks).<sup>21</sup> For each country, we keep track of which benchmarks were used; years in-between benchmarks will have the prices for final goods *interpolated* using the corresponding price trends from countries' national accounts data; and for years before the first or after the last benchmark for each country the prices of final goods are *extrapolated* using national account data (see online Appendix B).

In a second step the GEKS price indexes are used to obtain a  $(3 \times 1)$  vector of reference prices for  $C$ ,  $I$ ,  $G$  (and later, exports and imports).<sup>22</sup> The quantity of domestic final goods  $C$ ,  $I$ , and  $G$  are included within the  $(3 \times 1)$  vector  $\mathbf{q}_j$ .<sup>23</sup> Given the  $(3 \times 1)$  vector of reference prices for domestic final goods,  $\boldsymbol{\pi}$ , the PPP exchange rate can be defined as

$$(15) \quad PPP_j^g = \mathbf{p}'_j \mathbf{q}_j / \boldsymbol{\pi}'_j \mathbf{q}_j.$$

<sup>19</sup>As discussed in Section I and in the next section, PWT8.1 includes the TFP measure  $CWTP$  that is based on domestic absorption rather than output.

<sup>20</sup>Since output prices for government consumption,  $G$ , are typically unobservable, ICP provides information on relative input prices, notably relative wages. For PWT, we modify the ICP numbers by implementing a common productivity adjustment approach described in Chapter 4 of World Bank (2014); see also Heston (2013). This leads to results that are more comparable between countries and to what is implemented in ICP 2011.

<sup>21</sup>The new PWT9 will be based on the 2011 ICP and cover nearly 180 countries.

<sup>22</sup>Below, we outline how these reference prices are estimated from the GK procedure; see also online Appendix B.

<sup>23</sup>The relative quantity of these variables is obtained by dividing their relative value by the GEKS price index.

This equation shows that the PPP exchange rate is just the ratio of expenditure at local prices to that at reference prices measured in the currency of the base country, in our case the US. Because the PPP is in units of the currency of country  $j$  per unit of the currency of the base country, it is common to divide it by the nominal exchange rate to obtain what is called the “price level” of country  $j$ :

$$PL_j \equiv \frac{PPP_j}{\mathcal{E}_j}.$$

The ratio of price levels is typically known as the *real exchange rate* between countries. These price levels are given in PWT for each country relative to the United States. Denoting nominal GDP in national currency by  $GDP_j$ , and the trade balance by  $(X_j - M_j)$ , *real GDP on the expenditure side* is then computed as

$$(16) \quad CGDP_j^e \equiv \pi' \mathbf{q}_j + (X_j - M_j) / PPP_j^q = GDP_j / PPP_j^q.$$

The expression  $\pi' \mathbf{q}_j$  on the left is just real expenditure on final goods, which is obtained by deflating nominal expenditure  $\mathbf{p}'_j \mathbf{q}_j$  by the PPP exchange rate in equation (15). In the second term, we *also* deflate the trade balance by the same PPP exchange rate that is constructed over final goods. From the point of view of the representative consumer, we are essentially treating the trade balance as an income transfer that is then deflated by the local prices, including prices for nontraded goods. By this logic, one can view (16) as a measure of the standard of living for country  $j$ , but now extended to incorporate the trade balance.

In addition to  $CGDP_j^e$ , PWT8 also includes a measure of real consumption and a measure of real domestic absorption. The measure of real domestic absorption is equal to  $CGDP_j^e$  except for the trade balance, so  $CDA_j = \pi' \mathbf{q}_j$ . Real consumption includes both private ( $C$ ) and public consumption ( $G$ ), but in contrast to real domestic absorption excludes investment, so  $CCON_j = \pi_C q_{Cj} + \pi_G q_{Gj}$ . In PWT8, we provide these real consumption and real  $GDP^e$  variables and also, for the first time, we provide estimates of real GDP on the output side ( $GDP^o$ ) for the full set of PWT countries and all years. This requires relative price data for imports and exports, as discussed in Feenstra et al. (2009). Compared with their experimental estimates, the real  $GDP^o$  results in PWT8 are much more reliable due to the use of new relative prices of exports and imports that correct for quality, as constructed by Feenstra and Romalis (2014). This quality correction is crucial as the prices of traded goods are computed as unit values of export and imports products, rather than the precisely specified prices collected for consumption and investment goods in the ICP.

To correct the unit values for quality, recent literature such as Khandelwal (2010) and Hallak and Schott (2011) presume that a good that is imported in high quantity but without having a low price must be of high quality. One shortcoming of this approach is that a good might be imported in high quantity because there are many varieties of it (e.g., many models of cars from Japan).<sup>24</sup> So Feenstra and Romalis

<sup>24</sup>We have also computed the quality-adjusted export prices using the technique of Khandelwal (2010), who uses country population as a proxy for export variety. As shown in Feenstra and Romalis (2014, Figure XIII), there

(2014) refine this demand-side measurement by adding a supply side with monopolistically competitive firms. Using the assumption of free entry they solve for the variety of each good produced, so that differences in the range of varieties sold from each exporter to each importing country are accounted for. Dividing the unit-values of exports and imports by the quality estimates, quality-adjusted prices are obtained. This procedure is implemented at the level of four-digit Standard International Trade categories between each pair of countries, and then aggregated to 6 one-digit Broad Economic categories, such as consumer goods or fuel. The quality-adjusted price indexes in these broad categories show much less variation across countries than do the raw unit-values, since most of the variation in the unit values is due to quality.

The quality-adjusted trade prices are an important ingredient for real GDP<sup>o</sup>. They are averaged across countries to obtain reference prices for exports and imports. These are included within  $\Pi = (\pi, \pi^x, \pi^m)$  and applied to the revenue function<sup>25</sup> to measure real GDP on the output side as

$$(17) \quad CGDP_j^o \equiv \pi' \mathbf{q}_j + \pi'^x \mathbf{x}_j - \pi'^m \mathbf{m}_j = \frac{C_j + I_j + G_j}{PPP_j^q} + \frac{X_j}{PPP_j^x} - \frac{M_j}{PPP_j^m}$$

$$= \frac{GDP_j}{PPP_j^o},$$

where the equalities follow by defining the PPPs of final goods, exports, imports, and GDP as

$$(18) \quad PPP_j^q \equiv \frac{\mathbf{p}'_j \mathbf{q}_j}{\pi' \mathbf{q}_j}, \quad PPP_j^x \equiv \frac{\mathbf{p}'_j{}^x \mathbf{x}_j}{\pi'^x \mathbf{x}_j}, \quad PPP_j^m \equiv \frac{\mathbf{p}'_j{}^m \mathbf{m}_j}{\pi'^m \mathbf{m}_j},$$

$$PPP_j^o \equiv \frac{\mathbf{p}'_j \mathbf{q}_j + \mathbf{p}'_j{}^x \mathbf{x}_j - \mathbf{p}'_j{}^m \mathbf{m}_j}{\pi' \mathbf{q}_j + \pi'^x \mathbf{x}_j - \pi'^m \mathbf{m}_j}.$$

It is apparent that nominal exports and imports in (17) are not deflated by a PPP computed over final goods, as in (16), but are deflated by PPPs that are specific to exports and imports. The use of reference prices for all goods, including exports and imports as in (17), makes real GDP<sup>o</sup> an appropriate measure of the productive

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is then a strong negative correlation between export quality and population, and so a strong positive correlation between the quality-adjusted terms of trade and population. As a result, the Khandelwal procedure leads to countries with large populations, such as India, having  $CGDP^e$  noticeably higher than  $CGDP^o$ . We believe that this tendency is artificial (i.e., India does not have such a strong terms of trade) and it does not occur using our own methods.

<sup>25</sup>The revenue function presumes perfect competition, whereas the quality-adjusted export and import prices have been obtained from a model of monopolistic competition. This does not create any inconsistency for import prices, because the quality-adjusted demands are still a standard function of the quality-adjusted prices. But on the export side, monopolistically competitive firms are charging a fixed CES markup over marginal costs, contrary to the standard revenue function. Still, Feenstra and Kee (2008) show that in the monopolistic competition model with CES preferences, a well-specified GDP function is being maximized. Further, Burstein and Cravino (2015) allow for monopolistic competition in an international trade model, and find that conventional measures of GDP construction are still adequate to a first order. For these reasons and because there is no practical alternative, we are willing to use the quality-adjusted export prices even with the perfectly competitive revenue function.

capacity of countries. If we divide the PPPs in (18) by the nominal exchange rate, then we obtain the *price levels* of these components of GDP.

The reference prices used in computing real GDP<sup>o</sup> and GDP<sup>e</sup> have not been defined up to this point; in PWT8 we compute these based on the Geary-Khamis (GK) approach. The first equation is the definition of the PPP for GDP<sup>o</sup>,  $PPP_j^o$ , in (18). Given this PPP, the reference price for each product is computed as the (quantity-weighted) average of the country prices relative to their PPP:

$$(19) \quad \pi_i = \frac{\sum_{j=1}^C (p_{ij} / PPP_j^o) q_{ij}}{\sum_{j=1}^C q_{ij}}, \quad \pi_i^x = \frac{\sum_{j=1}^C (p_{ij}^x / PPP_j^o) x_{ij}}{\sum_{j=1}^C x_{ij}},$$

$$\pi_i^m = \frac{\sum_{j=1}^C (p_{ij}^m / PPP_j^o) m_{ij}}{\sum_{j=1}^C m_{ij}},$$

where the index  $i$  in the reference prices for final goods,  $\pi_i$ , runs over  $C, I, G$ , and in the reference prices for exports and imports,  $\pi_i^x$  and  $\pi_i^m$ , runs over the one-digit Broad Economic categories. Then  $PPP_j^o$  in (18) together with (19) are a system of equations that can be solved up to a normalization.

Real GDP on the expenditure side and output side will differ due to the terms of trade faced by countries. This is apparent by taking the difference between (16) and (17):

$$CGDP_j^e - CGDP_j^o = \left( \frac{PPP_j^x}{PPP_j^q} - 1 \right) \frac{X_j}{PPP_j^x} - \left( \frac{PPP_j^m}{PPP_j^q} - 1 \right) \frac{M_j}{PPP_j^m}.$$

To simplify this expression, we can divide by  $CGDP_j^o$  and rearrange terms to obtain

$$(20) \quad \underbrace{\frac{CGDP_j^e - CGDP_j^o}{CGDP_j^o}}_{\text{Gap}} = \underbrace{\frac{1}{2} \left( \frac{PPP_j^x}{PPP_j^q} - \frac{PPP_j^m}{PPP_j^q} \right)}_{\text{Terms of trade}} \underbrace{\left( \frac{X_j / PPP_j^x}{CGDP_j^o} + \frac{M_j / PPP_j^m}{CGDP_j^o} \right)}_{\text{Real openness}}$$

$$+ \underbrace{\left[ \frac{1}{2} \left( \frac{PPP_j^x + PPP_j^m}{PPP_j^q} \right) - 1 \right]}_{\text{Traded/nontraded price}} \underbrace{\left( \frac{X_j / PPP_j^x}{CGDP_j^o} - \frac{M_j / PPP_j^m}{CGDP_j^o} \right)}_{\text{Real balance of trade share}}.$$

We see that the gap between real GDP<sup>e</sup> and real GDP<sup>o</sup> can be expressed as the sum of two terms: the first is the terms of trade (expressed as a difference rather than a ratio) times real openness; and the second is the relative prices of traded goods (again expressed as a difference) times the real balance of trade. The influence of both these terms on the gap between real GDP from the expenditure and output sides has also been shown by Kohli (2004, 2006) and Reinsdorf (2010), and we will illustrate this relation with some examples from PWT8.1 in Section VI.

The above formulas are computed for each year, obtaining the measures of real GDP that are based on current-year reference prices, i.e.,  $CGDP_j^e$  and  $CGDP_j^o$ . To correct for changing reference prices over time, we use Corollary 1 to define the growth rate of real GDP<sup>o</sup> as

$$(21) \quad \frac{RGDP_{jt}^o}{RGDP_{jt-1}^o} \equiv \left[ \left( \frac{\Pi'_{t-1} \mathbf{y}_{jt}}{\Pi'_{t-1} \mathbf{y}_{jt-1}} \right) \left( \frac{\Pi'_t \mathbf{y}_{jt}}{\Pi'_t \mathbf{y}_{jt-1}} \right) \right]^{\frac{1}{2}}$$

$$= \left[ \left( \frac{\pi'_{t-1} \mathbf{q}_{jt} + \pi'^x_{t-1} \mathbf{x}_{jt} - \pi'^m_{t-1} \mathbf{m}_{jt}}{\pi'_{t-1} \mathbf{q}_{jt-1} + \pi'^x_{t-1} \mathbf{x}_{jt-1} - \pi'^m_{t-1} \mathbf{m}_{jt-1}} \right) \left( \frac{\pi'_t \mathbf{q}_{jt} + \pi'^x_t \mathbf{x}_{jt} - \pi'^m_t \mathbf{m}_{jt}}{\pi'_t \mathbf{q}_{jt-1} + \pi'^x_t \mathbf{x}_{jt-1} - \pi'^m_t \mathbf{m}_{jt-1}} \right) \right]^{\frac{1}{2}}$$

Thus, the quantities of final goods, exports, and imports change from  $t - 1$  to  $t$  in both ratios, and are evaluated using the reference prices from one period or the other, and then taking the geometric mean. PWT8 uses the growth rates from this formula to compute real GDP<sup>o</sup> in all years other than the 2005 benchmark, for which  $RGDP^o = CGDP^o$ .

In addition, the constant-price growth rates of real  $GDP^e$  are obtained by using only the reference prices  $\pi'_{t-1}$  and  $\pi'_t$  of the final consumption goods.  $RGDP^e = CGDP^e$  is defined by (16) in the benchmark year 2005, and its growth rate to other years is obtained as

$$(22) \quad \frac{RGDP_{jt}^e}{RGDP_{jt-1}^e}$$

$$\equiv \left[ \left( \frac{\pi'_{t-1} \mathbf{q}_{jt} + (X_{jt} - M_{jt})/PPP_{jt}^q}{\pi'_{t-1} \mathbf{q}_{jt-1} + (X_{jt-1} - M_{jt-1})/PPP_{jt-1}^q} \right) \left( \frac{\pi'_t \mathbf{q}_{jt} + (X_{jt} - M_{jt})/PPP_{jt}^q}{\pi'_t \mathbf{q}_{jt-1} + (X_{jt-1} - M_{jt-1})/PPP_{jt-1}^q} \right) \right]^{\frac{1}{2}}$$

Notice that in (22) we deflate nominal exports and imports by the PPPs for final goods,  $PPP_{jt}^q$  and  $PPP_{jt-1}^q$ , computed from the reference prices for those goods. This is in contrast to (21) where the actual reference prices of exports and imports are used.

Theorem 2 tells us that by deflating the observed difference in real GDP<sup>o</sup> by the Törnqvist quantity index of factor endowments, we obtain a meaningful measure of the productivity difference between the countries. The Törnqvist quantity index is constructed using the factor prices that are implied by the reference prices for goods,  $\Pi$ . In practice we do not observe these factor prices, and so we replace the theoretical expressions in (13)–(14) with versions that we can measure from the data:

$$(23) \quad CTFP_{jk} \equiv \frac{CGDP_j^o}{CGDP_k^o} / Q_T(\mathbf{v}_j, \mathbf{v}_k, \mathbf{w}_j, \mathbf{w}_k),$$

where we use  $CTFP_{jk}$  to denote the (current-year price) productivity of country  $j$  relative to  $k$ , and the Törnqvist quantity index of factor endowments  $Q_T$  is evaluated

with observed factor prices and shares. PWT8 includes  $CTFP_{jk}$  computed with current year prices for each country  $j$  relative to the United States. In addition to the production-side measure of  $CTFP_{jk}$ , PWT8 also includes a welfare-relevant measure of TFP based on the work of Basu et al. (2014). This measure is based not on relative  $CGDP^o$  levels, but instead on relative domestic absorption, CDA:

$$(24) \quad CWTFP_{jk} \equiv \frac{CDA_j}{CDA_k} / Q_T(\mathbf{v}_j, \mathbf{v}_k, \mathbf{w}_j, \mathbf{w}_k).$$

An analogous expression is used for *productivity growth* in each country, which is defined by reintroducing time subscripts and using real GDP and factor input growth rates obtained from national accounts data:

$$(25) \quad RTFP_{jt,t-1}^{NA} \equiv \frac{RGDP_{jt}^{NA}}{RGDP_{jt-1}^{NA}} / Q_T(\mathbf{v}_{jt}, \mathbf{v}_{jt-1}, \mathbf{w}_{jt}, \mathbf{w}_{jt-1}).$$

For this purpose, we have developed new data on factor inputs—capital and labor—and factor income shares.<sup>26</sup> Specifically, PWT8 (re)introduces a measure of the physical capital stock, based on long time-series of investment by asset. For each country, we distinguish investment in structures, transport equipment, and machinery, and for a range of countries, we also separately distinguish investment in computers, communication equipment, and software. Investments are cumulated into capital stocks using asset-specific geometric depreciation rates using the perpetual inventory method. The relative factor price of the capital stock is computed by aggregating asset-specific investment prices using shares of each asset in the total (current cost) capital stock. PWT has long included data on the number of workers in an economy, but a more accurate measure of relative labor input should account for the large differences in schooling across countries. To that end, PWT8 includes an index of human capital per worker based on the average years of schooling, linearly interpolated from Barro and Lee (2013), and an assumed rate of return for primary, secondary, and tertiary education, as in Caselli (2005).<sup>27</sup>

We have also developed new information about the share of labor income in GDP. An important measurement challenge, well known since Gollin (2002), is that self-employed workers earn income for both the labor and capital they supply. We follow Gollin (2002) in splitting this mixed income between capital and labor income using the same shares as found for nonmixed income. Where mixed income is not available as a separate data item in a country's national accounts, we impute the labor income of the self-employed either by assuming that self-employed earn the same average income as employees or based on the share of agriculture in value added. In online Appendix C, we go into greater detail on these measurement choices and their implications. One important result, though, is that the global decline in the corporate labor income share that was documented by Karabarbounis and Neiman (2014) is also found for our economy-wide labor shares. In computing

<sup>26</sup> See online Appendix C for more details on the data sources and measurement methodology.

<sup>27</sup> Though we note that this is an imperfect measure of human capital as differences in the returns to experience (Lagakos et al. 2014) and the quality of schooling (Hanushek and Woessman 2012) are not accounted for.



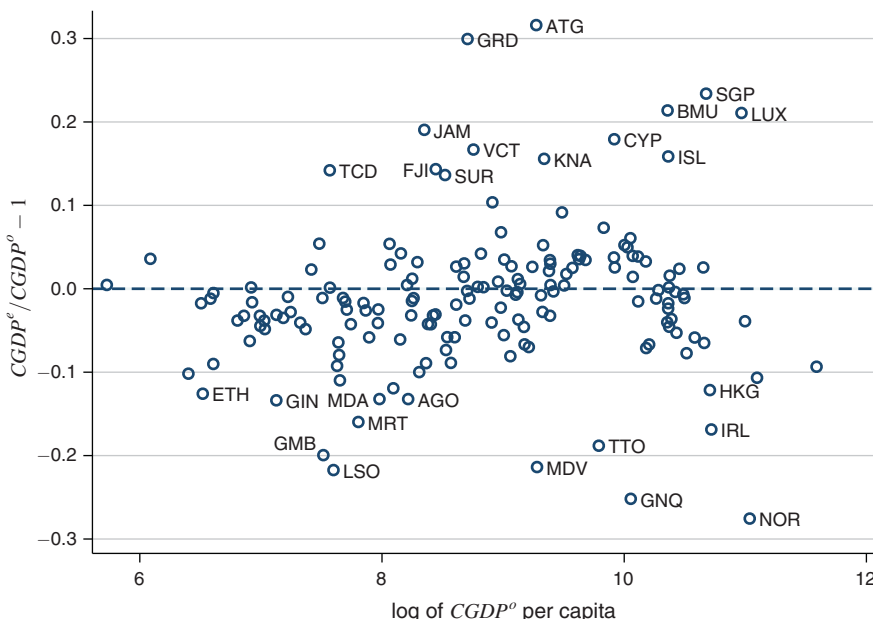


FIGURE 1. REAL GDP PER CAPITA IN 2005 AND THE GAP BETWEEN  $CGDP^e$  AND  $CGDP^0$

Notes: Includes 166 of the countries in PWT. Excluded is El Salvador with a gap of 1.5.

Source: Computations based on PWT8.1.

the overall quantity index of factor endowments, we assume that the income share of physical capital equals 1 minus the labor income share, though future work on distinguishing natural from physical capital, as done for one year in Caselli and Feyrer (2007), would be an important improvement.

### VI. Applications

Based on the next generation of PWT, version 8.1, we provide three applications to illustrate its usefulness: an analysis of the difference between real GDP from the expenditure and output sides; an analysis of the Balassa-Samuelson effect; and a decomposition of the variance of real GDP per capita into the variance of factor inputs and productivity (known as development accounting).

#### A. $GDP^e$ versus $GDP^0$

Figure 1 illustrates how real  $GDP^0$  differs from real  $GDP^e$  in 2005. For some countries the differences are clearly notable, with several absolute differences near 30 percent. At the same time, many differences are not so large: 153 of the 166 countries have a  $GDP^e$  level within 10 percent of their  $GDP^0$  level. Note also that the gap between  $CGDP^e$  and  $CGDP^0$  does not vary systematically with the level of  $CGDP^0$  per capita. To better understand what is driving these gaps, we use the decomposition introduced in equation (20). According to this, consumption possibilities can exceed productive capacity when a country faces favorable terms of

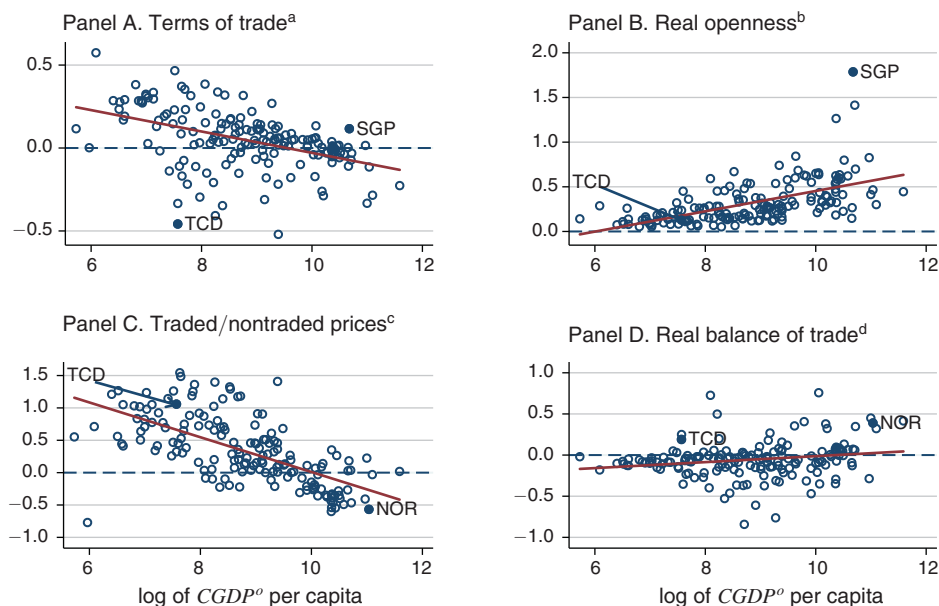


FIGURE 2. DECOMPOSING THE GAP BETWEEN  $CGDP^e$  AND  $CGDP^o$  IN 2005

Notes: See equation (19) for the definition of the concepts plotted in the four panels.

<sup>a</sup>Omitted is Zimbabwe (1.0)

<sup>b</sup>Omitted is El Salvador (4.2)

<sup>c</sup>Omitted are Tajikistan (2.4), Uzbekistan (3.9), and Zimbabwe (3.0)

<sup>d</sup>Omitted is El Salvador (-2.2)

Source: Computations based on PWT8.1.

trade and the gains are larger whenever real openness is larger. In contrast, a country only gains excess consumption possibilities from a positive real balance of trade when traded goods are expensive compared to nontraded goods. Following the basic argument from Section II this will mostly be the case in poorer countries while in rich countries, traded goods are relatively cheap. Figure 2 illustrates the decomposition of the gaps from Figure 1 in 2005, according to equation (19).

Panel A of Figure 2 shows that terms of trade are negatively related to  $CGDP^o$  per capita, which follows from the results of Feenstra and Romalis (2014).<sup>28</sup> There is a positive relationship between real openness and income levels as shown in panel B; a finding that is consistent with Alcalá and Ciccone (2004). Panel C shows how the ratio of traded to nontraded prices declines with income, consistent with the Balassa-Samuelson effect, while the real balance of trade in panel D shows a positive relationship with income, reflective of the Lucas (1990) paradox where capital flows from poor to richer countries. The overall gap between  $CGDP^e$  and  $CGDP^o$  is not systematically related with income levels, however, because the various positive and negative relationships with income levels cancel out when combined.

For illustration purposes, we have highlighted the observations for Chad (TCD), Singapore (SGP, panels A and B), and Norway (NOR, panels C and D). Figure 1

<sup>28</sup>Feenstra and Romalis (2014) find that quality-adjusted import prices are lower for poor countries, leading to the negative relationship between the terms of trade and country income. This relationship is weak before the mid-1990s, while there is a consistently significant negative relationship since 1996.

shows considerable positive gaps between  $CGDP^e$  and  $CGDP^o$  for both Singapore (+23 percent) and Chad (+13 percent), while the gap in Norway is strongly negative (−28 percent). The reason for Singapore’s large gap is a small but positive terms of trade combined with the largest observed real openness—its real balance of trade and traded/nontraded price ratio contribute little. In contrast, Chad had very negative terms of trade but combined with low real openness, the negative contribution to the overall gap is limited. Because of a high traded/nontraded price ratio and a positive real balance of trade, Chad’s overall gap ends up strongly positive. Norway, finally, also has a positive real balance of trade but because nontraded prices are relatively high in 2005, the overall result is a negative gap between  $CGDP^e$  and  $CGDP^o$ .

While the above discussion has highlighted some countries with large differences between  $CGDP^e$  and  $CGDP^o$ , for many important countries the difference is quite small. China, for example, has  $CGDP^e$  ( $CGDP^o$ ) per capita that is 13.7 percent (13.8 percent) of that in the United States in 2005 and 20.4 percent (20.5 percent) in 2011. The similar values for the expenditure- and output-side measures of real GDP follow from variables in (20) that are relatively small and offsetting in sign: China’s terms of trade is slightly negative, but its ratio of traded to nontraded prices is greater than unity with a positive but modest real balance of trade.<sup>29</sup>

### B. The Balassa-Samuelson Effect in PWT8.1

In panel C of Figure 2 we illustrated the Balassa-Samuelson or Penn effect for 2005: the observation that the relative price of nontraded goods to traded goods increases with the income level of a country. Surprisingly, Bergin, Glick, and Taylor (2006) found that there was no evidence of a Penn effect in the early 1950s, and that the effect gradually became significant and strengthened over time. Their analysis was based on PWT version 6 and we revisit it using version 8. Consider the regression

$$(26) \quad \ln\left(\frac{PPP_{it}^o}{\mathcal{E}_{it}}\right) = \beta_0 + \beta_1 \ln\left(\frac{CGDP_{it}^o}{POP_{it}}\right) + \varepsilon_{it},$$

where  $\mathcal{E}_{it}$  is the exchange rate and  $POP$  is the population of country  $i$  at time  $t$ .<sup>30</sup> The dependent variable in (26) is the price level of each country relative to the United States.

The finding of Bergin, Glick, and Taylor (2006) is puzzling, as the Balassa-Samuelson effect was already identified in data for the 1950s and 1960s

<sup>29</sup>We note that the 2005 prices for final consumption goods for China used in PWT8 have been adjusted downward by 20 percent as compared to the ICP values, which is the same adjustment that was made in PWT7 and reflects the fact that the ICP prices were collected in large part from urban areas in China. This correction is discussed further in Feenstra et al. (2013). Further adjustments for biases in ICP 2005 are also made in PWT8.1, based on Inklaar and Rao (2014) and described in Feenstra, Inklaar, and Timmer (2015b).

<sup>30</sup>Bergin, Glick, and Taylor (2006) divide the country’s GDP per capita level by the US level in every year, but this only affects the estimate of  $\beta_0$ . Also note that sometimes the exchange-rate-converted GDP per capita level is used as the explanatory variable instead of the PPP-converted GDP per capita level. We follow the approach of Bergin, Glick, and Taylor (2006), which was also advocated by Officer (1982). Officer argued that a productivity measure would be preferable to a GDP per capita level. Results using  $CGDP^o$  per capita or  $CTFP$  are very similar.

in, e.g., Balassa (1964), therefore raising the question why the effect shows up so much later in PWT8. One possibility could be that this effect is an emergent property and Bergin, Glick, and Taylor (2006) propose a model that yields this outcome. An alternative possibility is that the estimation of the PPPs used in the regression (26) in early years is problematic. As explained in Section V, PWT8 includes two types of observations: those based directly on ICP benchmark price survey results or interpolated between benchmarks; and those based on extrapolations from the oldest or most recent benchmarks using relative inflation rates from countries' national accounts data. The benchmark observations (and in effect the interpolated observations) make no assumptions regarding the evolutions of PPPs over time; they are simply based on the observed benchmark survey.

In contrast, extrapolating assumes that the change in PPPs is well-approximated by relative inflation. Deaton (2012) argues, however, that relative inflation will be a systematically biased estimate of the change in PPPs across countries. Specifically, he argues that under plausible conditions, the PPP of a poor country relative to a rich country will increase at a faster rate than implied by the difference in overall inflation. Figure 3 provides evidence in support of this contention. Panel A plots relative prices and income levels for benchmark or interpolated observations, while panel B plots observations based on extrapolations from earlier or later benchmarks. For both sets of observations, there is a significant positive relationship between price and income levels, but the regression line in panel A is significantly steeper than the line in panel B.<sup>31</sup> In online Appendix D we show more systematically that the extrapolation procedure used for nonbenchmark observations indeed lead to the supposed disappearance of the Balassa-Samuelson effect in early years.

The study of Bergin, Glick, and Taylor (2006) is based on PWT6 which relied exclusively on extrapolation of PPPs from a recent benchmark year, which would explain their findings. This illustrates the usefulness of including historical benchmark material and clearly distinguishing between benchmark/interpolated and extrapolated observations, as done in PWT8.

### *C. Capital and Productivity*

Traditionally, the main strength of PWT has been its information on GDP per capita, useful for comparing the standard of living across countries. Yet to gain an understanding of the (proximate) sources of the differences in living standards, we should analyze differences in the level of output, inputs, and productivity: see, e.g., Klenow and Rodríguez-Clare (1997); Hall and Jones (1999); and Caselli (2005). In PWT8, the introduction of relative prices of exports and imports and the resulting real  $GDP^o$  variable means that there is now a true measure of relative output. PWT has also long provided information on labor input, i.e., the number of workers, but information on physical capital has been absent since PWT version 6 and there has never been information in PWT on human capital or productivity. This has left researchers to their own devices in compiling productivity estimates. As a

<sup>31</sup>Note that we only include observations from ICP benchmark years (1970, 1975, 1980, 1985, 1996, and 2005) for a more balanced set of observations across the income spectrum in both panels. Online Appendix D shows results for the full range of years.

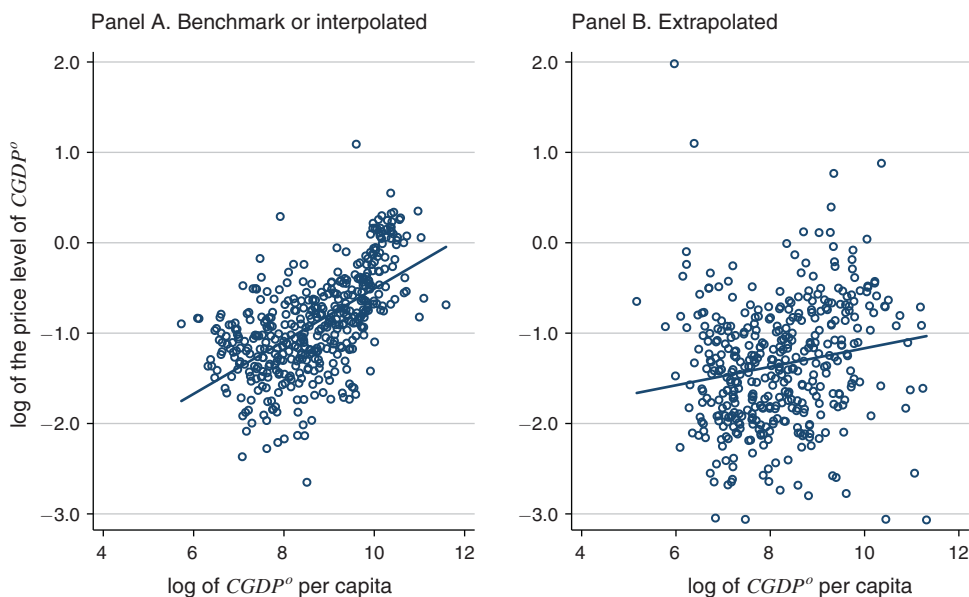


FIGURE 3. THE BALASSA-SAMUELSON EFFECT IN PWT8.1

*Notes:* Included are only observations in ICP benchmark years: 1970, 1975, 1980, 1985, 1996, and 2005. Observations are distinguished by whether the price level for a country is from that ICP benchmark, interpolated between ICP benchmarks, or extrapolated from an earlier or later benchmark. See online Appendix D for a comprehensive analysis. The solid line is the least-squares regression line; the slope of the regression line in panel B is significantly smaller than in panel A.

*Source:* Computations based on PWT8.1.

result these estimates tend to rely on numerous simplifying assumptions, such as a Cobb-Douglas production function and homogeneous physical capital.

The new version of PWT represents an important step forward by including measures of physical and human capital and estimates of productivity based on the translog production function (see Theorem 2) which allows for substitution elasticities to differ across countries and over time. The first novelty is to estimate physical capital stocks for all countries in PWT based on data of investment by asset. The second novelty is to estimate the share of labor income in GDP for a large majority of PWT countries. These are combined with (more standard) measures of human capital to arrive at measures of total factor productivity (TFP). A detailed description of the data is included as online Appendix C and here we provide an outline of the approach and show its implications for development accounting results as in Caselli (2005).

Physical capital stocks are computed by cumulating the depreciated past investments, but we distinguish investments by type of asset.<sup>32</sup> This has two important implications when contrasted with the study by Caselli (2005), which is representative for the broader literature. First, the average depreciation rate now varies across countries and over time, as countries differ in the asset composition

<sup>32</sup>Investment by type data is partly from National Accounts statistics, partly from estimates using the commodity-flow method along similar lines as Caselli and Wilson (2004).

of their capital stock and depreciation differs across assets. Second, while existing studies (implicitly) use the relative price of investment to compare the level of the capital stock across countries, we use information on the asset composition of the capital stock to compute a relative price of the capital stock. This relative price of the capital stock gives much larger weight to the price of buildings—which are comparatively cheap in poorer countries, than to the price of machinery, which is relatively more expensive as buildings are the longest-lived assets: see Hsieh and Klenow (2007). So while the price of investment goods relative to consumption goods declines rapidly with income—as in Hsieh and Klenow (2007)—there is a weaker relation with income levels when comparing the price of the capital stock to the price of consumption goods.

The typical approach in development accounting is to assume that the output elasticity of labor is identical across countries and constant over time at 0.7, yet the evidence in support of this assumption is modest at best. The oft-cited work of Gollin (2002) shows substantial cross-country variation in the income share of labor in GDP, as well as Bernanke and Gürkaynak (2002). More recently, Karabarbounis and Neiman (2014) shows that, for many countries, the labor share has been declining in the last two decades. In PWT8, we therefore estimate the share of labor income in GDP for as many countries and years as possible. Information on the labor compensation of employees is broadly available, but the labor compensation of self-employed workers needs to be separately estimated. Here we broadly follow the existing approaches in the literature, but on a substantially larger scale.<sup>33</sup> This yields some key findings, namely: (i) an average labor share of 0.52, which is much lower than the 0.7 that is typically assumed; (ii) no systematic variation of labor shares with income levels; (iii) declining labor shares over time in 89 of the 127 countries.

Combining the new information on labor shares, physical capital, and estimates of human capital (based on the average years of schooling of Barro and Lee 2013) yields data on overall factor inputs (denoted  $Q$ ) and relative productivity levels ( $CTFP$ ). These can be used to provide a variance analysis of real GDP per capita across countries as in Caselli (2005). Combining (20) with (23), we obtain a decomposition of current-price real GDP on the expenditure side:

$$\frac{CGDP_j^e}{CGDP_k^e} = CTFP_{jk} \times Q_T(\mathbf{v}_j, \mathbf{v}_k, \mathbf{w}_j, \mathbf{w}_k) \times \left( \frac{1 + Gap_j}{1 + Gap_k} \right),$$

where the  $Gap$  between real  $GDP^e$  and real  $GDP^o$  is defined by the various terms-of-trade and balance-of-payments expressions on the right of (20). We report summary statistics from this decomposition in Table 2 and illustrate how these new measures compare to the earlier measures based on simplifying assumptions, namely a Cobb-Douglas production function with labor share of 0.7 and homogeneous capital stock (baseline).

<sup>33</sup>This involves using data on total income (from capital and labor) of self-employed, assuming similar wages for self-employed as for employees and information on the importance in the economy of agriculture, the dominant sector for self-employed workers. See online Appendix C for details.

TABLE 2—COUNTING FOR CROSS-COUNTRY VARIATION OF  $CGDP^e$  PER CAPITA IN 2005

	Baseline	(1)	(2)
Variance ( $\ln(CGDP^e)$ )	1.433	1.433	1.433
Variance ( $\ln(1+Gap)$ )	0.006	0.006	0.006
Variance ( $\ln(Q)$ )	0.351	0.332	0.485
Variance ( $\ln(CTFP)$ )	0.412	0.452	0.345
Fraction of variance accounted for by factor inputs	0.253	0.232	0.338

Notes:  $CGDP^e$  is expenditure-based real GDP;  $Gap$  is the difference between expenditure-based and output-based real GDP;  $Q$  is inputs of physical and human capital per capita, and  $CTFP$  is total factor productivity. The baseline decomposition is based on a constant labor share of 0.7 and homogeneous capital. Variant (1) allows for asset heterogeneity and variant (2) also allows for variation in the labor share.

Source: Computations based on PWT8.1.

This exercise aims to account for differences in  $CGDP^e$  per capita by variation in the gap between  $CGDP^e$  and  $CGDP^o$ —the effect of the terms of trade on standards of living—variation in factor inputs and variation in TFP. The first column mimics the approach of Caselli (2005), the second column accounts for the heterogeneity of physical capital, and the third column also accounts for the heterogeneity of labor shares and this is our preferred measure. Accounting for labor share heterogeneity has an important impact on the variation in  $CGDP^e$  per capita that is accounted for by variation in factor inputs, which increases from 25.3 percent to 33.8 percent. The very small share of variation accounted for by the gap between  $CGDP^e$  and  $CGDP^o$  was already implicit in Figure 1, as there was no systematic relationship between this gap and income levels.

Important to note, though, is that physical capital in PWT only covers *produced* capital, such as buildings and machinery, not natural capital such as land or subsoil resources. This natural capital is particularly important in developing economies, as shown by Caselli and Feyrer (2007). Augmenting capital inputs with natural capital using data from World Bank (2011) leads to a decline in the variance of  $CGDP^e$  per capita accounted for by variation in factor inputs (to 27.6 percent), suggesting that efficiency differences in the use of natural capital might be bigger than that from produced capital. As yet, data are only available for a few recent years and are not yet ideally suited for cross-country comparisons of inputs levels. However, including natural capital would be an important future improvement for PWT.

## VII. Conclusions

From its inception, the International Comparisons Program (ICP), on which PWT is built, only collects the prices of final products—for consumption, investment, and the government—across countries. It was prohibitively expensive to further collect comparable prices for the whole range of industrial and intermediate inputs used in economies, many of which are also traded. This limitation means that calculations based on ICP prices only are best thought of as representing the standard of living of countries rather than their production possibilities. Feenstra et al. (2009) argued that a measure of the productive capacity of countries could be obtained by combining the ICP data with prices for exports and imports. These two approaches lead to

measures of real GDP on the expenditure-side and real GDP on the output-side, respectively, both of which are included in the new PWT version 8.1.

The second contribution of PWT8 is to improve upon the growth of real GDP previously reported in PWT, which was based on national accounts data. Johnson et al. (2013) criticized growth rates as being dependent on the benchmark year of ICP data, and thereby dependent on the version of PWT being used. That problem is resolved in PWT8 by using *multiple* ICP benchmarks: for all of our measures of real GDP, the growth rate will not change in between existing benchmark years as new benchmarks become available, unless the underlying nominal GDP data from the national accounts are revised. We have shown that incorporating multiple ICP benchmarks also ensures that relationships such as the Balassa-Samuelson effect remain apparent in the dataset, rather than disappearing when going back further in time.

The final contribution of PWT8 is to reintroduce a measure of the capital stock and, for the first time, include a measure of relative TFP across countries. We have shown that, compared to standard findings in the literature, cross-country variation in factor inputs can account for more of the cross-country variation in  $CGDP^e$  per capita. This is mostly because PWT8.1 incorporates new estimates of the labor share in GDP that vary in a meaningful fashion across countries and over time.

Taken together, these contributions show that PWT version 8 breaks new ground in providing a cross-country dataset that is closer linked to the theoretical concepts of welfare and production, more consistent over time and more transparent in its methods. It should be noted however, that revisions will remain part of future versions of PWT. There can be substantial changes to nominal and real national accounts data over time, which will be the principal source of changes in interpolated values as new versions of PWT become available. The release of the 2011 ICP provides new prices for final expenditure which, in conjunction with updated, quality-adjusted prices for exports and imports, will be used to compute real GDP on the expenditure side and output side in PWT version 9. The results for the period 2005–2011, which were *extrapolated* in PWT8, will then be *interpolated* between the 2005 and 2011 benchmarks in PWT version 9. Early analysis on the 2011 ICP prices suggests that they differ quite substantially from extrapolated prices using the 2005 benchmark (Deaton and Aten 2014; Inklaar and Rao 2014). Therefore, we can expect some discussion and analysis of the 2011 benchmark prices before they are used to revise the recent years and are incorporated into PWT version 9.

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