Accounting for Growth in the Age of the Internet: The Importance of Output-Saving Technical Change

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ABSTRACT

We extend the conventional Solow growth accounting model to allow innovation to affect consumer welfare directly. Our model is based on Lancaster's "New Approach to Consumer Theory," in which there is a separate consumption technology that transforms goods, measured at production cost, into utility. This technology can shift over time, allowing consumers to make more efficient use of each dollar of income. This is an *output-saving* technical change, in contrast to the Solow TFP *resource-saving* technical change. The output-saving formulation is a natural way to think about the free information goods available over the Internet, which bypass GDP and go directly to the consumer. It also leads to the concept of *expanded GDP* (EGDP), the sum of conventional supply-side GDP and a willingness-to-pay metric of the value of output-saving innovation to consumers. This alternative concept of GDP is linked to output-saving technical change and incorporates the value of those technology goods that have eluded the traditional concept. It thus provides a potentially more accurate representation of the economic progress occurring during the digital revolution. One implication of our model is that living standards, as measured by EGDP, can rise at a faster rate than real GDP growth, which may shed light on the question of how the latter can decline in an era of rapid innovation.

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I. Introduction

The digital revolution presents an interesting paradox. On the one hand, the revolution has transformed the economic landscape and has had a powerful impact on daily lives. On the other, real GDP growth has slowed in recent years, despite the evident boom in information technology. Per capita GDP growth declined from its 1995–2006 rate of 2.3 percent to 1.5 percent from 2010 to 2015. Various explanations of this seeming paradox have been offered. The sharp and prolonged decline is seen by some as pointing to a more serious problem than a prolonged recession. Robert Gordon (2016) has also argued that the decline reflects the relatively anemic character of the digital revolution compared with earlier technological revolutions.

The disconnect between macroeconomic estimates of GDP and microeconomic analyses of innovation is reminiscent of the famous Solow (1987) paradox: “You can see the computer age everywhere but in the productivity statistics.” Solow’s remark was interpreted by many as a mild rebuke to those enthusiasts who overhyped the impact of computers on productivity growth. It could also be interpreted as an observation about the failure of national statistics to capture the true impact of the computer revolution, a position championed by Alan Greenspan around the same time.[2] We are now in a similar debate about the later stages of the digital revolution, again raising the question of whether there is less than meets the eye because there really is less of an impact on true GDP than enthusiasts imagine, or whether the impacts are concealed by the mismeasurement of real GDP.

We suggest that both may be true to some extent and that the impact of the digital revolution cannot be properly assessed by focusing exclusively on how innovation affects the supply side of the economy. There is a growing conviction in the recent literature on growth accounting that the current round of innovation is not adequately captured by conventional real GDP, particularly that which is available without a direct cost, and there is also an emerging view that it may bypass GDP entirely.[3]

[2] Greenspan’s concerns were first expressed in remarks at an FOMC meeting in late 1996 in regard to a staff analysis of sectoral productivity trends (Corrado and Slifman, 1999).

[3] In her book on the history of GDP, Coyle (2014) concludes that “gross domestic product is a measure of the economy best suited to an earlier era” (p. 125). Feldstein (2017) reaches a similar conclusion: “A great deal of effort and talent has been applied over past decades to the measurement of real income and inflation. These problems are

How might this happen? The Internet accelerates the flow of information, and the increased flow can increase the utility that a consumer derives from a given amount of income. The mechanisms at work here include an improved consumer awareness of alternative options, more timely access to information, and superior matching of goods to wants. An important implication is that a general increase in the availability of information can increase consumer utility *without an increase in GDP*. Moreover, the growth in consumer welfare over time may reflect both improvements in the efficiency of production and improvements in the efficiency of consumption.

If this is true, a declining rate of real GDP growth may be consistent with the perception of a vibrant technological environment and the microeconomic analysis that supports it. And, if this is true, then Koopman's 1947 warning about the perils of measurement without theory suggests that a theoretical framework is needed that at least allows for an alternative non-GDP channel through which innovation operates. In this paper, we propose an extension of the conventional Solow production-function approach to growth analysis that permits consumers to make more efficient use of each dollar of income and allows for the possibility that living standards can be rising at a greater rate than is signaled by the growth rate of real GDP.

Our model is based on Lancaster's "New Approach to Consumer Theory" (1966a), which we adapt to the growth accounting problem in a way consistent with the assumptions of the Solow model. In the Lancaster framework, there is a separate *consumption technology* that transforms the goods acquired from their producers, measured at production cost, into consumption *activities* or *commodities* that give utility based on their characteristics. We draw from the Lancaster model the idea that the utility function can shift over time as the technology of consumption becomes more efficient. Efficiency can increase through costless improvements in product quality that allow better products to be purchased for the same amount of money or through an increase in effective information that allows the consumer to get more utility from a

extremely difficult. In my judgment, they are far from being resolved, and as a result, substantial errors of unknown size remain in our ability to measure both real output and inflation" (p. 161). Others point to the need to look beyond GDP (as, for example, Ahmad and Schreyer (2016), Brynjolfsson et al (2017), Nakamura (2014), Nakamura, Samuels and Soloveichik (2016), Hulten (2015), and Varian (2009, 2016).

given amount of expenditure.[4] An outward shift in the consumption technology causes the macroeconomic utility possibility frontier (UPF) to shift outward, even if the supply-side production possibility frontier (PPF) remains unchanged. The shift in the UPF is, in effect, output-saving technical change, and it is particularly relevant for understanding the growth dynamics of the consumer-oriented digital age, with its "free" goods.

There is, however, an important empirical asymmetry between the two sides of the growth account: Unlike GDP, utility is not directly observable. This leads us to reformulate our expanded growth model in terms of the associated expenditure function and the compensating and equivalent variations for which metrics exist and which, indeed, underpin much of the recent empirical literature on valuing the Internet and other seemingly free goods. This literature makes extensive use of the willingness-to-pay concept of valuation associated with these metrics, as well as the related concept of consumer surplus. This expenditure function approach then leads us to introduce a concept we term *expanded gross domestic product* (EGDP), which is simply the notional sum of conventional GDP plus the compensating/equivalent variation due to output-saving technical change. This expanded concept of GDP is a dollar metric of the welfare side of the economy, including output-saving technical change, and therefore provides a more complete account of the growth of the "new" economy. EGDP also provides an analytical "home" for the results of those studies seeking to measure the willingness-to-pay or consumer surplus associated with the hard-to-measure new goods of this economy.

The paper then moves beyond costless technical change to allow for resource-costly innovation. Whereas costless innovation envisions technical progress on the supply side as a process based on inspiration, learning, and knowledge spillovers, the alternative view treats innovation as a matter of systematic investments in technology, including, for example, expenditures for research and development (R&D). These intangible inputs essentially "produce" innovation using resources that must be paid for one way or another. From a welfare standpoint,

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[4] Search engines provide a concrete example of how the Internet makes consumer choice more efficient. A consumer faced with a choice between different products can often find information about product specifications and capabilities, the experience of other consumers, and explicit comparisons from rating organizations. Someone looking to buy a particular product can go on Amazon, for example, and see not only the price and availability of that item but also a range of similar items that may turn out to be preferable. And this can be done while shopping in a store to see if a better price is available online, using a smartphone or other mobile device. GPS and traffic maps are often of great utility when traveling, as is immediate access to health information in times of need. Timely access to general medical information can also be of great value.

the gains from fully costed innovation are of a different nature: Innovation of the costly sort does not convey the same benefits as the costless “manna from heaven” sort, be they output-saving or resource-saving technical change.

This paper does not attempt to resolve the debate over whether, or by how much, the benefits of economic growth are actually understated by the way GDP is currently measured. Rather, it attempts to extend the conventional growth accounting framework in such a way that the debate might, in time, be resolved. However, while the paper is essentially about theory, we do offer some comments on the growing body of empirical work on the boundaries of the digital economy to indicate both the current state of play and some of the orders of magnitude involved, as well as their implications for the EGDP measure of welfare growth.

II. Information, Utility, and Innovation

In their book *How Google Works*, Schmidt and Rosenberg (2014) argue that the world has entered an era in which “the Internet has made information free, copious, and ubiquitous” to the consumer. This is one of the defining characteristics of what they call the “Internet Century.” At the same time, there are many other sources of economic growth that affect consumer well-being, and this raises the question of how to measure the contribution of “free, copious, and ubiquitous” information to GDP and its relative importance compared with other factors. The question currently on many minds is whether the contribution is large enough to offset what appears to be a slowdown in real GDP growth, but there is the larger theoretical question of how, and whether, consumer information should be included in measured GDP.

Where in the models of standard growth theory does an increase in information enter the analysis? This question has a long history, and the answer given by Hayek in 1945 was that it was largely absent. He argued that the standard model of economic theory was so closely wedded to the formal mathematics of optimization that it took as given the information needed for the optimization process. Hayek argued “that the ‘data’ from which the economic calculus starts are never for the whole society ‘given’ to a single mind which could work out the implications, and can never be so given” (page 519). No individual consumer can hope to possess all the information relevant to fully rational choice, or even to form preferences for items or circumstances never before encountered and not likely to be encountered in the future. In either case, the provision of "free, copious, and ubiquitous" information has ample opportunity to increase consumer utility.

Stigler (1961) proceeded along much the same conceptual path in his analysis of price dispersion and the prevalence of advertising expenditures. He took academic economists to task for failing to recognize the importance of information:

> "One should hardly have to tell academicians that information is a valuable resource: Knowledge is power. And yet this occupies a slum dwelling in the town of economics. Mostly it is ignored: The best technology is assumed to be known; the relationship of commodities to consumer preferences is a datum. And one of the information-producing industries, advertising, is treated with a hostility that economists normally reserve for tariffs and monopolists" (page 213).

Both Hayek and Stigler emphasized that the link between consumer goods and consumer preferences cannot be treated as "a datum." Five years later, Lancaster (1966a) went further in his "New Approach to Consumer Theory," in which utility depends on the characteristics of goods consumed and not the goods themselves, and which introduced his concept of a consumption technology. He also proposed in a companion paper (1966b) that this technology could change over time.

The goal of this paper is to incorporate these ideas into conventional growth accounting analysis in order to expand the discourse on how innovation can affect consumer welfare. The impact of innovation on consumer welfare has received a lot of attention since the 1960s but has largely not found its way into conventional growth accounting, which has followed the neoclassical model developed by Robert Solow (1957), with a path-breaking extension by Jorgenson and Griliches (1967).[5] This model intentionally abstracts from many thorny real-world problems, like imperfect information and uncertainty, that make theoretical and empirical work difficult. The largest leap of faith, however, is the assumption that the myriad goods and services produced in a economy can be characterized by a single, stable, index of aggregate output and that this output is produced by aggregate indexes of labor and capital. Indeed, Solow, in the first sentence of his 1957 article, acknowledges that "… it takes something more than a 'willing

[5] An overview of the development of the Solow growth accounting model and the extensions that followed is given in Hulten (2001). The model is largely nonstochastic, but some randomness does creep into the model through fluctuations in demand, adjustment costs, and the discount and revaluation rates in the cost of capital variable. Information, in the form of R&D inputs, found its way into growth analysis in the 1960s.

suspension of disbelief' to talk seriously of the aggregate production function." Thirty years later, in his Nobel lecture, he added, "I would be happy if you were to accept that [growth accounting results] point to a qualitative truth and give perhaps some guide to orders of magnitude" (Solow, 1988). Samuelson (1962) called this aggregative approach a parable with a useful heuristic value.

The usefulness of this model in providing insights into the process of economic growth has been widely accepted. It has become an official program at the Bureau of Labor Statistics (BLS) and the mainstay of the current debate about the causes of slower growth. The question raised in this paper is whether the conventional framework, by itself, continues to provide a useful guide for understanding the digital economy. We suggest that this may no longer be the case in its current form and that it should be extended to allow for the possibility that freely available information can be used to improve the efficiency of consumer choice. Our approach is to merge Lancaster's idea of a consumption technology into the Solow supply-side model, with its emphasis on the production technology.

III. The Lancaster Model and Its Application

The essential feature of the Lancaster model is the specification of a utility function whose arguments are the "characteristics" of items that provide utility rather than the goods and services that enter the conventional utility function. Lancaster uses the example of a meal, which is more than just the items of food consumed, but a complex interaction of various factors.[6] In its fullest form, the conceptual model is quite complex. The model he actually works with is a simplified form, in which he assumes that characteristics, C_t, are functionally connected to outputs, Q_t. In this case, $C_t = BQ_t$, where B is a set of parameters that define the consumer's "technology" for transforming a collection of goods into the bundle of characteristics that provide utility. The associated utility function is then $U(C_t) = U(BQ_t)$. In the conventional formulation of utility theory, goods and commodities are identical and $B = 1$. In a more general form, one that will be

[6] "A meal (treated as a single good) possesses nutritional characteristics but it also possesses aesthetic characteristics, and different meals will possess these characteristics in different relative proportions. Furthermore, a dinner party, a combination of two goods, a meal and a social setting, may possess nutritional, aesthetic, and perhaps intellectual characteristics different from the combination obtainable from a meal and a social gathering consumed separately" (Lancaster (1966a), page 133). Subjective factors like ambience, mood, and novelty matter.

used in this paper, the consumption technology is $C_t = g(Q_t)$. It indicates that different levels of utility can be obtained from a given Q_t, depending on the efficiency with which the transformation occurs.

The consumption technology is central to the concerns of this paper (the characteristics approach less so). The availability of reliable information is clearly an important determinant of effective decision-making, and once this is accepted, it is but a straightforward extension to accept the possibility that increases in information could lead to increases in utility $U(g(Q_t))$ holding Q_t constant. If technical innovation can shift the structure of production toward greater productivity, why cannot it also shift the productivity of consumers in converting expenditure to well-being using the information disseminated via the Internet? As Stigler points out, the utility function is a process in which choices are made, and not a given "datum."

IV. Generalized Growth Accounting

A. The Conventional Supply-Side Analysis

Innovation operates through many "micro" channels and affects consumption technology in many complex ways, but the same can be said of the conventional Solow-Jorgenson-Griliches-BLS growth accounting model on the production side. Indeed, technical change in the aggregate production function is necessarily macroeconomic in its nature and is thus something of a black box that sweeps together microeconomic changes in technology along with much else. Since this paper extends this model to allow for a consumption technology in a way consistent with its assumptions, we treat this technology as a black box as well.

The standard version of the aggregate growth accounting parable starts with the aggregate production function. In this paper, we further assume this function has the Cobb-Douglas form with constant-returns-to-scale and Hicks-neutral technical change:

$$(1) \qquad Q_t = e^{\lambda t} (R_t)^{\alpha} (E_t)^{\delta} (S_t)^{\pi} (L_t)^{1-\alpha-\delta-\pi}.$$

This function relates the units of output produced (Q) to the inputs of intangible capital (the stock, R), tangible information and communication technology capital (ICT) equipment (the stock, E), and other non-ICT capital (the stock, S), as well as labor input (L). Output grows over time as the inputs increase or as technical change improves the productivity of outputs (here at the rate λ). The parameter α is the intangible capital's output elasticity, δ is ICT's elasticity, and

π is the non-ICT elasticity. Under the assumption of constant returns to scale, elasticities sum to one and (1-α-δ-π) is the residual labor elasticity. In this case, the production function (1) can be expressed in "intensive" form as

$$(1') \qquad Q_t/L_t = e^{\lambda t} (R_t/L_t)^{\alpha}(E_t/L_t)^{\delta}(S_t/L_t)^{\pi}.$$

The growth equation associated with *(1')* can then be expressed in terms of output per worker as:

$$(2) \qquad q - \ell \;\; = \lambda + \alpha\,(r\text{-}\ell) + \delta\,(e\text{-}\ell) + \pi\,(s\text{-}\ell).$$

Here, lowercase letters denote rates of growth. This formulation is based on the output elasticities (α, δ, and π) but could equally be formulated in terms of the corresponding shares in factor income (v_R, v_E, and v_S) under the assumption of competitive factor pricing. This is the way Solow proceeds in his derivation of the TFP residual. The factor shares can be computed from accounting data, and are the inputs and output, leaving the shift factor λ to be estimated as a residual.

The growth in output per worker is often used as an indicator of the growth in well-being enabled by the process of economic growth. Equation *(2)* indicates the growth in output per worker will increase when there is an increase in the productivity with which resources are used, λ, and when there is more capital per worker, in its various forms, weighted by their respective output elasticities (or income shares).

In this framework, technological innovation, in its broadest sense, involves the first three terms on the right-hand side of *(2)*: costless increases in productivity, λ, and the deepening of intangible capital stocks like R&D and coinvestments in ICT, $\alpha(r\text{-}\ell)$ and $\delta(e\text{-}\ell)$. The first is *resource-saving* innovation associated with the shift in the production function (λ); the second and third are *resource-using* innovation associated with the growth in intangible capital and ICT equipment. However, innovation also occurs in non-ICT capital via embodied technical change.[7]

[7] It might also be noted that costless increases in the quality of capital and intermediate goods that go unmeasured will appear as increases in λ.

B. Expanding the Conventional Framework to Include Utility

The taxonomy of innovation based on the decomposition shown in *(2)* follows the conventional practice of focusing on the sources of output growth originating on the supply side of the economy. This focus implicitly ignores the possibility that innovation can also occur in the consumption of goods, and specifically, that the consumption technology might also shift over time. It ignores, in effect, the "free, copious, and ubiquitous" information of Schmidt and Rosenberg's Internet Age. Our proposed remedy has two components. First, we assume that conventional growth accounting should, indeed, be extended to include the utility function even if the consumption technology were ignored, and second, that the utility function should include this technology.

The first step follows a well-traveled path, one forged by dynamic optimization theory, in which a standard intertemporal utility function is maximized subject to technology and labor, which grow at given rates, and an initial endowment of capital (which is thereafter an endogenous decision variable). The growth equation *(2)* can be regarded as a structural equation tracking the year-to-year movements along the optimal growth path of the economy, but the path described by *(2)* need not, in fact, be dynamically optimal. What is required is that factor inputs are paid the value of their marginal products and that the marginal rates of transformation on the supply side of the economy are equal to the marginal rates of substitution on the demand side in each year.

Our paper is by no means the first to link welfare change to the growth rate of real output and the sources of its growth. For example, Hulten (1979) uses the standard intertemporal utility maximization framework to develop a "dynamic residual," which is the weighted sum of the annual Solow TFP residuals. When labor and technical change grow at constant rates, steady-state consumption per worker grows at the Harrodian rate of technical change, which is also equal to the dynamic residual. Capital is absent, here, because it is endogenous. An important implication is that it is the Harrodian rate, the TFP rate divided by labor's share of income, that drives *long-term* welfare and output growth and not TFP itself (see also Hulten and Schreyer (2010)). This result is, however, consistent with the Basu and Fernald (2002) and Basu et al. (2016) result that the *annualized* growth of welfare per capita is proportional to TFP *and* capital stock growth. Since our paper expands the Solow model to include utility, it too follows the annualized approach (indeed, makes many of the assumptions of Basu et al. (2016), although there are also differences). Our main contribution relative to the past literature is to expand this line of analysis to include both a consumption technology and output-saving technical change.

Once the desirability of expanding the growth accounting model in this way is accepted, there is then the question of how an increase in Q affects $U(Q)$. One of the first issues that needs to be settled is whether $U(Q)$ should be regarded as an ordinal or cardinal function. The ordinal approach is usually adopted in price and allocation theory, while discussions of social welfare and income redistribution theory implicitly assume some degree of cardinality. In the latter, it is generally assumed that interpersonal and intertemporal comparisons of utility are meaningful and that marginal utility is an increment to actual well-being. The further assumption of diminishing marginal utility of income supports the case for progressive income taxation and income redistribution, as well as being associated with risk aversion. However, in the growth context, a declining marginal rate implies that a steady rate of real GDP growth brings progressively less well-being. Conventional growth theory thus implicitly assumes that this marginal utility is unitary, implying that the growth rate of well-being is identical to the growth rate in real GDP.[8] This in turn implies that the latter is a valid proxy for the former. Again, since the framework of this paper builds on the nonparametric Solow growth accounting model that implicitly assumes marginal utility is unitary, we, too, will make this assumption (and also avoid the need to formally parameterize the model).

Yet another question arises about the aggregation of utility. Does $U(Q)$ represent the total utility experienced by the population of size N from the consumption of Q units of output (the sum of individual utilities, somehow aggregated), or is it the utility of the representative consumer who receives Q/N units of output? Since the focus of this paper is on the welfare benefits of output growth and not how the benefits of growth are distributed across a population, we opt for the representative agent approach.

[8] As a concrete illustration of these issues, consider the Maddison (2007) estimate that U.S. real GDP per capita income increased around 20-fold between 1820 and the end of the 20th century. If each increment to income implies progressively less utility, this increase in income does not imply a 20-fold improvement in average living standards or personal well-being, whereas a constant marginal utility of income implies exactly this. Moreover, ordinal utility cannot speak to this issue, since it only implies that the standard of living in 2000 is preferred to 1820. It is hard to think about, much less estimate, the full benefits of economic growth and technological innovation if that were all that could be said.

Finally, it should be understood that the introduction of a utility function into growth analysis (particularly one that includes a consumption technology) moves growth accounting from an exercise based on a metric that is objective and in principle measurable (units of output largely transacted in markets) to one that is subjective and for which no directly measurable yardstick is available (utility). The lack of an operational yardstick is one reason that the utility side, which is part of the general equilibrium structure of an economy, is largely absent from traditional growth accounting. However, the fact that utility is subjective and impalpable does not mean that it can be ignored in an analysis of how innovation affects well-being, particularly when there is reason to believe that this is how many of the benefits of the digital revolution are realized.[9]

C. Expanding the Conventional Framework to Include Consumption Technology

The approach to the utility function model we adopt in this paper is shown in equation *(3)*. The utility of the representative agent is assumed to be a function of the consumption of that agent, C_t/N_t, where consumption C_t is the fraction $(1\text{-}\sigma_t)$ of output Q_t not saved, or $C_t = (1\text{-}\sigma_t)Q_t$. We also assume that the labor force L_t is connected to the population N_t by the labor force participation rate, ρ_t , so that $L_t{=}\rho_t N_t$. The utility of the representative agent then has the form

$$(3)\qquad U(C_t/N_t) \;=\; m\,(C_t/N_t) = m[\rho_t\,(1\text{-}\sigma_t)(Q_t\,/L_t)].$$

We assume, for simplicity, that σ is constant and the same for all agents, allowing us to avoid the problem of modeling the utility of future consumption by making saving a fixed proportion of output. We also assume that ρ is constant, implying that a consumer's endowment of time is allocated in a fixed proportion between work and leisure and that the labor force participation rate is also constant.

[9] Introducing a utility-welfare interpretation on growth accounting results is sometimes challenged on the grounds that GDP is a measure of resource use, not a measure of welfare. This is certainly true; *Q* is not *U(Q)*. Indeed, that is precisely the point of this study: There may be welfare effects of innovation that are not reflected in GDP. Both need to be included in a full assessment of innovation, and the welfare effects should be treated separately and not be shoehorned into an expanded measure of GDP.

Solow's "suspension of disbelief" comment must be extended to the formulation in *(3)* as well as to *(1)* and *(2)*. The utility function in *(3)* is a highly reductive parable of the factors that lead to human well-being. In this regard, the *World Happiness Report, 2013,* reports that six variables explain three-quarters of the international differences in average "life evaluations," to which GDP per capita contributes only about one-fifth of the total.[10]

Introducing a consumption technology into *(3)* adds a further degree of complexity to the link between GDP and utility, particularly when this technology is allowed to shift. This shift can be modeled in different ways, but for the purposes of this paper, we will again adopt a minimalist specification that preserves symmetry with the growth accounting model of equations *(1)* and *(2)*. This specification is basically the conceptual analogue of Hicks-neutral productivity change on the production side of the model in which the information available to the consumer increases at the rate θ and the information effect, $e^{\theta t}$, is multiplicative:

$$(4) \qquad U(C_t/N_t) = m\, e^{\theta t}\, [\rho_t\, (1-\sigma_t)(Q_t/L_t)].$$

The utility function in *(4)* is a straightforward extension of *(3)* that allows for a shift in the Lancaster consumption technology and permits the utility index to grow more rapidly over time when holding output constant (in a subsequent section, we will also allow for a shift in the consumption technology due to costless improvements in product quality).

When the utility function *(4)* is expressed in growth rate form, the result is an expanded growth accounting equation that combines the Solow growth accounting equation *(2)* with the consumer parameter θ. The expanded sources-of-growth account has the form:

$$(5) \qquad u = \theta + (q-\ell) = \theta + \lambda + \alpha\,(r-\ell) + \delta\,(e-\ell) + \pi\,(s-\ell).$$

The first equality in *(5)* indicates that the growth rate of utility is driven by the shift in the consumption technology and the growth rate of output per worker. It thus expands the discourse on the benefits of growth and innovation beyond the conventional output effect to include the

10 Other factors included years of healthy life expectancy, having someone to count on in times of trouble, perceptions of corruption, prevalence of generosity, and "freedom to make life choices" (Chapter 2 of the report by Helliwell and Wang). How these are linked to economic growth and the structural changes they bring is a question that goes far beyond economic theory, but major technological innovation is surely an important contributor. See also Stevenson and Wolfers (2013) for the link between income and happiness.

non-GDP benefits of the information revolution. A further implication is that real GDP growth alone is not a sufficient statistic for assessing the impact of technological revolutions on the standard of living, nor does a slowdown in the growth of real GDP necessarily imply that the growth of living standards has slowed.

We note, finally, that innovation in *(3)* and *(4)* is treated in essentially the same analytical way it is in the production side equations *(1)* and *(2)*, although different underlying mechanisms are at work. In both cases, the innovation is simply a time shift, either in the production function, $F(X,t)$, where X represents the vector of inputs, or in the utility function $U(Q,t)$. An alternative formulation would be to replace the time variable t with a variable Z that quantifies the factors involved in innovation; in other words, $F(X,Z_q)$ and $U(Q,Z_u)$. This approach requires a theory of innovation, in which components of Z variables are specified and their relation to the other variables made explicit. The commoditization approach adds more structure to the analysis, but it also introduces a host of measure problems. The Z innovation variables are often vaguely formulated, without secure units of quantity or the corresponding prices.

These problems are avoided when the $F(X,t)$ and $U(Q,t)$ "time residual" approach of this paper is used. The time residual sweeps together all the various sources of innovation without the need for full enumeration and specification. This is a both a virtue and a vice, since the residual includes other non Z variables that go unmeasured, as well as pure measurement errors. Abramovitz (1956) famously called the residual a measure of our ignorance.

However, it produces an actual measure. The Z commoditization approach requires prices, P^Z, to implement. However, when Z goods like the Internet and its applications are distributed without a charge, P^Z is zero, creating the very problems that our expanded framework seeks to address. As we will show in the next section, the value of innovation can be estimated using only the observable commodity prices P^X and P^Y.

D. The Price Dual

The Solow residual approach works empirically because both the left-hand side variable of the production function, output, and the right-hand side factor input variables are observable. The technology parameters can then be estimated nonparametrically via the Solow residual or parametrically using econometric methods. This is not the case with the expanded growth accounting model *(5)*, since the left-hand side variable is consumer utility. Because the utility variable is subjective and not directly observable, it is useful to recast the analysis in one that is: the consumer expenditure.

Under certain restrictive conditions, the utility formulation can be represented by its price dual, the expenditure function, which is the minimum expenditure associated with a given level of utility U^* and output price level P. When a consumption technology is added to the analysis, as in *(4)*, the generic expenditure function has the form

$$(6) \qquad e(P,U^*) = e^{-\theta t}\, \xi(P\,,U^*).$$

This is the minimum expenditure needed to maintain utility at the level U^* given P and the level of consumer information. The growth rate of expenditures over time depends on the expenditure-share weighted growth rates of the prices, the negative growth rate of the information parameter θ, and the rate of change of U^*. This analysis can also be framed using the indirect utility function associated with the expenditure function.

The factor price frontier associated with a generic constant-return Hicks-neutral production function $Q = e^{\lambda t} f(L,K)$ has the form $P = e^{-\lambda t}\, \phi(P_L, P_K)$. Substitution into *(6)* gives

$$(7) \qquad e(P\,,U^*) = e^{-\theta t}\;\xi(e^{-\lambda t}\, \phi(P_L, P_K),U^*).$$

The minimum expenditure needed to support U^* falls with an increase in information, when goods are produced more efficiently and their price falls. In its growth rate form, equation *(7)* is the dual counterpart of the primal form *(4)*.

The expenditure function offers a natural way to think about the consequences of innovation, since it defines the compensating variation (V^C) and the equivalent variation (V^E) of duality theory. When a change in the price of a good causes the level of utility to rise or fall, the compensating variation is the amount of expenditure needed to regain the old utility level at the new prices (P^*). Expressed in terms of the expenditure function, the compensating variation can be written:

$$(8) \qquad V^C \;=\; e(P^*,U_1) - e(P^*,U_0).$$

Since utility in the new period is increased by $e^{\theta t}$, U_1 is defined as $e^{-\theta t}$ U_0. This formulation thus provides a willingness-to-pay metric for the change in utility resulting from change in θ, and, in principle, provides a method for estimating the size of this parameter. The equivalent variation, V^E, has a parallel formulation in terms of the original prices.

What is the relevance of this analysis for the issues at hand? The parameter θ is a proxy for the "free, copious, and ubiquitous" information available to the consumer as a result of the digital revolution. The compensating and equivalent variation approach provides a way of estimating the value of this information, which is otherwise missing from GDP. It is worth noting that this estimation relies on the commodity price, P, and not the price of the information whose value is estimated by V.

V. Expanded GDP and Welfare Measures in a Model with Multiple Outputs

A. An Illustrative Two-Product Model

The simple model of the preceding sections is formulated with a single good. This simplicity is adequate for demonstrating how, in principle, consumer well-being may increase more rapidly than GDP. However, it is also true that Lancaster's original conception of the consumer technology involves multiple goods and the idea that utility is derived as much from the way goods are combined as from the goods *per se* (the meal versus its separate components). In this section, we extend our model to the case of two goods in order to draw out the intuition behind output-saving innovation and its link to a generalized concept of GDP. The two-good case permits the use of graphical analysis and conveys the same result as the more general case of N goods.

The two-good case introduces a new degree of complexity into the analysis. Instead of representing the aggregate economy with the single-good production function *(1)*, there are now separate production functions for each good and a multiproduct production possibility frontier (PPF), indicating the maximal combinations of the goods that can be produced with these functions by a given amount of total labor, capital, and the technologies for producing the two goods. The dynamics are also more complex: Technological innovation in the production of individual goods (λ_1 and λ_2) may change the composition of output as well as changing its overall quantity. The latter is the shared-weights sum of λ_1 and λ_2 (Hulten (1978)).

The geometry of the two-good case is shown in Figure 1 for goods X and Y, along with the production possibility frontier, *PPF*, and the utility function of the representative consumer,

U (we also switch to a discrete-time analysis to accommodate the use of graphs). The equilibrium between utility and production (supply and demand) is initially at the tangency point A in Figure 1, where the ratio of marginal costs equals the ratio of marginal utilities. The relative prices are defined by the slope of the tangent line at A, which also defines the initial level of GDP, $P^X{}_0X_0 + P^Y{}_0Y_0$.

The PPF shifts outward from the origin as the inputs of labor and capital increase and as improvements in technology increase the productivity of these inputs (the λ-effect). Since the focus of this paper is on innovation, we concentrate on the λ-effect by holding capital and labor constant in this figure. This effect is shown in the figure as a shift from PPF_0 to PPF_1 for the case of price-neutral shift in the technologies of the two sectors. The output bundle shifts from (X_0,Y_0) at the point A to (X_1,Y_1) at the point B on the line *bb*, and real GDP increases from $GDP_0 = P^X{}_0X_0+P^Y{}_0Y_0$ to $GDP_1 = P^X{}_0X_1+P^Y{}_0Y_1$. Given that the industry rates of productivity change, $\lambda_i = \lambda$, are the same in the production of both goods, (X_1,Y_1) equals $((1+\lambda)X_0, (1+\lambda)Y_0)$. The level of utility increases from U_0 to U_1.

Where Figure 1 illustrates the supply-side λ-effect, Figure 2 shows the consumer-side θ-effects of output-saving innovation. A neutral change in information increases the amount of utility attainable from a given bundle of X and Y, and it appears as an *inward* shift in the utility function in Figure 2.[11] The old U_0 shifts inward to a point C in the figure, interior to the PPF, at which the bundle (X'_1,Y'_1) yields the same utility as the (X_0,Y_0) bundle before the shift. However, the expenditure needed to attain U_0 falls to $P^X{}_0X'_1+P^Y{}_0Y'_1$, as represented by the line *cc* in the figure. Since the indifference curve U_1 is now tangent to the *PPF* at A, *the same amount of GDP*, $P^X{}_0X_0+P^Y{}_0Y_0$, supports a higher level of well-being. This is the essence of output-saving technical change: innovation that results in a higher level of utility obtainable from the same amount of income.

B. Output-Saving Innovation, the Compensating Variation, and Expanded GDP

The value of a higher level of utility in monetary terms is one of the central interests of this study, and, in fact, of much of the empirical literature on recent trends in innovation. A common

[11] The two-good utility function shown in the figures is defined in a three-dimensional space, and the individual indifference curves shown in the figures are projections of the three-dimensional function onto the two-dimensional product space, XY. An upward shift in the former thus leads to an inward shift in the latter.

solution is to employ the compensating variation, *V*, of equation *(8)* for this purpose. In the context of this paper, the compensating variation can then be used as a dollar metric of output-saving innovation. The requisite *V* is implicit in the price lines *cc* and *aa* in Figure 2, which define a monetary metric of the distance between the indifference curves U_0 and U_1.

The main question of this paper is whether conventionally measured GDP provides an adequate account of the benefits of the technological revolution currently under way. To get at this question, Figure 3 expresses the monetary metric *V* in a way that clarifies its relation to GDP. In this figure, an upward translation of the indifference curves now places U_0 tangent to the invariant equilibrium point *A*, i.e., (X_0,Y_0). U_1 in now associated with a different point in Figure 3 than it was in Figure 2. This upward translation of the utility function also translates the units of measurement. These must now be in utility-effectiveness units X^e and Y^e. Since $X_0 = X_1$ and $Y_0 = Y_1$ at *A*, one solution is to express the values at *B* in Figure 3 in utility-loading units, $X^e_1 = eX_0$ and $Y^e_1 = eY_0$. These utility-loaded values are located on the utility-possibility frontier UFP^e shown in that figure. The compensating variation, *V*, is now repositioned relative to GDP, but while its position has changed, its magnitude remains the same.

The geometry of Figure 3 can be used to relate *V* directly to the rate of output-saving technical change, θ. Given the outward $(1+\theta)$ shi`ft in U_1, the point (X^e_1,Y^e_1) is equivalent to $((1+\theta)X_0, (1+\theta)Y_0)$. In view of *(8)*,

$$(9) \quad V = (P^X_0 X^e_1+P^Y_0 Y^e_1) - (P^X_0X_0 +P^Y_0Y_0) = \theta\, (P^X_0X_0 +P^Y_0Y_0)= \theta\, \mathrm{GDP}_0. \, .$$

This implies that the discrete-time rate of change of *V* equals the unobserved θ divided by the level of initial GDP_0. In other words, the *V* in *(9)* captures the monetary effect of a θ-shift in the utility function. This shift plays the same role in the consumption technology that the λ-shift does in the production technology seen in Figure 1, with the difference that the value of the λ-shift is measured by the change in real GDP as per the Solow residual (indeed, where the magnitude of the Solow residual is a measure of the value of the λ shift). The *V* in Figure 3, on the other hand, is measured outside of the GDP framework using a willingness-to-pay (WTP) metric, and the *V* operationally defines the location of the new level of utility U_1 (though, conceptually, it is equally the other way around).[12]

The estimation of the compensating variation V (in one form or another) is the subject of many empirical studies (some of which are reviewed in a subsequent section). The contribution of the framework of equation *(9)* is to show how the results could be used to identify the unobserved output-saving technical change parameter θ and the associated the change in utility.

What do these results mean for the measurement of GDP? A further extension links the monetary metric V to an alternative measure of GDP that includes the value of output-saving technical change. It is evident in Figure 3 that the higher utility, U_1, is supported by a notional expenditure line *aa* at the point *A*. This line indicates the amount of aggregate value associated with *A*, which is the sum of the value of goods produced, GDP, and the willingness to pay for the information that makes consumption of those goods more efficient. We term this notional amount EGDP and observe that

$$(10) \quad EGDP = P^X_0 X^*_1 + P^Y_0 Y^*_1. = V + P^X_0 X_0 + P^Y_0 Y_0 = V + GDP_0 = (1+\theta)\, GDP_0.$$

EGDP is a welfare-based index that indicates how much the consumer would have had in the previous period to spend in order to attain the utility level, U_1, made possible by costless innovation. It thus provides (in principle) a monetary metric for assessing the consequences of innovation on economic prosperity, beyond the contribution of GDP.[13]

EGDP in *(10)* is based on Figure 3, which treats GDP as a constant, but this need not be the case. A more general formulation combines all the factors that cause GDP to grow: a shift in the PPF due both to the productivity change λ (as in Figure 1) and growth in the inputs of labor and capital, as well as the output-saving innovation of Figure 3.

[12] To elaborate, both the λ process and the θ process represent costless increases in the stock of knowledge, the former relevant to production and the latter to consumption. Costless increments to the stocks give rise to an implicit willingness to pay. The Solow residual establishes the value of the former, whereas external valuation is needed for the latter. By extension, there is an implicit willingness to pay for the respective λ and θ stocks. Discovering the WTP values of the implicit stock is by no means an easy task, since it involves the unknown rate of depreciation of knowledge in the respective stocks. This exercise would be of value in establishing the size of the total stocks of capital, which form part of the true wealth of a nation.

[13] Again, it is useful to interpret V as an implicit investment that increases utility.

$$(10') \quad EGDP = V + GDP_1 = (1+\theta)\, GDP_1 = (1+\theta)\, [GDP_0 + \Delta GDP_0],$$

where the change in real GDP is

$$(11) \quad \Delta GDP_0 = P^X_0\, (X^e_1 - X_0) + P^Y_0 (Y^e_1 - Y_0) Y^e_1.$$

The changes in Y and X at the industry level can be further broken down into their Solow growth accounting components.

The overall result is that EGDP can be used as a monetary metric to summarize the combined effects of the factors influencing output growth and welfare. Other factors that affect GDP and EGDP will be introduced in subsequence sections. Another implication is that EGDP can grow more rapidly than GDP during surges in innovation, implying consumer welfare may grow faster than output measured at resource cost.

C. Consumer Surplus and the Problem of Empirics

Since neither utility nor expenditure in *(10')* are directly observable, ways must be found to estimate V from non-GDP sources. The most promising current candidate is the willingness-to-pay approach used in a variety of contexts, like cost-benefit studies of government regulations, environmental damage, infrastructure projects, and, increasingly, the study of "free" technology goods like Internet applications. Different approaches have been used in the literature to get at benefits of these technology goods, including consumer surplus, valuation of time, and estimation of systems of demand equations.[14] All involve restrictive special assumptions, both in their application and aggregation into a total across goods.

The consumer surplus method is an important case in point. The consumer surplus is the area under the demand function for a given good and above its supply function, and it can be measured by estimating these functions. However, this estimation is subject to the vagaries of model specification and other econometric issues, and it is cumbersome when applied to the estimate of a time series of the V required for an implementation of EGDP in *(10')*. Moreover, consumer surplus is a partial equilibrium technique, and using it to estimate individual V_i leads to

[14] A partial list of recent studies includes Goolsbee and Klenow (2006), Varian (2009, 2016), Greenstein and McDevitt (2011), Brynjolfsson and Oh (2012), Chen et al. (2014), Nevo (2016), Brynjolfsson et al. (2017), and Cavallo (2017). This list does not include references to the large literature on health care. For an expenditure function approach, see Redding and Weinstein (2017).

a problem of aggregating the result to get at a total *V*. Varian (1992) shows that exact aggregation is only possible under strong restrictions on the utility function. Finally, the demand framework of consumer surplus presupposes the existence of an underlying price and quantity for what is essentially a commoditized *Z*-good discussed earlier.

The use of econometric methods applied to the expenditure functions and system of demand equations is also subject to econometric issues. Redding and Weinstein use the latter, but this approach assumes that time-varying demand shifts cancel, on average. This assumption identifies many important parameters but may be problematic when applied to capturing the benefits of a general shift in the expenditure function due to improvement in consumer information.

A problem also arises when relative prices change over time. This leads to the problem of which prices to use: before or after those changes, or a combination of the two (in continuous time models, the problem is one of "path dependence" (Hulten (1973)). This is the well-known problem of the compensating versus the equivalent variation. It is, on the other hand, attenuated by the fact that the two variations bracket consumer surplus for a wide variety of utility specifications. Moreover, these estimation problems are certainly not unique to EGDP. The GDP accounts have been around for many decades, and, despite a great deal of progress in improving the statistical system, they remain a work in progress.

VI. Accounting for Costless Improvements in Product Quality

A. Product Quality Change and EGDP

Much of the innovation occurring during the recent revolution in technology has come in the form of new or improved products. Part of this innovation is the result of resource-costly expenditures on R&D and marketing, but another part has accrued to consumers at little or no cost (successive models of computers and cell phones, Internet applications, and in the area of health, vaccines). We will explore the costly dimension of innovation in a subsequent section and focus now on the costless aspects and their relation to EGDP. This is motivated by the fact that costless improvements in product quality improve the efficiency of consumption expenditures as better products become available that satisfy the same wants but cost less. The consumer can thus obtain more utility from a given level of expenditure, as with a costless increase in information, increasing EGDP for a given level of GDP.

In keeping with the treatment of θ in the preceding analysis, we assume that the costless component of product quality grows at a constant rate β and that it augments the utility function in *(4)* in the same manner as the information parameter θ. The expanded utility function then has the form

$$(4') \qquad U(C_t/N_t) = m\, e^{\beta t}\, e^{\theta t}\, [\rho_t\, (1\text{-}\sigma_t)(Q_t/L_t)].$$

The corresponding growth rate of utility function in *(5)* is

$$(5') \qquad u = \beta + \theta + (q\text{-}\ell).$$

Output-saving technical change is now the sum of β and θ, and while they represent different processes, both shift the consumption technology in Figure 3, and the combined (β+θ) affects EGDP in the same way the θ did in the preceding sections.

Although both result in output-saving technical change, β and θ differ in the empirics needed to establish their respective magnitudes. A key difference lies in the fact that product quality is embodied in the goods consumed, whereas consumer information is more about how they are chosen and used. From a measurement perspective, product embodiment has the advantage of producing data that can be used to estimate β. Indeed, the estimation of this parameter is a well-traveled path. The basic idea is that one model of a particular good Q may be better in the eyes of the consumer than the previous model because it has more of a desirable characteristic and thus conveys more utility. The consumer is thus willing to pay a price premium for the superior version, one which is based on the difference in marginal utilities, and the measurement of this price premium provides a way to estimate the extent of the quality differential. To make this explicit, we use the notation Q^e_t to represent the effective (characteristic-based) units of output as experienced by the consumer and continue to denote the units of resource-based output produced by Q_t (this follows the distinction made by Triplett

(1983)). The wedge between the two, if any, can then be used to define the rate of product quality change β as $Q^e_t = e^{\beta t} Q_t$.[15]

The measurement procedures used to estimate are based on the price analogue of this equation. The consumer expenditure for Q_t is equal price times quantity, P_tQ_t, and this must also equal the total amount spent on output measured in efficiency units, $P^e_t Q^e_t$. It thus follows that $P^e_t = e^{-\beta t}P_t$. Only the P_t is observed, but several methods are available to estimate P^e_t and β. First, the hedonic price method regresses the observed transaction price of a sample of goods on a set of observed characteristics to estimate the shadow price of each characteristic. The price of a bundle with more, or a different mix, of characteristics can then be estimated and, by extension, the efficiency price of a bundle with more characteristics. This method is typically used in cases where there are increases the existing (observable) characteristics of a good over time, like computers, or for products in which heterogeneous characteristics are packaged into one price, like houses. [16]

In cases where an older version of a durable good persists in the market after the arrival of a superior model, an overlap method can also be used. When quality change is costless and a new model of a good appears in the marketplace, the real resource cost of the superior model when it arrives, time t, is the same as the real cost of the inferior model one year earlier, when it was new. If the inferior model is to remain the marketplace in time t, it must sell at a discounted price that is competitive with the efficiency price of superior variety, i.e., P^e_t, that the consumer could purchase as an alternative to the older model. In this the case, observing this discounted price of the older surviving model, along with the resource price P_t, identifies β, in view of the relation $P^e_t = e^{-\beta t}P_t$. In practice, these methods are supplemented by the BLS with other techniques, including the matched-model and imputation methods (Groshen et al. (2017)).[17]

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[15] Computers are a good, if somewhat extreme, example of the difference between Q_t and Q^e_t. Moore's Law has resulted in a dramatic increase over time in the efficiency of computing, as new models of computers have embodied more a faster processor speed, better graphics, and more memory. The resource-based quantity Q_t has not increased at anywhere near the same rate.

[16] Since the objective this paper is to introduce consumer utility considerations into the conventional growth framework and examine its implications, we do not go into the many important issues raised by the characteristics approach for price indexes or for consumer demand and expenditure (e.g., Deaton and Muellbauer, 1980).

[17] When goods drop out of the CPI sample entirely, as for example, when they are discontinued by a store or by the producer, or are rotated out of the CPI sample, procedures are used to value the newly arrived goods. These changes

B. Conflicting Approaches to Accounting for Product Quality

The decomposition of the expanded sources-of-growth model of this paper draws a boundary between resource cost and noncost improvements in welfare. In equations *(4)* and *(4')*, costless quality change is assigned to the consumption technology side of this boundary, whereas GDP *measured at resource cost* is located on the other side. However, this is not the way it is treated in the conventional GDP accounting theory, where the preferred concept of GDP is based on units of *effective* output, Q^e_t, rather than resource cost units of Q_t. The latter reflect the units produced by the production function, whereas units of effective output are defined with respect to the benefits received by the user without cost and thus do *not* reflect the units actually transacted in the marketplace.

The efficiency-output paradigm envisions a production function that treats β as a shift parameter of the production technology, rather than a shift parameter of the consumption technology, and "output" as $Q^e_t=(1+\beta)^t Q_t$ (the discrete time counterpart of $Q^e_t=e^{\beta t}Q_t$). What this means for the conventional approach of Figure 1 is shown in Figure 4, which now portrays the commodity space in both the units of the goods produced and the efficiency units, which are assumed to grow at the rate β for both goods. The economy is initially at the point *A*, at which both efficiency and production units are the same, i.e., $(X^e_0,Y^e_0) = (X_0,Y_0)$. After the costless change in product quality, (X_0,Y_0) units of the goods are still produced, but they are now the equivalent of $((1+\beta)X_0,(1+\beta)Y_0)$, denoted by (bX_0,bY_0) in Figure 4. If there is no change on the supply-side production of output in *resource units* when the economy moves from *A* to *B*, the point (X_0,Y_0) remains unchanged at the point *A*, as does the PPF_0 and the ratio of the marginal production costs. Given the assumption of proportional shifts in the indifference curves, relative prices are thus unchanged. However, the locus of attainable product combinations measured in *efficiency units* shifts to PPF^e, and *B* is the new effective-output bundle and U_1 is the new and higher level of utility,.

The result is that, while *nominal* GDP is unchanged in Figure 4, "real" GDP has risen by the factor $b =(1+\beta)$, while the corresponding efficiency prices have fallen by this factor.

can result in various biases (as noted in the subsequent section of new and free goods). These procedures can also simply result in reversing price discounts because of obsolescence.

However, it is important to note that “real” GDP rises because the components $P^X{}_0X_0$ and $P^Y{}_0Y_0$ are now deflated by the efficiency-corrected price indexes P^X/P^{Xe} and P^Y/P^{Ye}. In view the preceding analysis, these price deflators, P^{Xe} and P^{Ye}, are determined by the ratio of the marginal utility of new and old versions of a product. *In other words, what appears as “real” GDP in Figure 4 is actually determined on the utility side of model.* It is thus no accident that the structure of Figure 3 is virtually identical to that of Figure 4. Both *e* and *b* are utility-loaded transformarion of X_0 andY_0, with *e* equal to *b*,. The PPF_e of Figure 4 is thus equivalent to the UPF^e of the Figure 3.

The difference between Figures 3 and 4 is thus essentially a matter of convention in the way economic accounts are organized, a distinction without a difference since both reflect changes in utility rather than resource cost. We argue in this paper that this fact be made explicit and not buried in the synthetic concept of efficiency output. This argument for locating β on the consumption side of the accounts is buttressed by the inability of the current efficiency-output approach of Figure 4 to account for the information effect, θ, which refers to the more effective use of existing goods, not to an increase in the effectiveness embodied in the nature of the goods themselves. A further argument for situating β outside GDP is that, because of the difficulties in measuring quality, the cost-of-goods pricing method that is widely used for deflation does not actually capture changes in quality. This is particularly evident in expert services such as education and medicine, where the item priced may be a doctor’s appointment or a semester of schooling.

C. New Technology and Free Technology

The treatment of new goods that arrive in the marketplace is a question that looms large in discussions of the contribution of the digital economy to GDP and welfare. A new good is one with characteristics that have no near precedent in the choice space of the consumer, as opposed to a good whose quality has improved.[18] Given its prior absence, how should the introduction of this contribution be valued? How much does GDP change as a result of its arrival in the marketplace? Valuing a new good at its observed price when it appears may understate the true

[18] A conceptual problem arises with this definition because what is a “new” good at a low level of aggregation (Windows 7 versus 10) can also be thought of as a higher quality good at a more aggregated level (productivity software).

benefits it brings, since this entry price will reflect (in part) a cost of production that may be low compared with the value of the innovation. A new vaccine may, for example, cost little in the way of resources, but bring enormous benefits. The theoretical solution advanced by Hicks (1940) and Rothbarth (1941), and extended by Hausman (1996, 1999) is to estimate a "reservation" price of the new good, the price at which the quantity demanded of the good is zero (i.e., the price at which the demand curve intersects the price axis). The result is essentially a consumer surplus solution (Hausman, 2003), and can also be thought of in terms of the compensating variation (Romer, 1994). In terms of the aggregate price index needed to convert nominal GDP into real GDP, the reservation price serves as a quality correction, one that indicates a higher value to the consumer per units of resource cost. However, one problem with this solution is that it is based on estimation and requires assumptions.[19] Another is that it takes time and resources, and the BLS, which is largely responsible for the measurement of prices and quality change in the U.S., must produce these results on a monthly basis (Groshen et al. (2017)).

Another set of problems arises when applying techniques like consumer surplus, expenditure functions, demand estimation, price hedonics, or matched-price models: They presume the existence of an observable market price. This is not always the case with some of the most important digital economy goods. The Internet and its apps are not priced as individual goods with a price per unit consumed. Instead, a general Internet access fee may be charged by a service provider (although access may also be freely available in some cases). Internet applications are widely available without a direct use charge (again, with exceptions). Many applications are supported by the marketing revenues they are able to generate or are provided *pro bono publico* through such activities as crowdsourcing. The absence of observable unit prices, or an artificial zero price, has led researchers to use alternative measurement strategies, like the valuation of time and the use of indirect payments (for example, Nakamura et al. (2016)).

D. Contingent Goods

Griliches (1992) observes that "in many services sectors, it is not exactly clear what is being transacted, what is the output, and what services correspond to the payments made to their

[19] Yet a further issue is that digital platforms typically involve two-sided networks. As networks expand, they become more useful to users. This dynamic increase in utility is akin to the increase in utility due to the advance of knowledge that we highlight and is also output-saving.

providers" (page 7). There is a wedge between the output of a good and its outcome, arising from the contingent nature of many goods, and such a wedge is particularly prevalent in those involving these "expert" industries. A visit to the doctor is usually in response to some perceived health problem, but you do not buy an improvement in health *per se*; you buy advice and perhaps an intervention that may or may not cause an improvement. That outcome is contingent on the initial state of health, the doctor's input, and the actions taken by the patient in response. Other expert services in education, legal matters, and finance can be modeled using a similar framework, since they represent an attempted transition from one state of being to another, appropriately defined. In the case of education, schools may provide educational services, but learning also depends on student motivation, ability, and family inputs.

Contingent-state goods have a natural interpretation in the Lancaster framework. The output from the standpoint of the consumer is the improvement (objective and subjective) in the initial state of being (health, knowledge, financial, or legal status). Moreover, improvements in subjective outcomes may be contingent on the state of health or education and may have their greatest impacts when poor states are present. It is thus logical to locate the outcome in the consumption technology and assign the associated expert and ancillary services to the production side. This approach allows for the possibility that outcomes may be improved to a greater degree than suggested by the resource commitment implied by GDP and is one channel through which an increase in available information can shift the consumption technology.

VII. Technical Innovation with a Resource Cost

Our formulation of the expanded growth account *(5')* includes both costless and resource-costly innovation. Because of their different implications for welfare, as well as the growing importance of the latter, a deeper look is in order. Costless innovation arises from several sources. First, there are spillovers arising from the difficulty in protecting property rights for costly innovations where rights are hard to enforce because of the nonrival nature of the good and the free-rider problem. This often occurs with information goods like the Internet, as well as with the technology involved in product and process innovation. Second, there is what Eric von Hippel (2016) calls "free innovation." This includes contributions to the common good through crowdsourcing and *pro bono* innovations like open-source software. We might also include unanticipated learning by doing. Finally, there is just plain inspiration and creativity. Costless innovation appears in the expanded growth account *(5)* through the term λ in the production technology and the θ and β of the consumption technology.

Costly innovation, on the other hand, results from systematic investments in innovation. Firm-specific own-account investment in intangible capital like R&D and its coinvestments in organizational development and marketing have resulted in improvements in the processes of production, and product quality and new goods — in effect, endogenizing some part of the λ and β, which are "purchased" at the cost of the resources.[20] The kind of innovation, in effect, offers the consumer the opportunity to buy "better" goods at a higher price that reflects that cost. They are not a gift, "manna from heaven," as before. This implies that the transaction units of the improved good already embody the effects of the innovation, which, in turn, implies that the *produced* β belongs on the resource side of the expanded growth account in *(5)*, whereas the costless β belongs on the welfare side. Unfortunately, costly product quality change, β^*, is typically buried in prices of the transaction units and not recorded separately. It should, nevertheless, be treated conceptually as a separate effect and recorded on the resource side of the taxonomy.[21]

How does this innovation fit into the overall framework of production and growth? It is explicitly represented in the production function *(1)* by the stock on intangible capital R_t, and implicitly by the investment in intangible capital that is embedded as part of the output Q_t. It also appears as capital-embodied technical change in the ICT capital stock E_t, and its investment component of Q_t. In the growth rate formulation *(5)* and *(5')*, the contributions of intangible capital and ICT capital to the growth rate of the output per unit of labor $(q-\ell)$ are represented by $\alpha(r-\ell)$ and $\delta(e-\ell)$, the share-weighted growth rates of the respective capital/labor ratios. The rate

[20] Corrado, Hulten, and Sichel (2005, 2009). See also Nakamura (2001).

[21] We note, in passing, that the time-cost associated with consumption is also missing from this analysis. We have finessed the work-leisure decision by assuming that time is allocated in fixed proportions between work and leisure, but we recognize that a more sophisticated version of our analysis would recognize that the consumption technology requires a time input, just as time-use enters the production technology through labor input. The information revolution has reduced the time required for many activities and thus a saving in time cost. However, the advent of new or improved goods may also involve start-up costs and a learning curve, and the consumption of goods takes time (as in watching television or communicating via social media). An extension of our model, perhaps along the lines of Stigler and Becker (1977), would enrich our analysis but would not change our basic conclusion about the importance of the consumption technology for understanding the effects of the information revolution.

of costless process-oriented technical change λ (the shift in the production function) is proxied by the Solow residual estimate of TFP, adjusted for the presence of intangible capital.[22]

VIII. Some Empirics

A. The Supply Side

The relative importance of the $\alpha(r-\ell)$, $\delta(e-\ell)$, and TFP terms in equation (2) has been estimated by Corrado, Hulten, and Sichel (2009), involving an extension of the conventional Solow sources-of-growth model used by the BLS. The updated numbers from this study by Corrado and Hulten (2010, 2014) for the U.S. private business sector show a major shift in the relative importance of resource-costly innovation vis-à-vis TFP. TFP accounted for some 60 percent of the growth in $q-\ell$ in the 20 years from 1950 to 1972, the start of the energy crisis and productivity slowdown of the 1970s. The $\alpha(r-\ell)$ and $\delta(e-\ell)$ terms accounted for only 16 percent. The 22 years before the Great Recession saw a significant reversal in the importance of resource-costly innovation. During the period from 1985 to 2007, the last year before the onset of the Great Recession, these two sources of growth accounted for nearly 45 percent of $(q-\ell)$, while the contribution of TFP fell to just under 40 percent. From the start of the Great Recession to 2011, the growth rate of TFP collapsed, the magnitude of $\delta(e-\ell)$ term fell by half, but $\alpha(r-\ell)$ maintained the same growth rate it had during the 2000–2007 period.[23]

Two further points are worth noting. When combined, costless and resource-costly innovation account for the bulk of economic growth since 1950. When the terms $\alpha(r-\ell)$ and $\delta(e-\ell)$ are added to TFP, they account for three-quarters of the growth of $q-\ell$ over the period 1950–

[22] The introduction of intangible capital into the growth accounting model does come at a cost. The bulk of this type of capital is produced within firms on "own account" rather than acquired in the marketplace. It embodies much of the proprietary intellectual property of the firm, and it is nonrival and subject to expropriation. It must therefore be protected by patents, copyrights, or secrecy. Successful protection thus creates market power and monopolistic pricing, if for no other reason than the necessity of recovering fixed overhead R&D and other related costs. This resulting pricing strategy thus violates the perfect competition assumption that underlies conventional growth accounting. Additional questions are raised when the intellectual property protection is time limited and it eventually becomes freely available or when it is made obsolete by a superior rival innovation.

23 An even more significant reversal occurred in the composition of investment spending. The investment rate in intangible capital rose from 8 percent of U.S. private GDP in the late 1970s to 14 percent by 2010, and in investment in ICT equipment increased from 4 percent to 6 percent in 2007 after peaking at 6 percent around 2000. By contrast, the private investment rate in tangible capital fell over this period from 12 percent to 8 percent, and the non-ICT portion fell from 8 percent to 4 percent.

1972, and for 85 percent for the period 1985–2007. The acceleration is consistent with the onset of the current phase of the digital revolution starting in the 1980s. However, while the importance of this index of innovation has increased, its character has changed from the free "manna" of TFP growth toward the costly systematic investments needed to obtain it.

B. The Consumer Welfare Side

What is missing from the preceding analysis is the contribution of output-saving innovation. As we argued earlier, the growth rate q-ℓ is only part of the growth rate of welfare in equation *(5')*, which also includes the output-saving term $\beta+\theta$. Sections V and VI have discussed some of the issues involved in obtaining price metrics of the non-GDP component of EGDP and these parameters, but putting a dollar amount on these non-GDP benefits is difficult and research is still in its early days. Evidence "on the ground" suggests the contribution of these benefits may be quite significant.

The onset of the digital revolution and the uptake of digital economy goods have been rapid. Surveys by the U.S. Census Bureau (2014) show that the fraction of U.S. households with a computer at home rose from about one-quarter in 1993 to more than three-quarters in 2012 and that the fraction with Internet use at home went from one-fifth in 1997 to four-fifths by 2012. Studies by the Pew Research Center (Anderson (2015), Perrin (2017), Perrin and Jiang (2018), Pew Research Center (2017)) also found that the share of adults who use at least one social media site increased from less than one-tenth in 2005 to two-thirds in 2015, and market penetration of smartphones more than doubled from 2011 to 2016, from 35 percent to 77 percent. A 2018 Pew survey of U.S. adults found that one-quarter of the respondents reported being online "almost constantly," while 43 percent reported going online several times a day. Those in the 18-to-29-year-old cohort were found to be particularly heavy users, with almost 40 percent saying they were online almost constantly. This is Schmidt and Rosenberg's "free, copious, and ubiquitous" information revolution in action.

Then there are major advances in medicine, which have created notable costless benefits for consumers, even though those benefits have unfolded over a longer period of time than those of the digital revolution. Average life expectancy has increased from 50 to 80 years over the course of the last century, creating a huge amount of surplus value using a standard value-of-life approach — around $1.2 million per person, according to estimates by Murphy and Topel (2006). While not all of the increase is due to medical innovation, and that which is innovation-related is often expensive, there has also been a lot of consumer surplus and output-saving innovation. Vaccines are an extremely cost-effective way of preventing some of the most feared diseases in history, a regimen of cheap low-dose aspirin can reduce the risk of heart attack, major advances in the technology of diagnostics and record retrieval and sharing have improved health outcomes, and minimally invasive surgical techniques have led to significant decreases in recovery times and increases in patient comfort. Anyone who remembers a visit to the dentist 50 years ago will appreciate the comfort factor. Assigning a dollar value to these advances is challenging, but it is part of what Cutler and Berndt (2001) have called the "output movement" in health economics, which attempts to measure the impact of medical care on health outcomes rather than the amount of resources expended. The wedge between the two is part of the difference between GDP and the EGDP of this paper, and the growth in the wedge due to costless innovation is output-saving technical change.

A review of the existing empirical studies of the information technology finds a wide range of results, with estimates of its benefits in the range of $100 billion to $1 trillion. Viewed against the overall size of GDP, currently around $18 trillion, the effects seem relatively small. A comprehensive study by Groshen et al. (2017) also attributes a relatively small impact of this technology on GDP. They cite the study by Lebow and Rudd (2003) as evidence for a 6.5 percent annual bias in the "PC services (including Internet)" component of the Personal Consumption Expenditures price deflators used to measure the growth of real GDP, but they also note that the GDP share of PC services and Internet was only 0.6 percent in 2015, so the overall impact on GDP growth was only -0.04 percentage point per year. This figure jumps to -0.26 when biases in medical care deflators are counted.

These estimates pertain to consumption expenditures. Groshen et al. provide a parallel calculation for the information technology components of investment spending. These include communication equipment, computers and peripherals, other information systems equipment, and software. They cite the Byrne, Fernald, and Reinsdorf (2016) estimates of the annual biases in investment price deflators, which range from 0.9 percent for software to 12 percent for computers and peripherals. However, the GDP share of these categories is still small, only 3.6

percent, so the overall bias in real GDP growth was only -0.15 percentage point per year. The Byrne et al. study also addresses the question of whether the various biases are enough to explain the slowdown in real GDP growth after 2007. They find "considerable evidence" of mismeasurement bias, but "no evidence that the biases have gotten worse since the early 2000s." In his summary assessment of the literature, Syverson (2016) concludes that the "the surplus created by Internet-linked digital technologies fall far short of the $2.7 trillion or more of 'missing output' resulting from the productivity growth slowdown."

These analyses accept that biases do exist that understate the impact of these goods and that they may be quite large, but argue that the GDP share of digital goods is too small for them to matter much in the larger picture. However, it should also be recognized that the Internet's direct contribution to GDP is zero, so its share is similarly zero. Some part of the Internet's resource cost is recaptured in advertising fees, but the higher price of the advertised goods affect the GDP share of those goods, not of the Internet. The small GDP share for a group of goods that include the Internet is therefore not the final word on the problem. And, in any event, the GDP share is not the relevant share in the EGDP approach of this paper, since it does not take into account the compensating variation, V. The Internet may not contribute directly to GDP, but its V may still be large: If the high-end $1 trillion estimate of digital economy value is used as an estimate of V (a big "if") and added to the $18 trillion GDP in 2015, EGDP is $19 trillion. The implied digital-good share of EGDP is then about 5 percent, almost 10 times larger than the estimated GDP share of the conventional analysis. And, if the $1 trillion estimate for digital goods seems implausibly large relative to GDP, then think of health care and imagine the size V associated with a cure of coronary artery disease or Alzheimer's disease.

IX. Summary and Final Thoughts

We have proposed an extension of conventional GDP that lays the groundwork for empirical work that may capture some of the broader effects of innovation by incorporating an explicit utility function. It does so by integrating Lancaster's idea of a consumption technology into the conventional supply-side model of growth accounting and allowing certain types of innovation to shift that technology. This shift is, in effect, output-saving because it allows consumers to use their income more efficiency in the production of utility. We have then used this new framework to define a welfare-based concept of GDP, EGDP, which includes the compensating variation associated with output-saving innovation. EGDP follows Koopman's injunction against measurement without theory.

Our proposed extension of growth analysis adds output-saving technical change to the list of innovation mechanisms already familiar from conventional growth accounting, which include costless shifts in the production function (Solow), improvements in product quality in which a better product is equated to more of the older lower-quality good it replaces, and resource-costly technical and organization improvements resulting from investments in intangible capital. These three sources are shown in the schematic diagram in Figure 5, in which technology (costless and costless) is applied to labor and capital to produce GDP. In the conventional interpretation of GDP, this output is then transferred to consumers and is the source of their well-being. We have added a separate consumption technology to this chain of causality, and introduced the possibility that innovation may cause *both* the production *and* consumption technology to shift due to innovation, whereas the Solow framework allowed for shifts in the production function alone. Adding a consumption technology to the picture allows for output-saving technical change and adds a separate mechanism through which consumer welfare is enhanced. We have proposed adding the value of this enhanced welfare to GDP to arrive at what we have called EGDP.

Figure 5 emphasizes that our intent is not to supplant GDP, which Samuelson and Nordhaus (2000) call "One of the Great Inventions of the 20th Century," but to augment it in a way that allows important questions about the Internet Age to be addressed more accurately. What we propose is, in effect, to add a fourth source of consumer value to supplement value derived from the primary, secondary, and tertiary sectors of traditional resource-based GDP accounting. This "quadrary" sector lies outside the resource-using boundary of GDP that largely encompasses the other three and accounts for the non-GDP welfare gains to the consumer from economic activity and innovation studied in this paper.[24] EGDP is offered as a comprehensive

[24] Our "quadrary" sector differs from the "quaternary" sector proposed by Kennessy (1987), which rearranges the existing resource-using sectors to form a fourth that includes finance, insurance, and real estate, other (nontransport and nontrade) services, and government administration industries. The Kennessy taxonomy leaves aggregate GDP unchanged, whereas our fourth sector adds to resource-based GDP to arrive at EGDP.

measure of all four "sectors." It poses real measurement challenges, but so did GDP at the inception of the national accounting movement.

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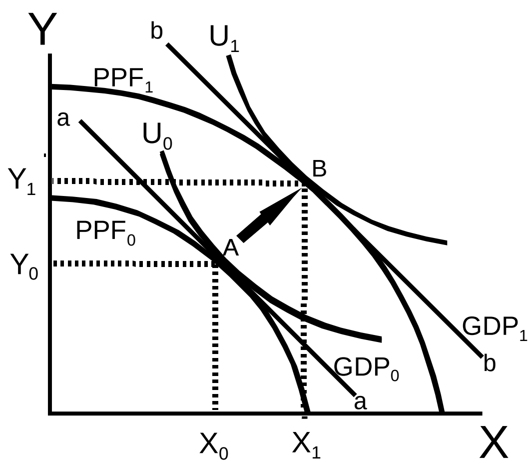


Figure 1

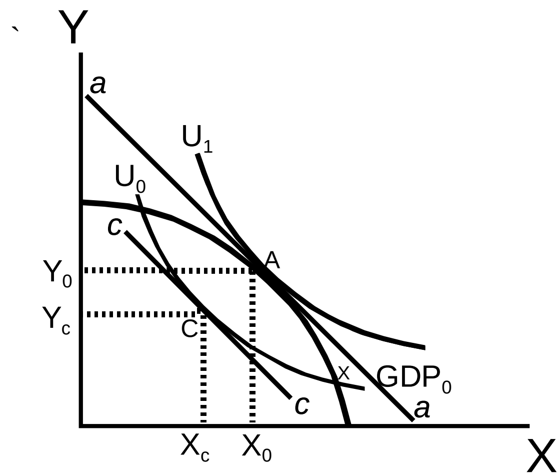


Figure 2

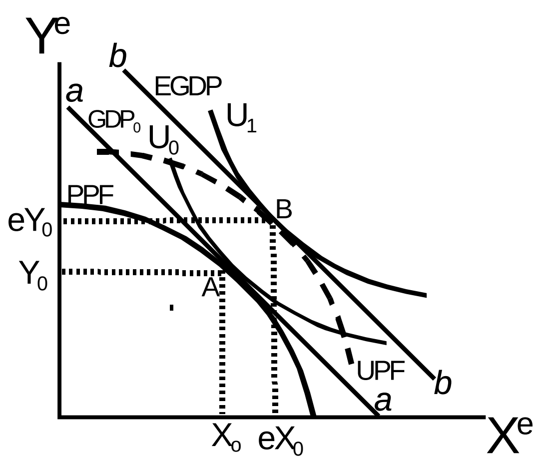


Figure 3

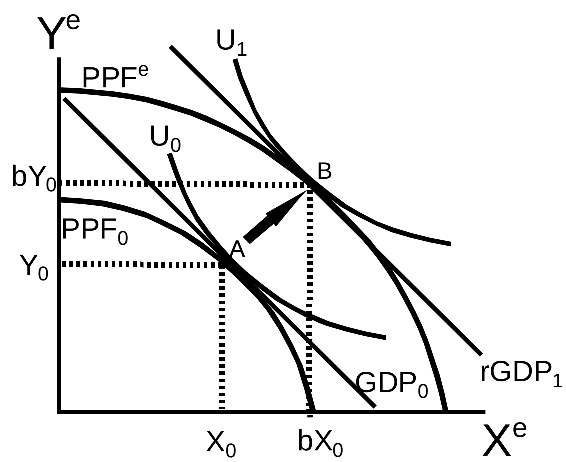
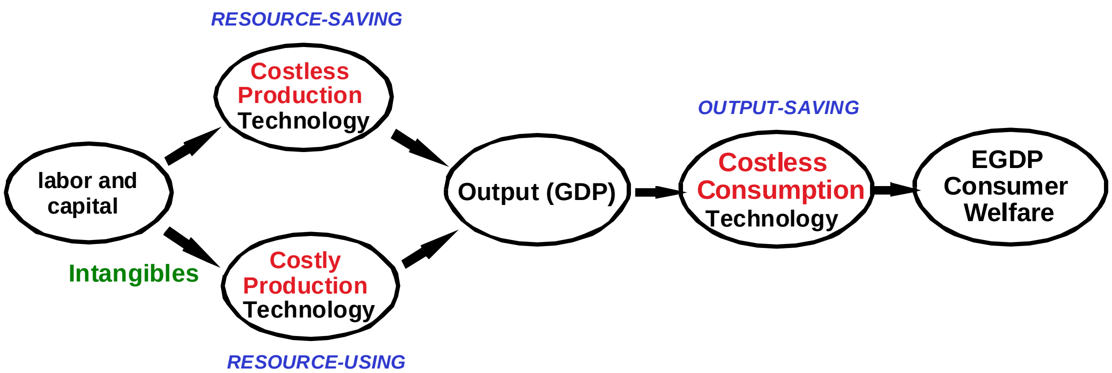


Figure 4


RESOURCE-SAVING
Costless
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labor and
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Costly
Production
Technology
RESOURCE-USING
Output (GDP)
OUTPUT-SAVING
Costless
Consumption
Technology
EGDP
Consumer
Welfare

Figure 5