ECONOMIC MEASUREMENT CHALLENGES IN THE DIGITAL ECONOMY[‡]

Measuring the Impact of Free Goods on Real Household Consumption[†]

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A puzzling development over the past 15 years is the decline in total factor productivity in many advanced economies. Part of this decline may be due to the rapid growth of free digital goods.¹ Statistical agencies have no reliable way to measure the benefits of the introduction of free goods. This is true even when the provision of the goods is paid for via advertising. Yet these free goods are enormously popular and surely create substantial utility for households.

In this paper, we suggest a methodology that will allow statistical agencies to form rough approximations to the benefits that flow to households from new free goods. The present paper draws heavily on the contributions of Brynjolfsson et al. (2019) (subsequently referred to as BCDEF) and Diewert, Fox, and Schreyer (2019).

In Section I, we outline how the reservation price methodology introduced by Hicks (1940, p. 114) can be used to measure the consumption benefits to households of new products that are

provided at zero cost or costs that are close to zero. This Hicksian approach relies on normal index number theory but requires the estimation of reservation prices. In Section II, we show how choice experiments about compensation for product withdrawals can be used to estimate these reservation prices. Section III concludes.

I. Basic Index Number Theory and Hicksian Reservation Prices

Suppose that we are given nonnegative, non-zero price and quantity data for $T + 1$ periods for a representative utility-maximizing household. The period t price vector is (p_t^0, p^t) , and the period t quantity vector is (q_t^0, q^t) for $t = 0, 1, \dots, T$ where p^t and q^t are N dimensional price and quantity vectors, and p_t^0 and q_t^0 are the period t price and quantity for product 0.

The true (fixed base) Fisher quantity or volume index for period t relative to period 0 is defined as follows, for $t = 1, \dots, T$:²

$$(1) \quad Q_F^t \equiv \left\{ \frac{p_0^0 q_t^0 + p^0 \cdot q^t}{p_0^0 q_0^0 + p^0 \cdot q^0} \right\}^{1/2} \times \left\{ \frac{p_0^t q_0^t + p^t \cdot q^t}{p_0^t q_0^0 + p^t \cdot q^0} \right\}^{1/2}.$$

The ratio of period t nominal consumption to period 0 nominal consumption for the representative household is

$$(2) \quad \frac{V^t}{V^0} = \frac{p_0^t q_0^t + p^t \cdot q^t}{p_0^0 q_0^0 + p^0 \cdot q^0}.$$

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¹In this paper, we will use the word “goods” to include both goods and services.

²Notation: $p^0 \cdot q^t \equiv \sum_{n=1}^N p_n^0 q_n^t$ where $p^0 \equiv [p_1^0, \dots, p_N^0]$ and $q^t \equiv [q_1^t, \dots, q_N^t]$.

If the household has certain preferences,³ then the Fisher quantity index defined by (1) is equal to the household's utility ratio between periods t and 0; that is, $Q_F^t = f(q_0^t, q^t)/f(q_0^0, q^0)$.

Suppose that commodity 0 is a new product that was not available in period 0 but is available in periods 1 to T . There is a Hicksian reservation price for product 0 in period 0 that will induce consumers to demand 0 units of the product ($q_0^0 = 0$). Denote this reservation price by $p_0^{0*} > 0$ (see Hicks 1940, p. 114). Suppose further that in periods 1 to T , the new product is *free* so that the prices p_0^t equal 0 for $t = 1, \dots, T$. Thus, the product 0 prices and quantities satisfy the following assumptions, for $t = 1, \dots, T$:

$$(3) \quad p_0^{0*} > 0; \quad q_0^0 = 0; \quad p_0^t = 0; \quad q_0^t > 0.$$

Now substitute (3) into (1) and (2). We find that the true Fisher quantity index for period t relative to period 0, Q_F^t , and the corresponding nominal GDP value ratio, V^t/V^0 , are equal to the following expressions for $t = 1, \dots, T$:

$$(4) \quad Q_F^t \equiv \left\{ \frac{p_0^{0*} q_0^t + p^0 \cdot q^t}{p^0 \cdot q^0} \right\}^{1/2} \left\{ \frac{p^t \cdot q^t}{p^t \cdot q^0} \right\}^{1/2},$$

$$(5) \quad \frac{V^t}{V^0} = \frac{p^t \cdot q^t}{p^0 \cdot q^0}.$$

Because the price is zero, nominal household consumption growth simply ignores product 0. However, product 0 does play a role in the growth of real household consumption (measured at final demand prices) as equations (4) above indicate. The problem with Q_F^t defined by (4) is that the period 0 reservation price p_0^{0*} is not directly observable. We need a way to estimate the period 0 reservation price p_0^{0*} in order to evaluate (4).⁴

³ See Diewert (1976). The utility function must be equal to $[\sum_{i=0}^N \sum_{k=0}^N a_{ik} q_i q_k]^{1/2}$, or the dual unit cost function must be equal to $[\sum_{i=0}^N \sum_{k=0}^N b_{ik} p_i p_k]^{1/2}$, where the parameter matrices $A \equiv [a_{ik}]$ and $B \equiv [b_{ik}]$ must satisfy certain restrictions.

⁴ Feenstra (1994) developed a way to implement methods for estimating reservation prices in the context of consumers having CES preferences. Diewert and Feenstra (2019) developed methods for estimating reservation prices in the context of preferences that are exact for the Fisher price and quantity index, but the methods are far from easy to implement. Hausman (1996) also estimated reservation prices, and in addition, used consumer surplus concepts to measure the benefits of new products.

The *incorrect volume measure* for household consumption in period t that simply ignores product 0 is the fixed base Fisher index Q_F^{t*} defined as follows for $t = 1, \dots, T$:

$$(6) \quad Q_F^{t*} \equiv \left\{ \frac{p^0 \cdot q^t}{p^0 \cdot q^0} \right\}^{1/2} \left\{ \frac{p^t \cdot q^t}{p^t \cdot q^0} \right\}^{1/2}.$$

The ratio of the true volume index Q_F^t defined by (4) to the incorrect volume index Q_F^{t*} defined by (6) is⁵

$$(7) \quad \begin{aligned} \frac{Q_F^t}{Q_F^{t*}} &= \left\{ \frac{p_0^{0*} q_0^t + p^0 \cdot q^t}{p^0 \cdot q^t} \right\}^{1/2} \\ &= \left[1 + \left(\frac{p_0^{0*} q_0^t}{p^0 \cdot q^t} \right) \right]^{1/2} \\ &\approx 1 + \left(\frac{1}{2} \right) \left(\frac{p_0^{0*} q_0^t}{p^0 \cdot q^t} \right) > 1. \end{aligned}$$

If the hybrid share of product 0 in period t , $p_0^{0*} q_0^t / p^0 \cdot q^t$, grows over time (e.g., due to the growth of free goods, q_0^t), the downward bias in the incorrect Fisher index Q_F^{t*} will grow.

It is straightforward to modify the methodology to deal with the situation where the price of the new product in periods 1 to T is not zero: replace assumptions (3) with the following assumptions, $t = 1, \dots, T$:

$$(8) \quad p_0^{0*} > 0; \quad q_0^0 = 0; \quad p_0^t > 0; \quad q_0^t > 0.$$

The new value ratio and the new true Fisher quantity index Q_F^{t**} are defined as follows:

$$(9) \quad \frac{V^t}{V^0} = \frac{p_0^t q_0^t + p^t \cdot q^t}{p^0 \cdot q^0},$$

$$t = 1, \dots, T;$$

$$(10) \quad \begin{aligned} Q_F^{t**} &\equiv \left\{ \frac{p_0^{0*} q_0^t + p^0 \cdot q^t}{p^0 \cdot q^0} \right\}^{1/2} \\ &\quad \times \left\{ \frac{p_0^t q_0^t + p^t \cdot q^t}{p^t \cdot q^0} \right\}^{1/2} \\ &= \left[1 + \left(\frac{p_0^t q_0^t}{p^t \cdot q^t} \right) \right]^{1/2} Q_F^t, \end{aligned}$$

⁵ A first-order Taylor series approximation to $g(x) \equiv (1+x)^{1/2}$ around $x=0$ is $1 + (1/2)x$, which is the approximation used in (7).

where Q_F^t is defined by (4). Assume that the statistical agency uses a fixed base Fisher price index to deflate the true expenditure ratio defined by (9). Since the period 0 reservation price is not available to the statistical agency, a fixed base matched products Fisher index could be used to deflate the true value ratio defined by (9). In this case, the incorrect Fisher quantity index for period t , Q_F^{***} , will be defined as

$$(11) \quad Q_F^{***} \equiv \left\{ \frac{p_0^t q_0^t + p^t \cdot q^t}{p^0 \cdot q^0} \right\} / \left[\frac{p^t \cdot q^t p^0 \cdot q^0}{p^0 \cdot q^0 p^t \cdot q^t} \right]^{1/2}$$

$$= \left\{ \frac{p_0^t q_0^t + p^t \cdot q^t}{p^t \cdot q^t} \right\} Q_F^*$$

$$= \left[1 + \left(\frac{p_0^t q_0^t}{p^t \cdot q^t} \right) \right] Q_F^*,$$

where Q_F^* is defined by (6). Thus, the ratio of the new true Fisher volume index, Q_F^{**} , to the new incorrect Fisher volume index, Q_F^{***} , is

$$(12) \quad \frac{Q_F^{**}}{Q_F^{***}} = \frac{\left[1 + \left(\frac{p_0^t q_0^t}{p^t \cdot q^t} \right) \right]^{1/2} Q_F^*}{\left[1 + \left(\frac{p_0^t q_0^t}{p^t \cdot q^t} \right) \right] Q_F^*}$$

using (10) and (11),

$$= \left[1 + \left(\frac{p_0^t q_0^t}{p^t \cdot q^t} \right) \right]^{-(1/2)} \frac{Q_F^*}{Q_F^*}$$

$$= \frac{\left[1 + \left(\frac{p_0^* q_0^*}{p^0 \cdot q^0} \right) \right]^{1/2}}{\left[1 + \left(\frac{p_0^t q_0^t}{p^t \cdot q^t} \right) \right]^{1/2}} \quad \text{using (7),}$$

$$\approx \frac{1 + \left(\frac{1}{2} \right) \left(\frac{p_0^* q_0^*}{p^0 \cdot q^0} \right)}{1 + \left(\frac{1}{2} \right) \left(\frac{p_0^t q_0^t}{p^t \cdot q^t} \right)}.$$

If the new product is free in periods $t \geq 1$, so that $p_0^t = 0$, then it can be seen that (12) collapses down to the simpler formula (7).

As was the case with the bias formula (7), the bias formula (12) cannot be implemented without an estimate for the period 0 reservation price p_0^* for the new product. Therefore, a key contribution of the present paper is to show (in

the following section) how choice experiments⁶ can be used to provide an approximation to the missing reservation price p_0^* .

The Hicksian methodology assumes that the consumer has latent preferences over new products before they enter the marketplace or before they are discovered by the consumer.⁷ Advertising can cause consumers to discover new products, and hence advertising can have beneficial welfare effects due to the expansion of the consumer's effective consumption set.

The business costs of producing advertising will in general not equal the consumer benefits of advertising; they are motivated by profit maximization considerations in a monopolistic competition framework.⁸ They will not be proportionate to the benefits of these new products for consumers except by coincidence.⁹

Therefore, even when free goods are supported by advertising, simply measuring expenditures on advertising will not provide a meaningful estimate of the welfare gains from the free goods.¹⁰

⁶Including the online surveys implemented by BCDEF and Brynjolfsson, Collis, and Eggers (2019).

⁷A weakness of the Hicksian approach is that the discovery of a new product does not materially change the consumer's preferences over previously discovered products; i.e., before a new product is discovered by the consumer, the consumer's preferences are given by $f(0, q)$; after discovery of product 0, the preferences are given by $f(q_0, q)$. However, a revolutionary new product may cause the consumer's preferences to change from $f(0, q)$ to a new utility function, $f^*(q_0, q)$.

⁸For this reason (and other reasons, including the fact that the present international methodology for measuring GDP excludes most household production), it would also be useful to introduce a new version of GDP that would be household oriented. Moreover, advertising typically has a *direct negative* effect on consumer surplus due to being intrusive or raising privacy concerns; see Papies, Eggers, and Wlömert (2011).

⁹For many products, cost of advertising is zero or a trivial fraction of benefits, while for other products, especially unsuccessful products, it may be that advertising expenses greatly exceed consumer benefits.

¹⁰Of course, there are some problems with the above simple computations: (i) Comparisons of real consumption cannot be made going from period $t - 1$ to period t ; instead, we have to compare periods t and $t - 1$ with period 0 and so the resulting comparisons are indirect. (ii) To really model the benefits of a new free product, we need to also bring the allocation of time into the picture (e.g., Brynjolfsson and Oh 2012). Integrating these approaches is left to the future.

II. Compensation for Product Withdrawals and Reservation Prices

Define the *household's conditional cost function*, $c(u, p, q_0)$, as follows:¹¹

$$(13) \quad c(u, p, q_0) \equiv \min_q \{p \cdot q : f(q_0, q) \geq u\}.$$

This cost function minimizes the cost of consuming commodities q conditional on having q_0 units of the new commodity 0 in order to achieve the target level of utility u . The household's *regular cost function*, $C(u, p_0, p)$, is defined as follows:

$$\begin{aligned} (14) \quad C(u, p_0, p) &\equiv \min_{q_0, q} \{p_0 q_0 + p \cdot q : f(q_0, q) \geq u\} \\ &\equiv \min_{q_0} \left\{ \left[\min_q \{p \cdot q : f(q_0, q) \geq u\} \right] + p_0 q_0 \right\} \\ &= \min_{q_0} \{c(u, p, q_0) + p_0 q_0\}. \end{aligned}$$

We assume (q_0^t, q^t) is a solution to the cost minimization problem defined by $C(u^t, p_0^t, p^t)$, where $u^t = f(q_0^t, q^t)$ and q^t is a solution to the conditional cost minimization problem defined by $c(u^t, p^t, q_0^t)$ for some period $t \geq 1$.

Thus, using definition (14) for (u^t, p_0^t, p^t) , we have the following equalities:

$$\begin{aligned} (15) \quad p^t \cdot q^t + p_0^t q_0^t &= C(u^t, p_0^t, p^t) \\ &= \min_{q_0} \{c(u^t, p^t, q_0^t) + p_0^t q_0^t\} \\ &= c(u^t, p^t, q_0^t) + p_0^t q_0^t. \end{aligned}$$

We assume that $c(u^t, p^t, q_0)$ is differentiable with respect to q_0 at $q_0 = q_0^t > 0$. Thus, the first-order necessary condition for the cost minimization problem in (15) implies the following equality:

$$(16) \quad \frac{\partial c(u^t, p^t, q_0^t)}{\partial q_0^t} = -p_0^t.$$

Note that equation (15) also implies the following equality:

$$(17) \quad c(u^t, p^t, q_0^t) = p^t \cdot q^t.$$

¹¹This section draws heavily on BCDEF and Diewert, Fox, and Schreyer (2019).

Choice experiments come into play at this point by asking households in period t how much money it will take for the household to give up its use of the new commodity.¹² The answer is the following conditional cost minimization problem:

$$\begin{aligned} (18) \quad c(u^t, p^t, 0) &\equiv \min_q \{p^t \cdot q : f(q, 0) = u^t\} \\ &> c(u^t, p^t, q_0^t), \end{aligned}$$

where the inequality follows from the assumptions that $q_0^t > 0$ and that f is increasing in its arguments and hence $c(u, p, q_0)$ is decreasing in q_0 . Define the *monetary compensation* m^t that is additional to $p^t \cdot q^t$ that is required to keep the household at the period t utility level u^t without using q_0 as follows:

$$\begin{aligned} (19) \quad m^t &\equiv c(u^t, p^t, 0) - p^t \cdot q^t \\ &= c(u^t, p^t, 0) - c(u^t, p^t, q_0^t), \end{aligned}$$

where we have used (17) to derive the second equality.¹³ Note that utility and the prices of continuing commodities are held constant on the right-hand sides of (19).¹⁴ Assuming that m^t can be estimated through choice experiments or other methods, it can be seen that estimates for $c(u^t, p^t, 0) = p^t \cdot q^t + m^t$ can be determined.¹⁵ We convert m^t into a period t *average compensation price per unit of q_0 foregone* by setting m^t equal to $w_0^t q_0^t$:

$$(20) \quad w_0^t \equiv m^t / q_0^t.$$

Using (19) and (20), we can write the cost difference, $c(u^t, p^t, 0) - c(u^t, p^t, q_0^t)$, as follows:

$$(21) \quad c(u^t, p^t, 0) - c(u^t, p^t, q_0^t) = w_0^t q_0^t.$$

¹²Put another way, what is the income required for the household to achieve its period t utility level u^t using commodities that are available in period t but excluding the use of the new commodity?

¹³This is equation (27) of BCDEF, which they describe as a global willingness to accept function.

¹⁴Thus, the right-hand side of (19) does not equal either a Hicksian price or quantity variation; it is a Hicksian-like *mixed variation*.

¹⁵In the context of free digital goods, this is what BCDEF called "total income": actual income ($p^t \cdot q^t$) plus the additional income (m^t) required to achieve the same level of actual period t utility $u^t \equiv f(q_0^t, q^t)$.

At this point, we assume that $c(u^t, p^t, q_0)$ is also differentiable with respect to q_0 at $q_0 = 0$; that is, we assume a one-sided derivative exists at this point. Thus, we can form the following two first-order Taylor series approximations:

$$\begin{aligned}
 (22) \quad c(u^t, p^t, 0) & \\
 & \approx c(u^t, p^t, q_0^t) + \frac{\partial c(u^t, p^t, q_0^t)}{\partial q_0} [0 - q_0^t] \\
 & = c(u^t, p^t, q_0^t) - p_0^t [0 - q_0^t] \quad \text{using (16)} \\
 & = c(u^t, p^t, q_0^t) + p_0^t q_0^t;
 \end{aligned}$$

$$\begin{aligned}
 (23) \quad c(u^t, p^t, q_0^t) & \\
 & \approx c(u^t, p^t, 0) + \frac{\partial c(u^t, p^t, 0)}{\partial q_0} [q_0^t - 0] \\
 & = c(u^t, p^t, 0) - p_0^{t*} [q_0^t - 0] \\
 & = c(u^t, p^t, 0) - p_0^{t*} q_0^t,
 \end{aligned}$$

where p_0^{t*} is the *Hicksian reservation price for the new product 0* in period t , which is defined as $-\partial c(u^t, p^t, 0)/\partial q_0$. This reservation price is not directly observable, but we will be able to solve for it shortly using the estimate from the choice experiments w_0^t defined by (20). The approximate equalities (23) can be rewritten as

$$(24) \quad c(u^t, p^t, 0) \approx c(u^t, p^t, q_0^t) + p_0^{t*} q_0^t.$$

A more accurate approximation to $c(u^t, p^t, 0) - c(u^t, p^t, q_0^t)$ can be obtained if we take the following arithmetic average of the two first order approximations (22) and (24):

$$(25) \quad c(u^t, p^t, 0) - c(u^t, p^t, q_0^t) \approx \frac{1}{2}(p_0^t + p_0^{t*})q_0^t.$$

The approximation given by (25) will be an exact one if $c(u^t, p^t, q_0)$ is a quadratic function of q_0 between 0 and q_0^t ; see the quadratic approximation lemma in Diewert (1976).

Note that the left-hand side of (25) is equal to the left-hand side of (21) for each period t . Thus, the right-hand sides are approximately equal to each other, and we obtain the following approximate equalities:

$$(26) \quad w_0^t q_0^t \approx \frac{1}{2}(p_0^t + p_0^{t*})q_0^t.$$

Recall that q_0^t , w_0^t , and p_0^t are observable. Thus, we can use (26) to solve for the unknown period t reservation price p_0^{t*} . The approximate solution is

$$(27) \quad p_0^{t*} \approx 2w_0^t - p_0^t.$$

If households are reluctant to surrender their units of q_0 , so that the average period t compensation price w_0^t is greater than the period t market price p_0^t , then from (27) the period t reservation price for product 0, p_0^{t*} , will be greater than the observed period t price for a unit of q_0 , p_0^t . Note that if the commodity 0 is a free good or service in period t , then $p_0^t = 0$, and the approximate reservation price is twice the estimated compensation price from the choice experiment, $p_0^{t*} \approx 2w_0^t$.

We have found a reservation price, p_0^{t*} , for a period t indifference surface, but what we want is a reservation price for period 0. We temporarily restrict ourselves to the case where $N = 1$, so that $q = q_1$ is now a scalar. For period 0, the consumer's utility-maximizing vector when commodity 0 is not available is $(q_0^0, q_1^0) = (0, q_1^0)$. The slope of the indifference curve through this point is $-p_0^{0*}/p_1^0$. When $N = 1$, equation (21) becomes $p_1^t q_1^{t*} = p_1^t q_1^t + w_0^t q_0^t$, which can be solved for q_1^{t*} , where $p_1^t q_1^{t*} = c(u^t, p^t, 0)$. The slope of the period t indifference curve through the point $(0, q_1^{t*})$ is $-p_0^{t*}/p_1^t$. But when $N = 1$, $f(q_0, q)$ becomes $f(q_0, q_1)$, and because $f(q_0, q_1)$ is assumed to be linearly homogeneous, all of the indifference curves that pass through the q_1 axis will have the same slope. We will have $-p_0^{0*}/p_1^0 = -p_0^{t*}/p_1^t$ and thus, using (27),

$$(28) \quad p_0^{0*} = \frac{p_0^{t*}}{p_1^t/p_1^0} \approx \frac{2w_0^t - p_0^t}{p_1^t/p_1^0}.$$

Thus, the period 0 reservation price for product 0 is the *inflation-adjusted carry backward period t reservation price*; the period t reservation price p_0^{t*} for the new commodity is deflated by an index of inflation for the continuing commodity q_1 between periods 0 and t , p_1^t/p_1^0 .

For the general N case we replace the one commodity price index for continuing commodities, p_1^t/p_1^0 , by the fixed base Fisher index P_F^{t*} that compares the prices for continuing commodities in period t with their counterparts in period 0; that is, define $P_F^{t*} \equiv [p^t \cdot q^t p^0 \cdot q^0 / p^0 \cdot q^0 p^t \cdot q^t]^{1/2}$.

Replace p_1^t/p_1^0 in (28) by P_F^{t*} , and we obtain the following approximate equality:

$$\begin{aligned}
 (29) \quad & p_0^{0*} q_0^t / p^0 \cdot q^t \\
 & \approx q_0^t \frac{2w_0^t - p_0^t}{P_F^{t*} p^0 \cdot q^t} \\
 & = 2(m^t/p^t \cdot q^t) \frac{P_P^t}{P_F^{t*}} - (p_0^t q_0^t / P_F^{t*} p^0 \cdot q^t)
 \end{aligned}$$

using (20), where P_P^t is the fixed base Paasche price index defined over continuing commodities; that is, $P_P^t \equiv p^t \cdot q^t / p^0 \cdot q^t$. Now substitute (29) into (12) to get an approximation to the bias term, Q_F^{t*} / Q_F^{***} , in terms of m^t instead of in terms of the reservation price p_0^{0*} . If p_0^t is zero or tiny and if P_P^t is approximately equal to P_F^{t*} , then the right-hand side will be approximately equal to $2m^t/p^t \cdot q^t$, and Q_F^{t*} / Q_F^{***} , the ratio of the true Fisher volume index to the incorrect Fisher volume index, will be approximately equal to $1 + m^t/p^t \cdot q^t$.

III. Conclusion

We have demonstrated how estimates of the amount of money consumers have to be paid to give up free digital goods can be translated into estimates of reservation prices and then to adjusted estimates of real household consumption that take into account household consumption of free products. Several approximations were required to accomplish this translation, but in the end we are simply applying normal index number theory to the problem. In other words, we did not use consumer surplus arguments to derive our final estimates for real household consumption. There are additional approximations required to extend our analysis from a single household to cover aggregation over consumers. Thus, there are many weaknesses in our analysis, but we think that it is preferable to have a rough estimate of the benefits of free digital products than to have no estimate whatsoever.

Two important points emerged from our analysis. First, the present production-oriented GDP measures are not satisfactory for measuring real household consumption. They will be increasingly inaccurate as free goods, such as those made possible by the digital revolution, become more important. A new measure of aggregate output that changes the present production boundary and focuses on household welfare is

required. A second important point that emerged is that advertising expenditures are not an adequate substitute for measuring the benefits of new goods to the household sector. Instead, we need to draw on estimates such as those provided by choice experiments.

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