GDP-B: ACCOUNTING FOR THE VALUE OF NEW AND FREE GOODS IN THE DIGITAL ECONOMY

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ABSTRACT

The welfare contributions of the digital economy, characterized by the proliferation of new and free goods, are not well-measured in our current national accounts. We derive explicit terms for the welfare contributions of these goods and introduce a new metric, GDP-B which quantifies their benefits, rather than costs. We apply this framework to several empirical examples including Facebook and smartphone cameras and estimate their valuations through incentive compatible choice experiments. For example, including the welfare gains from Facebook would have added between 0.05 and 0.11 percentage points to GDP-B growth per year in the US.

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"The welfare of a nation can scarcely be inferred from a measure of [GDP]."
                                                  – Simon Kuznets, 1934.

1. Introduction

We develop a new framework for measuring welfare change and real GDP growth in the presence of new and free goods[1]. The increased proliferation of such goods is a key characteristic of the digital economy. New, sometimes very specialized, goods appear with increasing rapidity,[2] and free goods (such as information and entertainment services) are increasingly available at zero price, reflecting the very low marginal costs of digital replication and distribution. Even when free goods have an implicit price,[3] this price is not usually observed so a price of zero is applied. Thus, the positive quantities of these goods that are consumed have a measured price of zero and measured value of zero in the conventional national accounts. Hence, they are not reflected in standard statistical agency reports for GDP or related metrics like productivity, which are typically defined in terms of GDP. Furthermore, despite GDP's widespread use as a proxy for welfare, it is not the correct metric for this purpose, at least as conventionally measured.

Our framework provides a means by which to understand the welfare contributions from these goods and the potential mismeasurement that arises from not fully accounting for them. We use this framework to derive an explicit term that is the marginal value of a new good on welfare change, providing a means for estimating welfare change mismeasurement if the good is omitted from statistical

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[1] Throughout this paper, we use the word "goods" to refer to goods and services collectively.
[2] Goolsbee and Klenow (2018, Table 3), using Adobe Analytics data on online transactions for millions of products across many different categories, find that roughly half the sales volume online for 2014-2017 is for products that did not exist in the previous year.
[3] See Nakamura, Samuels and Soloveichik (2016) and Brynjolfsson and Oh (2012) for examples of how to think about the valuation of "free" media.

agency collections. This can shed light on the debate regarding the potential of the digital economy to generate productivity, economic growth and welfare gains.[4] If measurement is lacking, through methodological challenges, statistical agency budgets or data availability, then we are severely hampered in our ability to understand the impact of new technologies, goods on the economy, and consequently the prospects for future productivity, economic growth and welfare.[5]

A problem in assessing the full impact of the introduction of a new good on real GDP growth is that we would really need national statistical offices to recalculate their estimates of real GDP including the new goods with, for example, estimated Hicksian reservation prices for the period before they are sold in positive quantities; the reservation price of a good is the price which would induce a utility maximizing potential purchaser of the product to demand zero units of it.[6] However, we are able to use our framework to derive a close approximation to the addition to real GDP growth that would be required to account for the welfare gains from the introduction of a new good, without having to recalculate the official GDP numbers published by national statistical offices.

Free goods are addressed through generalizing the standard microeconomic model of household cost minimization. It is then possible to re-work our welfare change and real GDP growth adjustment terms to allow for there to be free goods. Our

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[4] Among others, see, for example, Gordon (2016) and Cowen (2011) giving a pessimistic view and Sichel (2016), Mokyr, Vickers and Ziebarth (2015) and Brynjolfsson and McAfee (2011, 2014) giving a more optimistic view.

[5] Among others, see, for example, Feldstein (2017), Groshen *et al.* (2017), Hulten and Nakamura (2017), Syverson (2017), Ahmad and Schreyer (2016), Byrne, Fernald and Reinsdorf (2016), Brynjolfsson and Saunders (2009), Brynjolfsson and Oh (2012), Greenstein and McDevitt (2011), Brynjolfsson, Eggers and Gannamaneni (2018) and Brynjolfsson, Collis and Eggers (2019).

[6] See Hicks (1940), Diewert (1980), Hausman (1981, 1996), Feenstra (1994), Diewert, Fox and Schreyer (2018), and Diewert and Feenstra (2017).

new metric is labelled *GDP-B,* as it captures the *benefits* associated with new and free goods and thus goes "beyond GDP".[7] In addition, our calculations of GDP-B make it easy to calculate a corresponding productivity metric, *Productivity-B* which simply uses GDP-B as its numerator.

We provide several empirical examples of free digital goods where we quantify these welfare and GDP growth adjustment terms. Specifically, we draw on the work of Brynjolfsson, Collis and Eggers (2019) who developed an approach to directly estimate consumer welfare by running massive online choice experiments. They explored both hypothetical and incentive compatible choice experiments to estimate willingness to accept values for giving up access to a good. While hypothetical choice experiments might suffer from hypothetical bias, incentive aligned choice experiments, which make choices consequential, have been shown to be externally valid (Ding, Grewal and Liechty 2005; Ding 2007; Carson, Groves and List 2014; Bishop et. al. 2017). We therefore constructed incentive compatible discrete choice experiments to estimate the potential impact on welfare growth by Facebook, a free social networking service which had rapid diffusion and quickly accumulated many diverse users. We ran our experiments on a representative sample of the US internet population recruited through an online survey panel. We use the results to provide estimates of the adjustments to welfare change and real GDP-B growth from Facebook's launch in 2004 through 2017.

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[7] See e.g. Jones and Klenow (2016), Coyle and Mitra-Kahn (2017), Corrado *et al.* (2017) and Jorgenson (2018). Some national statistical offices are considering producing a spectrum of expanded GDP measures. Heys (2018) presented options being considered by the UK Office of National Statistics, which include incorporating welfare adjustments for private and publically provided free goods. Our approach in this paper provides a way of doing this.

In a laboratory setting in the Netherlands, we also ran incentive compatible choice experiments to estimate the consumer welfare created by several other popular digital goods, including Instagram, Snapchat, Skype, digital Maps, LinkedIn, Twitter as well as Facebook. Although we did not have a representative sample of the population in the laboratory, our results are indicative of the approximate size of the adjustment term to real GDP-B growth which would need to be added to account for the welfare gain from these digital goods.

We also show the need for properly adjusting for quality changes in calculating GDP-B growth so that welfare changes are properly inferred. This issue is particularly acute for smartphones which have substituted (to varying degrees) a panoply of other devices including cameras, GPS, landline phones, gaming consoles, ebook readers, personal computers, video and audio players, maps/atlases, alarm clocks, calculators and sound recorders,[8] as well as numerous new capabilities that previously were unavailable at any price like real-time traffic and various types of social networking and messaging applications. What is more, new features are added frequently and quality of existing features changes rapidly. In fact, application developers conduct thousands of A/B tests every day and tweak features to improve user experience. Groshen *et al*. (2017) discuss how the US Bureau of Labor Statistics (BLS) adjusts for quality changes using hedonic methods. However, they mention that this approach is ruled out for smartphones since the set of relevant characteristics for the hedonic models constantly keep on changing. While there has been a subsequent development in that the BLS commenced hedonic quality adjustments for smartphones from January 2018,[9]

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[8] See https://www.huffingtonpost.com/steve-cichon/radio-shack-ad_b_4612973.html (accessed Feb 10, 2019) and also Hal Varian's presentation at Brookings (https://www.brookings.edu/wp-content/uploads/2016/08/varian.pdf, accessed March 19, 2019).
[9] See "Measuring Price Change in the CPI: Telephone hardware, calculators, and other consumer information items", available at https://www.bls.gov/cpi/factsheets/telephone-hardware.htm.

such explicit hedonic quality adjustment is still very limited internationally, with the UK being a standout early adopter of this approach for smartphones, commencing in 2011 (see Wells and Restieaux (2014)).

Hence, to advance understanding of the consumer benefits from quality change, we conduct an incentive compatible BDM lottery study (Becker, DeGroot, and Marschak 1964) in a university laboratory in the Netherlands to elicit consumers' valuations for smartphone cameras. We find that there is a large difference between the contribution of smartphone cameras towards conventionally-measured GDP and the welfare generated by these cameras for consumers as reflected in GDP-B. As a result, not accounting for quality adjustments in smartphones leads to a significant underestimate of GDP-B growth.

The rest of the paper is organised as follows. The next section sets out some preliminary definitions that will be used in the subsequent sections. Section 3 looks at the problem of new goods, and shows how the impact of new goods on welfare change and real GDP growth can be estimated to a high degree of approximation. Section 4 extends this framework to the case of free goods and introduces our preferred measure, GDP-B. Section 5 provides the empirical examples of Facebook and other popular free digital goods to quantify adjustments to welfare change and GDP-B growth for not accounting for these goods. Section 6 presents results from the smartphone camera laboratory study to highlight potential biases due to not performing quality adjustments. Section 7 concludes with a summary and some implications.

2. Preliminaries

We assume that a consumer has a utility function, f(q), which is continuous, quasiconcave and increasing in the components of the nonnegative quantity vector $q \geq 0_N$. For each strictly positive price vector $p \gg 0_N$ and each utility level u in the range of f, we can define the dual cost function C as follows:

(1) $C(u,p) \equiv \min_q \{p \cdot q \; ; f(q) \geq u\}$.

We are given the price and quantity data, (p^t, q^t) for periods t = 0, 1. We assume that the consumer minimizes the cost of achieving the utility level $u^t \equiv f(q^t)$ for t = 0, 1 so observed expenditure in each period is equal to the minimum cost of achieving the given utility level in each period; i.e., we have

(2) $p^t \cdot q^t = C(f(q^t),p^t)$ for t = 0, 1.

Valid measures of utility change over the two periods under consideration are the following Hicksian *equivalent and compensating variations* (Hicks, 1942):[10]

(3) $Q_E(q^0, q^1, p^0) \equiv C(f(q^1), p^0) - C(f(q^0), p^0)$;
(4) $Q_C(q^0, q^1, p^1) \equiv C(f(q^1), p^1) - C(f(q^0), p^1)$.

The above variations are special cases of the following Samuelson (1974) family of quantity variations: for $p \gg 0_N$, define:[11]

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[10] These are Hick's original definitions of equivalent and compensating variations. Hicks (1946, 331-332) appears to provide an alternative definition of the equivalent variation as $C(f(q^1), p^1) - C(f(q^1), p^0)$ and the compensating variation as $C(f(q^0), p^1) - C(f(q^0), p^0)$. The existence of alternative definitions has caused significant confusion in the literature; see Diewert (1992, p. 567, footnote 10).

[11] These measures of overall quantity change are difference counterparts to the family of Allen (1949) quantity indexes in normal ratio index number theory. The Allen quantity index for reference price vector p is defined as the ratio $C(f(q^1), p)/C(f(q^0), p)$.

(5) $Q_S(q^0, q^1, p) \equiv C(f(q^1), p) - C(f(q^0), p)$.

Hence there is an entire family of cardinal measures of utility change defined by (5), with one measure for each reference price vector p.

The variations defined by (3) and (4) are not observable (since $C(f(q^1), p^0)$ and $C(f(q^0), p^1)$ are not observable) but the following Laspeyres and Paasche variations, V_L and V_P, are observable:

(6) $V_L(p^0, p^1, q^0, q^1) \equiv p^0 \cdot (q^1 - q^0)$;

(7) $V_P(p^0, p^1, q^0, q^1) \equiv p^1 \cdot (q^1 - q^0)$.

Note that V_L and V_P are difference counterparts to the Laspeyres and Paasche quantity indexes, $Q_L = p^0 \cdot q^1 / p^0 \cdot q^0$ and $Q_P = p^1 \cdot q^1 / p^1 \cdot q^0$, respectively. Hicks (1942) showed that V_L approximates Q_E and V_P approximates Q_C to the accuracy of a first order Taylor series approximation; see also Diewert and Mizobuchi (2009; 345-346). The observable Bennet (1920) variation or indicator of quantity change V_B is defined as the arithmetic average of the Laspeyres and Paasche variations in (6) and (7):

(8) $V_B(p^0, p^1, q^0, q^1) \equiv \tfrac{1}{2}(p^0 + p^1) \cdot (q^1 - q^0)$

$$= p^0 \cdot (q^1 - q^0) + \tfrac{1}{2}(p^1 - p^0) \cdot (q^1 - q^0)$$

$$= V_L\left(p^0, p^1, q^0, q^1\right) + \frac{1}{2} \sum_{n=1}^{N} \left(p_n^1 - p_n^0\right)\left(q_n^1 - q_n^0\right) .$$

Thus the Bennet variation is equal to the Laspeyres variation $V_L(p^0, p^1, q^0, q^1)$ plus a sum of N Harberger (1971) consumer surplus triangles of the form $(1/2)(p_n^1 - p_n^0)(q_n^1 - q_n^0)$.

An alternative decomposition of the Bennet variation is the following one:

(9) $V_B(p^0, p^1, q^0, q^1) \equiv \frac{1}{2}(p^0 + p^1) \cdot (q^1 - q^0)$

$$= p^1 \cdot (q^1 - q^0) - \frac{1}{2}(p^1 - p^0) \cdot (q^1 - q^0)$$

$$= V_P\left(p^0, p^1, q^0, q^1\right) - \frac{1}{2}\sum_{n=1}^{N}\left(p_n^1 - p_n^0\right)\left(q_n^1 - q_n^0\right).$$

Thus the Bennet variation is also equal to the Paasche variation $V_P(p^0, p^1, q^0, q^1)$ minus a sum of N Harberger consumer surplus triangles of the form $(1/2)(p_n^1 - p_n^0)(q_n^1 - q_n^0)$.

It is possible to relate the observable Bennet variation to a theoretically valid Samuelson variation of the form defined by (5). However, in order to do this, we need to assume a specific functional form for the consumer's cost function, $C(u, p)$. If the cost function has a flexible, [12] translation-homothetic normalized quadratic functional form, then Proposition 1 in Diewert and Mizobuchi (2009; 353) relates the observable Bennet variation, $V_B(p^0, p^1, q^0, q^1)$ defined by (8) or (9) to the unobservable equivalent and compensating variations defined by (3) and (4); i.e., we have the following exact equality:

(10) $V_B(p^0, p^1, q^0, q^1) = \frac{1}{2}Q_E(q^0, q^1, p^0) + \frac{1}{2}Q_C(q^0, q^1, p^1).$

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[12] Diewert (1974) defined a flexible functional form as one that provides a second order approximation to a twice continuously differentiable function at a point.

That is, with certain assumptions on the functional form for the consumer's cost function (and using normalized price vectors), the observable Bennet variation can be shown to be *exactly equal* to the arithmetic average of the unobservable equivalent and compensating variations.[13] Hence, there is a strong justification from an economic perspective for using the Bennet quantity variation. Also, it has a strong justification from an axiomatic perspective (Diewert, 2005).

Finally, we can note that value change can be decomposed into Bennet quantity and price variations, as follows:

$$(11) \ p^1 \cdot q^1 - p^0 \cdot q^0 = V_B(p^0, p^1, q^0, q^1) + I_B(p^0, p^1, q^0, q^1),$$

where $V_B(p^0, p^1, q^0, q^1) \equiv \frac{1}{2}(p^0 + p^1) \cdot (q^1 - q^0)$ and $I_B(p^0, p^1, q^0, q^1) \equiv \frac{1}{2}(q^0 + q^1) \cdot (p^1 - p^0)$. Equation (11) can thus provide a decomposition into quantity and price components for any value change, including a change in nominal GDP.

3. The New Goods Problem

We can now apply the above results to measure the benefits of the introduction of a new good to a consumer who cannot purchase the good in period 0 but can purchase it in period 1. First, we have to make an additional assumption. We

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[13] Normalized prices are needed for this result to be true: "If there is a great deal of general inflation between periods 0 and 1, then the compensating variation will be much larger than the equivalent variation simply due to this general inflation, and an average of these two variations will be difficult to interpret due to the change in the scale of prices. To eliminate the effects of general inflation between the two periods being compared, it will be useful to scale the prices in each period by a fixed basket price index of the form $\alpha \cdot P$, where $\alpha \equiv [\alpha_1, \ldots, \alpha_N] > 0_N$ is a nonnegative, nonzero vector of price weights." Diewert and Mizobuchi (2009, 352-353). They recommend choosing α so that a fixed-base Laspeyres price index is used to deflate nominal prices (footnote 34, page 368).

assume that there is a shadow or reservation price for the new good in period 0 that will cause the consumer to consume 0 units of the new good in period 0. This type of assumption dates back to Hicks (1940; 114).[14]

Let the new good be indexed by the subscript 0 and let the *N* dimensional vectors of period t prices and quantities for the continuing goods be denoted by p^t and q^t for t = 0,1. The period 1 quantity of good 0 purchased during period 1 is also observed and is denoted by q_0^1. The period 0 reservation price for good 0 is not observed but we make some sort of estimate for it, denoted as $p_0^{0*} > 0$. The period 0 quantity is observed and is equal to 0; i.e., $q_0^0 = 0$. Thus the price and quantity data (for the *N+1* goods) for period 0 is represented by the *1+N* dimensional vectors (p_0^{0*}, p^0) and $(0, q^0)$ and the price and quantity data for period 1 is represented by the *1+N* dimensional vectors (p_0^1, p^1) and (q_0^1, q^1). We adapt our first expression for the Bennet variation, (8), to accommodate the new good. We find that our new Bennet variation is equal to the following expression:

$$(12)\ V_B([p_0^{0*}, p^0], [p_0^1, p^1], [0, q^0], [q_0^1, q^1])$$

$$= \tfrac{1}{2}(p^0 + p^1)\cdot(q^1 - q^0) + \tfrac{1}{2}(p_0^{0*} + p_0^1)(q_0^1 - 0)$$

$$= p^0\cdot(q^1 - q^0) + \tfrac{1}{2}(p^1 - p^0)\cdot(q^1 - q^0) + p_0^1(q_0^1 - 0) - \tfrac{1}{2}(p_0^1 - p_0^{0*})\,(q_0^1 - 0)$$

$$= p^0\cdot(q^1 - q^0) + \tfrac{1}{2}(p^1 - p^0)\cdot(q^1 - q^0) + p_0^1 q_0^1 - \tfrac{1}{2}(p_0^1 - p_0^{0*})q_0^1.$$

From the last equation on the right hand side of (12), we see that the first term, $p^0\cdot(q^1 - q^0)$ is simply the change in consumption valued at the real prices of period

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[14] There is now quite a literature on this topic and for alternative approximate welfare gain estimates; see Hausman (1981) (1996), Feenstra (1994) and Diewert and Feenstra (2017), and the references in these publications. Diewert has been applying the above Hicksian reservation analysis in the ratio context (i.e., in the context of the true cost of living index) for a long time; see Diewert (1980; 498-505), (1987; 378) (1998; 51-54). A weakness in these theories is the difficulty in determining the appropriate reservation prices.

0, a Laspeyres variation as in (6); the second term, $\frac{1}{2}(p^1 - p^0)\cdot(q^1 - q^0)$, is the sum of the consumer surplus terms associated with the continuing goods; the next term, $p_0^1 q_0^1$, is the value of consumption of the new good in period 1, valued at the price for good 0 in period 1 (this is the usual price times quantity contribution term to the value of real consumption of the new good in period 1 which would be recorded as a contribution to period 1 GDP); and the last term, $-\frac{1}{2}(p_0^1 - p_0^{0*})q_0^1$ $= \frac{1}{2}(p_0^{0*} - p_0^1)q_0^1$ is the additional consumer surplus contribution of good 0 to overall welfare change, which would not be recorded as a contribution to GDP. Note that the first two terms are a measure of the welfare change we would get by just ignoring the new good in both periods. Thus the last two terms give the overall contribution to welfare change due to the introduction of the new good.

If we assume that the reservation price for the new good in period 0, p_0^{0*}, is equal to the observable price for the new good in period 1, p_0^1, then the last term in (12), the consumer surplus term for the new good, vanishes. However, it is likely that the reservation price for period 0, p_0^{0*}, is much higher than the corresponding actual price for good 0 in period 1, p_0^1.[15] Thus if we assume that $p_0^{0*} = p_0^1$ and evaluate (12), then the downward bias in the resulting Bennet measure of welfare change will be equal to a Harberger-type triangle, $-\frac{1}{2}(p_0^1 - p_0^{0*})(q_0^1 - 0) =$ $\frac{1}{2}(p_0^{0*} - p_0^1)q_0^1$.

It is of interest to gauge the extent to which GDP growth is underestimated by not fully capturing the introduction of the new good. As comparisons may be made between periods far apart (e.g. before the introduction of the good and the most recent period), we will now be explicit about the point raised in footnote 13 of section 2; value change comparisons are difficult to interpret if the values are not

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[15] Hausman (1996) argued that for cereals, the reservation price was about twice the price at the introduction of the new good, whereas Feenstra (1994) takes it to be infinity.

expressed in comparable units. Hence, we recommend using real prices where, for example, the base period's prices are inflated by using the Consumer Price Index (CPI) to put them into comparable units with the current period's prices.[16]

Let γ denote one plus the rate of growth of the CPI between periods 0 and 1 (which may not be adjacent periods).[17] Then, adapting a result from Diewert (2005; 335), value change can be expressed as follows, where P and Q are price and quantity indexes, respectively, that satisfy $P \times Q = p^1 \cdot q^1 / p^0 \cdot q^0$.[18]

$$(13) \quad p^1 \cdot q^1 - \gamma p^0 \cdot q^0 = \gamma p^0 \cdot q^0 [p^1 \cdot q^1 / \gamma\, p^0 \cdot q^0 - 1]$$

$$= \gamma p^0 \cdot q^0 [PQ/\gamma - 1]$$

$$= \tfrac{1}{2}\, \gamma p^0 \cdot q^0 [\, 2\mathscr{P}Q - 2]\quad \text{where } \mathscr{P} \equiv P/\gamma,$$

$$= \tfrac{1}{2}\, \gamma p^0 \cdot q^0 [(1+Q)(\mathscr{P} - 1) + (1 + \mathscr{P})(Q - 1)]$$

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[16] Alternatively, we could deflate current prices to put them into the same units as the earlier period. Having units in a distant past period is, however, typically more difficult to interpret than using current period units. We recommend putting values into comparable units for both welfare and GDP growth adjustments, especially in high inflation environments or if periods are far apart in time. Similarly for spatial comparisons.

[17] We prefer to use the CPI rather than the GDP deflator for adjusting for general inflation, as the GDP deflator behaves perversely if import prices change. This is because the immediate effect of e.g. a fall in import prices is to increase the deflator; see Kohli (1982; 211). Also, Diewert (2002; 556, footnote 14) noted the following: "An example of this anomalous behavior of the GDP deflator just occurred in the advance release of gross domestic product for the third quarter of 2001 for the US national income and product accounts: the chain type price indexes for C, L, X and M decreased (at annual rates) over the previous quarter by 0.4%, 0.2%, 1.4% and 17.4% respectively but yet the overall GDP deflator increased by 2.1 %. Thus there was general deflation in all sectors of the economy but yet the overall GDP deflator increased. This is difficult to explain to the public!"

[18] That is, the formulae for the indexes P and Q are such that the product test from the axiomatic approach to index
numbers is satisfied.

We can see that (13) can be decomposed into two components, a price change indicator, $\mathcal{J}_E$, and a quantity change indicator, $\mathcal{V}_E$:[19]

(14) $\mathcal{J}_E = \frac{1}{2}\, \gamma p^0 \cdot q^0\, (1+Q)(\mathcal{P} - 1)$;

(15) $\mathcal{V}_E = \frac{1}{2}\, \gamma p^0 \cdot q^0\, (1+ \mathcal{P})(Q - 1)$

If P (in $\mathcal{P} \equiv P/\gamma$) and Q are replaced by superlative indexes,[20] such as the Fisher or Törnqvist, then the resulting indicators in (14) and (15) can also be called superlative. A corollary of Proposition 9 of Diewert (2005; 338) is that the Bennet indicator of quantity change approximates any superlative indicator to the second order at any point where the two quantity vectors are equal and where the two price vectors are equal.

The U.S. uses the superlative Fisher quantity index (the geometric mean of the Laspeyres and Paasche indexes given in section 2) for constructing real GDP, so we consider the following expression for the Fisher superlative quantity change indicator, $\mathcal{V}_E{}^F$:

(16) $\mathcal{V}_E{}^F \equiv \frac{1}{2}\, \gamma p^0 \cdot q^0\, (1+ \mathcal{P}^F)(Q^F - 1) \approx \frac{1}{2}(\, \gamma p^0 + p^1)\cdot(q^1 - q^0) = \mathcal{V}_B,$

where $\mathcal{P}^F \equiv P^F/\gamma$, where $P^F \equiv [(p^1 \cdot q^0/p^0 \cdot q^0)(p^1 \cdot q^1/p^0 \cdot q^1)]^{1/2}$ is the Fisher price index, or GDP deflator in our context, γ is one plus the growth rate of the CPI between periods 0 and 1, and $Q^F \equiv [(p^0 \cdot q^1/p^0 \cdot q^0)(p^1 \cdot q^1/p^1 \cdot q^0)]^{1/2}$ is the Fisher quantity index,

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[19] Diewert (2005; 333-337) derived these indicators in introducing the economic approach to indicators of price and quantity change, and called them "economic" indicators. Hence, the subscript "E" stands for "economic".

[20] See Diewert (1976) on superlative index numbers.

or real GDP growth in our context, and $\mathcal{V}_B$ is the Bennet quantity indicator where the price weights have been adjusted for general inflation.[21] Recall that the Bennet indicator of quantity change is the symmetric arithmetic average of first-order approximations to the Hicksian equivalent and compensating variations of equations (3) and (4). Alternatively, under the Diewert-Mizobuchi (2009) assumptions on the functional form for the consumer's cost function, the Bennet indicator is exactly equal to the arithmetic average of the equivalent and compensating variations. Hence, the Fisher superlative quantity change indicator, $\mathcal{V}_E^F$ in (16), can be interpreted as an approximation to a welfare change indicator, $\mathcal{V}_B$.

Re-arranging (16), we get an expression for an approximation to the Fisher quantity index:

$$(17) \quad Q^F \approx [(\gamma p^0 + p^1)\cdot(q^1 - q^0)]/[\ \gamma p^0\cdot q^0\ (1+\mathcal{P}^F)]\ +1$$

Note that the numerator is two times the Bennet variation, $\mathcal{V}_B$. Allowing for new goods, from (12) we have the following:

$$(18) \quad 2\mathcal{V}_B = 2\gamma p^0\cdot(q^1 - q^0) + (p^1 - \gamma p^0)\cdot(q^1 - q^0) + 2p_0{}^1 q_0{}^1 - (p_0{}^1 - \gamma p_0{}^{0*})q_0{}^1$$

Then replace the numerator in (17) with (18). If Q^F omits the new good in period 0, then the (approximate) amount missing from Q^F is $(\gamma p_0^{0*} - p_0^1)q_0^1/[\gamma p^0 \cdot q^0 (1+\mathscr{P}^F)]$, which can simply be added to Q^F if p_0^{0*} is known or can be estimated.[22]

Real GDP growth can then be adjusted, to a second-order approximation, for not fully capturing the introduction of a new good as follows:

(19) $\text{GDP-N} = Q^F + (\gamma p_0^{0*} - p_0^1)q_0^1/[\gamma p^0 \cdot q^0 (1+ \mathscr{P}^F))$

where GDP-N denotes GDP growth adjusted for the introduction new goods.

4.   The Free Goods Problem

Consider a household whose preferences over N market goods and M goods that are available to the household with no visible charge can be represented by the utility function $f(q, z)$ where $q \geq 0_N$ and $z \geq 0_M$ are vectors which represent the consumption of market goods and of free goods respectively. We assume that $f(q, z)$ is defined over the nonnegative orthant in R^{N+M} and has the following properties: (i) continuity, (ii) quasiconcave in q and y and (iii) $f(q, z)$ is increasing if all components of q increase and increasing if all components of z increase.

We define two cost or expenditure functions that are dual to f. The first cost function is the consumer's *regular cost function*, $C(u, p, w)$, that is the solution to the following cost minimization problem which assumes (hypothetically) that the

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[22] Note that this assumes that we are either able to adjust the GDP deflator, P^F, and the CPI, γ, for the price changes in new goods, or that such goods have negligible net impact on these inflation measures. This may depend on how these respective indexes have been constructed. See Diewert, Fox and Schreyer (2018) for expressions of biases in Laspeyres, Paasche, Törnqvist and Fisher indexes arising from not appropriately accounting for new and disappearing goods.

household faces positive prices for market and free goods so that $p \gg 0_N$ and $w \gg 0_M$ in (1):[23]

(20) $C(u, p, w) \equiv \min_{q, z} \{p \cdot q + w \cdot z: f(q, z) \geq u, q \geq 0_N, z \geq 0_M\}$.

We also define the household's *conditional cost function*, $c(u, p, z)$, which is the solution to the cost minimization problem defined by (21) below, where the household minimizes the cost of market goods needed to achieve utility level u, conditional on having the vector $z \geq 0_M$ of free goods at its disposal:

(21) $c(u, p, z) \equiv \min_{q} \{p \cdot q: f(q, z) \geq u, q \geq 0_N\}$.

It can be shown (using feasibility arguments) that $c(u, p, z)$ has the following properties where $u \in$ Range f, $p \gg 0_N$, and $z \geq 0_M$: (i) for fixed u and z, $c(u, p, z)$ is nonnegative and linearly homogeneous, concave and nondecreasing in p and (ii) for fixed u and p, $c(u, p, z)$ is nonincreasing and convex in z. If in addition, $f(q, z)$ is linearly homogeneous in q and z (the homothetic preferences case), then $c(u, p, z)$ is linearly homogeneous in u, z for fixed p.

If the household faced positive prices $w \gg 0_M$ for its "free" goods, then the regular cost function minimization problem defined by (20) could be decomposed into a two stage minimization problem using the conditional cost function c; i.e., we have, using definition (20):

(22) $C(u, p, w) \equiv \min_{q, z} \{p \cdot q + w \cdot z: f(q, z) \geq u; q \geq 0_N, z \geq 0_M\}$

$= \min_{z} \{c(u, p, z) + w \cdot z: z \geq 0_M\}$.

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[23] We assume u is in the range of $f(q, z)$.

Suppose $z^* \geq 0_M$ solves the cost minimization problem that is defined in the second line of (22) and suppose further that $c(u, p, z^*)$ is differentiable with respect to the components of z at $z = z^*$. Then the first order necessary conditions for z^* to solve the cost minimization problem imply that the following first order conditions hold:

(23) $\nabla_z c(u, p, z^*) = -w$.

With $z = z^*$, we can go to the cost minimization problem defined by (21) and find a q solution which we denote by q^*; i.e., q^* is a solution to:

(24) $\min_q \{p \cdot x: f(q, z^*) \geq u, q \geq 0_N\}$.

It can be seen that (q^*, z^*) is a solution to the regular cost minimization problem defined by (20) so that:

(25) $C(u, p, w) \equiv \min_{q, z} \{p \cdot q + w \cdot z: f(q, z) \geq u, q \geq 0_N, z \geq 0_M\}$
$\qquad = p \cdot q^* + w \cdot z^*$.

Thus the imputed marginal valuation prices $w \equiv -\nabla_z c(u, p, z^*) \geq 0_M$ are appropriate prices to use when valuing the services of free goods in order to construct cost of living indexes or measures of money metric utility change.

Note that due to the fact that $c(u, p, z)$ is decreasing and convex in the components of z, the marginal price for an additional unit of z_m, $w_m(u, p, z) \equiv$

$-\partial c(u, p, z)/\partial z_m$, will be nonincreasing in z_m; i.e., it will usually decrease as we add extra units of z_m to the household's holdings of free goods.[24]

We define "global" willingness to pay measures for free goods using the conditional cost function. Consider a household that holds no free goods, has utility $u^* = f(q^*, 0_M)$ where q^* is the observed market goods consumption vector and the household faces the vector of market goods prices p. We assume that the household minimizes the market cost of achieving its utility level so that $p \cdot q^* = c(u^*, p, 0_M)$. Now suppose that the household acquires the vector of free goods $z^* > 0_M$. Since $c(u^*, p, z)$ is decreasing in z, the amount of income that the household would require to attain the same level of utility u^* is reduced to $c(u^*, p, z^*) < c(u^*, p, 0_M)$. Thus in theory, the consumer should be willing to pay $c(u^*, p, 0_M) - c(u^*, p, z^*)$ to acquire the bundle of free goods z^*. Thus define the "global" *willingness to pay function* for the acquisition of z^* as follows:

(26) $W_P(u^*, p, z^*) \equiv c(u^*, p, 0_M) - c(u^*, p, z^*)$.

If the household holds the amount $z^{**} > 0_M$ of free goods, then we can develop an analogous willingness to accept measure as follows. Let q^{**} denote the household's observed market goods consumption vector and we again assume that the household faces the vector of market goods prices p. Let $u^{**} \equiv f(q^{**}, z^{**})$. We assume that the household minimizes the market cost of achieving its utility level u^{**} so that $p \cdot q^{**} = c(u^{**}, p, z^{**})$. Now suppose that the household disposes of its vector of free goods z^{**}. The amount of income that the household would require

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[24] If consumers can have the free good in unlimited amounts, then its price will be zero. However, even if the price is zero, if quality improves, the marginal willingness to pay for the improved quality will be positive, hence $w_m(u, p, z)$ will be greater than zero. We thank Marshall Reinsdorf for this point.

to attain the same level of utility u^{**} is increased to $c(u^{**}, p, 0_M) > c(u^{**}, z^{**})$. Thus in theory, the consumer should be willing to sell its free goods for the amount $c(u^{**}, p, 0_M) - c(u^{**}, z^{**})$, i.e. the amount that they would accept for giving up the free goods. Thus define the *"global" willingness to accept function*, for the disposal of z^{**} as follows:

(27) $W_A(u^{**}, p, z^{**}) \equiv c(u^{**}, p, 0_M) - c(u^{**}, p, z^{**})$.

For welfare measurement purposes, it is useful to define *marginal* willingness to accept functions. Thus let e_m be a unit vector of dimension M with a 1 in component m and zeros elsewhere for $m = 1,...,M$. Assume that the household holds $z \geq 1_M$ units of the free goods, faces market prices p, has $q > 0_N$ units of market goods and $p \cdot q = c(u, p, z)$ where $u = f(q, z)$. Define the *m^{th} marginal willingness to accept function*, $W_m(u, p, z)$ as follows:

(28) $W_m(u, p, z) \equiv c(u, p, z-e_m) - c(u, p, z)$; $m = 1,...,M$.

Survey, experimental or indirect methods can be used in order to obtain approximate measures for these marginal willingness to accept functions. Let $W(u, p, z)$ denote the vector $[W_1(u, p, z),...,W_M(u, p, z)]$. It can be seen that $W(u, p, z)$ is a discrete approximation to the marginal valuation price vector $w \equiv -\nabla_z c(u, p, z)$ that was defined earlier by (23).[25]

Assuming that we have valuations for the free goods, we can extend the Bennet welfare change variation of (12) to include these goods. Following the set up for

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[25] If $z_m = 0$, then we need to change the definition of $W_m(u, p, z) \equiv c(u, p, z-e_m) - c(u, p, z)$ to the corresponding marginal willingness to pay function, $W_m^{*}(u, p, z) \equiv c(u, p, z) - c(u, p, z+e_m)$.

regular goods in the previous section, let a new "free" good be indexed by the subscript 0 and let the N dimensional vectors of period t prices and quantities for the continuing goods be denoted by w^t and z^t for t = 0,1. The period 1 quantity of good 0 purchased during period 1 is also observed and is denoted by z_0^1. The period 0 reservation price for good 0 is not directly observed but we make an estimate for it, denoted as $w_0^{0*} > 0$. The period 0 quantity is observed and is equal to 0; i.e., $z_0^0 = 0$. Thus the price and quantity data (for the N+1 goods) for period 0 is represented by the 1+N dimensional vectors (w_0^{0*}, w^0) and $(0, z^0)$ and the price and quantity data for period 1 is represented by the 1+N dimensional vectors (w_0^1, w^1) and (z_0^1, z^1).

Then, in an extension of (12), welfare change including both new and free goods can be written as follows, where we again adjust period 0 prices by the one plus the growth rate of the CPI between periods 0 and 1, γ:

$$(29)\ V_B = \gamma p^0 \cdot (q^1 - q^0) + \tfrac{1}{2}(p^1 - \gamma p^0) \cdot (q^1 - q^0) + p_0^1 q_0^1 - \tfrac{1}{2}(p_0^1 - \gamma p_0^{0*}) q_0^1$$

$$+\ \gamma w^0 \cdot (z^1 - z^0) + \tfrac{1}{2}(w^1 - \gamma w^0) \cdot (z^1 - z^0) + w_0^1 z_0^1 - \tfrac{1}{2}(w_0^1 - \gamma w_0^{0*}) z_0^1,$$

where the second line gives the contribution of the continuing and entering "free" goods.

If the concern is that real GDP omits the contribution from continuing free goods, then we can use the results of the previous section and re-write (19) to adjust real GDP growth, Q^F, as follows to reflect the welfare effects of free goods:[26]

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[26] Welfare change in (29) should also be adjusted for general inflation, especially if inflation is high or if the periods being compared are far apart in time, and similarly for spatial comparisons.

(30) GDP-F = Q^F + $[2\gamma w^0 \cdot (z^1 - z^0) + (w^1 - \gamma w^0) \cdot (z^1 - z^0) + 2w_0{}^1 z_0{}^1]$/[$\gamma p^0 \cdot q^0$ (1+

$\mathscr{P}^F$)),

where GDP-F denotes GDP growth adjusted for free goods.[27]

Including both regular and free new goods, we get the following expression for our adjusted real GDP growth:

(31) GDP-B = Q^F + $(\gamma p_0{}^{0*} - p_0{}^1) q_0{}^1$/[$\gamma p^0 \cdot q^0$ (1+ $\mathscr{P}^F$)]

$\qquad\qquad\qquad$ + $[2\gamma w^0 \cdot (z^1 - z^0) + (w^1 - \gamma w^0) \cdot (z^1 - z^0) + 2\gamma w_0{}^1 z_0{}^1]$ /[$\gamma p^0 \cdot q^0$

$\qquad$ (1+ $\mathscr{P}^F$)]

$\qquad\qquad\qquad$ + $(\gamma w_0{}^{0*} - w_0{}^1) z_0{}^1$/[$\gamma p^0 \cdot q^0$ (1+ $\mathscr{P}^F$)),

where the first line of (31) is the adjustment arising from the entry of a new good, the second line is an additional contribution from accounting for continuing free goods, and the third line is the adjustment term arising from the entry of a new free good.[28] Thus GDP-B denotes GDP growth adjusted for new and free goods.[29] As GDP-B in (31) nests GDP-N from (19) and GDP-F from (3), we propose this as the generic term for these types of measures.

An alternative, simpler, approach to adjusting GDP for free goods is as follows. Using equation (25), we can define *total income* (T) as follows:

(32) T $\equiv$ C(u, p, w) = $p \cdot q^*$ + $w \cdot z^*$,

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[27] Note that this assumes that we are either able to adjust the GDP deflator, P^F, and the CPI, γ, for the price changes in continuing free goods, or that such goods have negligible net impact on these inflation measures.

[28] Obviously, (31) can easily be generalized to the case of multiple new regular and free goods.

[29] The "B" in GDP-B can be thought of as standing for the "benefits" arising from new and free goods, or "beyond", as in the literature promoting broader measures of economic wellbeing "beyond GDP".

where (q^*, z^*) is a solution to the cost minimization problem with positive prices w $\gg 0_M$ for the "free" goods. Hence, (32) gives the total income required so that a certain level of utility can be attained through the consumption of market and free goods. Then $w \cdot z^*$ is the amount a consumer should be willing to pay to acquire the bundle of free goods z^*; see the willingness to pay function of equation (26). Alternatively, $w \cdot z^*$ is the amount of income needed to compensate for giving up the consumption of free goods, while maintaining the same level of utility; see the willingness to accept function of equation (27). Deflating the resulting nominal total income growth between periods 0 and 1, T^1/T^0, by the GDP deflator, P, gives real total income growth, GDP-B$_T$:

(33) GDP-B$_T \equiv (T^1/T^0)/P$

The GDP deflator will typically be the wrong deflator, as it does not take into account new (and disappearing) goods, which would usually mean that the deflator is too high.[30] The resulting quantity index then provides a lower bound estimate on the actual real growth rate.[31]

This total income approach has the advantage of not needing the period 0 reservation price for any new good, as the quantity consumed of the good in this period is 0 so that $T^0 = p^0 \cdot q^0$.

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[30] This is because new goods typically fall in price after their introduction. Also, note that by using the GDP deflator here, there is an implicit assumption that an appropriate reservation price for the free good is the price observed in period 1 carried back to period 0. This is the carry-backward method discussed by Diewert, Fox and Schreyer (2018).

[31] Diewert, Fox and Schreyer (2019) have subsequently generalized this Total Income approach to consider non-free new goods. They show that, under some assumptions, the difference between GDP-B in (33) and standard GDP can be interpreted as the amount by which a maximum overlap quantity index (as typically calculated by national statistical offices) understates an approximate "true" Fisher index calculated using reservation prices for the new goods.

To summarize, GDP-B describes the extension of GDP to incorporate consumer benefits arising from digital goods, as measured through experiment evidence. Our first method (equation 31) uses this experimental evidence on consumer valuations to derive an extension of GDP which is consistent with standard Hicksian concepts of welfare change. Our second ("total income") method (equation 33) extends GDP by including the extra income needed to achieve the same level of utility without the digital goods as with the digital goods.

Just as our approach makes it possible to calculate GDP-B in a way that accounts for new and free goods, it is straightforward to calculate an alternative measure of labor productivity by dividing GDP-B by hours worked. To distinguish it from conventionally-measured productivity, one can label this new metric *Productivity-B*.

5. Empirical Examples of GDP-B Applied to Free Digital Goods

In this section we apply our methodology to study the welfare gains generated by free digital goods. First, we consider the case of Facebook, using online choice experiments to elicit user valuations. Then we consider the valuation of a broader range of digital goods, using laboratory experiments in the Netherlands.

a) Valuing Facebook in the US

To estimate the consumer welfare created by Facebook, we conducted incentive compatible discrete choice experiments on a representative sample of the US internet population. Specifically, we set quotas for gender, age, and US regions to match US census data (File and Ryan 2014) and applied post-stratification for education and household income to obtain our sample. Because our focus is on Facebook users, we disqualified participants who did not use Facebook in the

previous twelve months (but we can account for the overall number of Facebook users using secondary data).

In the experiment, each participant was asked to make a single discrete choice between two options: 1) keep access to Facebook or 2) give up Facebook for one month and get paid $E. We allocated participants randomly to one of twelve price points: E = (1, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 1000). Before participants made the decision, we informed them that their decisions were consequential such that we would randomly pick one out of every 200 participants and fulfil that person's selection (Ding, Grewal and Liechty 2005; Ding 2007; Carson, Groves and List 2014). We also informed them about how we can monitor their Facebook online status remotely. In order to check if the selected participants gave up Facebook and qualified for the payment, we monitored their online status on Facebook for 30 days.[32]

We recruited respondents through an online professional panel provider, Research Now,[33] during the year 2016-17.[34] A total of 2885 participants completed the study including at least 200 participants per price point. We targeted consumers that were 18 years or older and lived in the US. We further asked consumers to select all online services they have used in the last twelve months from a list of 14 options, including a non-existent online service which we used as an attention check. We selected Facebook users for this study and disqualified users who selected the non-existent service. Participants were randomly allocated to one of

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[32] It is possible to remotely monitor when someone is last logged in on Facebook for any friend on Facebook.

[33] https://www.researchnow.com/

[34] These experiments are also reported in Brynjolfsson, Collis and Eggers (2019). In this paper, we combine the studies conducted in summer 2016 and summer 2017 to come up with estimates for the year 2016-17.

the price points and we combine responses from all participants to estimate the demand curve.

We fitted a binary logit model to the participants' decisions using the monetary values (in log scale) as predictors. Figure 1 shows the observed shares of participants willing to keep Facebook and the fitted line according to the logit model. According to the model, the median willingness-to-accept (WTA) price for giving up Facebook for one month is $42.17 (bootstrapped 95% confidence interval = [$32.53; 54.47]).[35]

Next, we provide an empirical illustration of the theoretical framework for free goods provided in Section 4. We consider the period from 2003 to 2017; Facebook was founded in 2003-04 and hence became a new free good that year. In our notation of the previous section, 2003 is then period 0 and 2017 is period 1. Assuming a simple linear relationship, the median WTA for Facebook in 2017 ($42.17/month), translates to ($w_0^1=$) $506.04/year ([390.36; 653.64]).[36] Note that this is price for giving up the 2017 version of Facebook, which includes all its attributes at the time, including the number of users, or size of the social network. We also need to determine the reservation price for Facebook in 2003 (w_0^{0*}); recall that the reservation price is the price which would induce a utility maximizing potential purchaser of a good to demand zero units of it. Here the good which is having its demand reduced to zero is the 2017 version of Facebook.

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[35] This "willingness to accept" price corresponds to the global willingness to accept function in equation (27) of Section 4. That is, it is the income needed in compensation for giving up the free good if the same utility level is to be maintained.

[36] Brynjolfsson et al. (2019), find that the relationship between valuation and time period is roughly log-linear and not linear, i.e. valuation for 1 year is a less than 12 times valuation for 1 month. Using hypothetical choice experiments, we find that it is closer to 10 times the valuation for 1 month. Here we assume a linear relationship for simplicity since it is not feasible to do a one-year incentive compatible study for Facebook.

Following Hausman (1996), we could consider a reservation price of twice the median WTA (deflated to 2003 dollars); the reservation price for before the 2004 launch of Facebook is a then ($w_0^{0*}= 2w_0^1/\gamma \approx$) \$780. This is likely to be a very conservative estimate. Note that the observed demand curve in Figure 1 reflects a much higher reservation price. In fact, there is a significant portion of the sample (>20%) which values Facebook at more than \$1,000 per month. Apple-Cinnamon Cheerios, the product considered by Hausman, can be regarded as quite different to Facebook; it is a new variety of breakfast cereal with plenty of close substitutes, whereas Facebook can be characterized as a novel product.[37] In contrast to the low reservation price from applying Hausman's estimate, the approach of Feenstra (1994) uses a CES framework which requires that all reservation prices are infinity. This seems unreasonably high in our context.[38]

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[37] Reinsdorf and Schreyer (2017, p. 5) note the following regarding the consequences for consumer price inflation of delaying the price measurement of such products: "…novel products may initially exhibit distinctive price change behaviour. The most common pattern is for prices of truly novel products to decline quickly at first, so the bias is upward."

[38] "Thus the CES methodology may overstate the benefits of increases in product availability." Diewert and Feenstra (2017, p.3).

Figure 1: WTA demand curve for Facebook
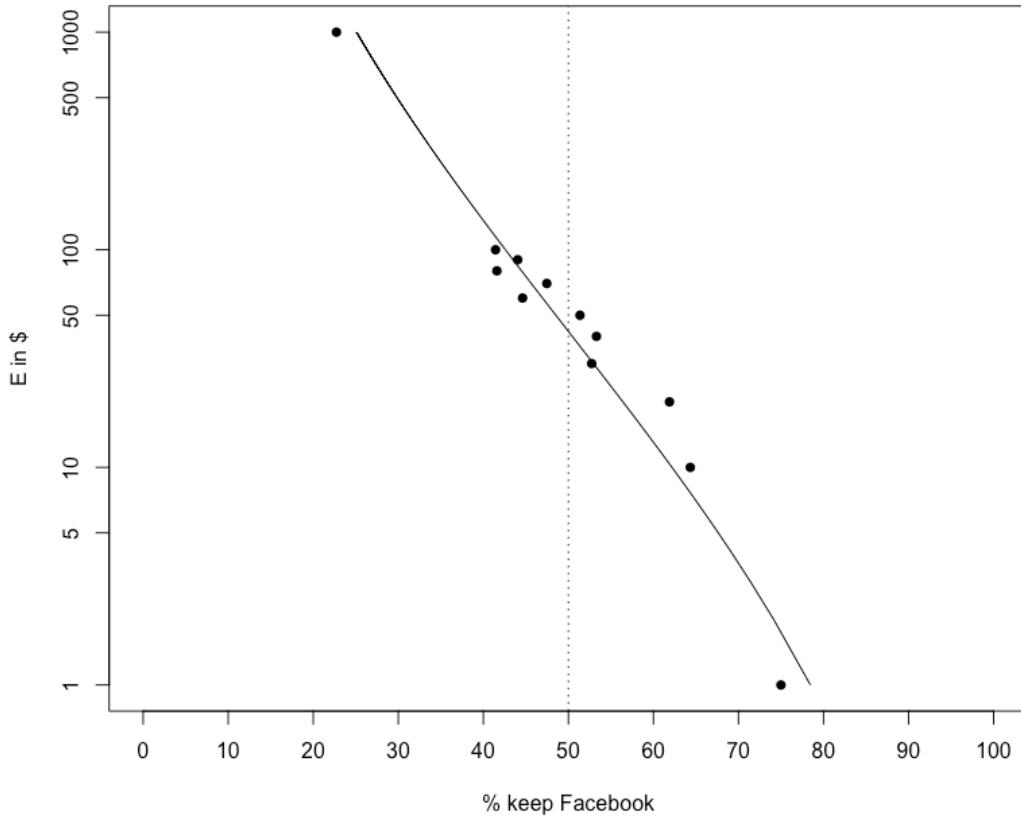
Hence, we focus on an alternative approach and estimate the intercept term in a linear regression of WTA on the corresponding share of users who keep Facebook, as plotted in Figure 1; this is the estimate of the monthly WTA that gives a share of zero. Our estimate is from a regression that omits the two extreme observations, for E = \$1 and E = \$1,000 (p-value = 0.0000, R^2=0.88).[39] At extreme values, even a small number of noisy responses will disproportionately affect the reservation

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[39] We also estimated a regression using all observations. This resulted in a poorer fit (p-value = 0.0038, R^2=0.52) and a much higher estimate of the reservation price (\$8,126 in 2003\$). Using this higher estimate, we would find that the contribution to welfare change over the period 2003-17 is \$1,013 billion (in 2017\$) which translates to an average of \$72 billion per year. Per user, the welfare change over the period 2003-17 is \$5,018 which translates to \$358.48 on average per year.

price. Multiplying the estimate by twelve yields the 2017 annual reservation price and deflating, using the CPI, yields the reservation price in 2003 dollars. Using this approach, we estimate the reservation price (w_0^{0*}) to be \$2,152 in 2003 dollars.

The estimated contribution to welfare due to Facebook in the U.S. over the period 2003-17 is \$231 billion (in 2017\$) which translates to \$16 billion on average per year.[40] The per user welfare gain over the period 2003-17 is \$1,143. Considering that this is a single new service, this estimate is substantial.[41] At the same time, given that the definition of users is that they access their Facebook account via any device at least once per month and the average user is Facebook for more than 40 minutes per day,[42] then this estimate does not seem excessive.

Next we turn to GDP-B growth to get an idea of the change that would result from extending the usual definition of GDP to include a free service such as Facebook. From the last line of equation (31) of Section 4, we have the following:

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[40] Notes:

w_0^1 = \$506.04 (95% C.I.: [390.36; 653.64])

γ = 1 + Growth rate of CPI = 1.3

Number of Facebook users in US in 2017 = 202 million

Data sources:

Chained CPI-All Urban Consumers, not seasonally adjusted, index for December 2003 to December 2017 is 1.2975, or 29.75%. https://www.bls.gov/cpi/data.htm

Internet users who access their Facebook account via any device at least once per month. https://www.statista.com/statistics/408971/number-of-us-facebook-users/

[41] Note that we are not accumulating benefits from the years in between 2003 and 2017. We are simply comparing the welfare change between two periods: 2003 when Facebook did not exist and 2017 when the 2017 version existed. The comparison between these two years, as opposed to any of the intervening years, is of interest as there was no close substitute to any subsequent version of Facebook in 2003. In the intervening years, if each version of Facebook, with increasing network size, is treated as a new good then we would need to also model the impact of the exiting versions of Facebook. We do not have the valuations required to do such a study.

[42] See https://www.emarketer.com/Chart/Average-Time-Spent-per-Day-with-Facebook-Instagram-Snapchat-by-US-Adult-Users-of-Each-Platform-2014-2019-minutes/211521

Adjustment to real GDP-B growth from accounting for Facebook over 2003-2017

$$= (\gamma w_0^{0*} - w_0^1)z_0^1/[\gamma p^0 \cdot q^0 (1+ \mathscr{P}^F)]$$

$$= (\gamma w_0^{0*} - w_0^1) \text{ x No. of Facebook users in US in 2017} / \gamma(\text{Nominal GDP in 2003})(1+ \mathscr{P}^F)$$

The GDP adjustment is a lower bound on the amount to add to GDP-B growth using this approach because we use official estimates of γ and P^F (which are unadjusted for the introduction of new goods) in the denominator. Normally, γ and P^F would be lower if we account for the fact that the price of the new goods typically fall following their introduction.[43]

From Table 1, for the reservation price of $w_0^{0*} = \$2,152$ in 2003, accounting for Facebook would increase real GDP-B growth by 1.54 percentage points from 2003 to 2017 (or, using the 95% CI estimates of w_0^1: [1.44, 1.62]). In other words, this amounts to an increase in real GDP-B growth of 0.11 percentage points on average per year over this period and an identical increase in Productivity-B. Real GDP grew by 28.82% and real GDP-B grew by 29.16% including the contribution from Facebook. Average real GDP growth over this period was 1.83% per year. Adding the contribution of Facebook means that GDP-B grew by 1.91% per year.[44] Considering that this is for just one product, including the benefits from Facebook results in a large impact on such an encompassing measure of economic activity as GDP-B and productivity-B.

Table 1: GDP-B Contributions, Facebook

	Total Income	Reservation Price

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[43] See Diewert, Fox and Schreyer (2018) and Reinsdorf and Schreyer (2017).
[44] The corresponding growth estimate from using the reservation price estimated using all observations ($8,126) is 2.20% per year on average.

Reservation Price w_0^{0*}, 2003$	—	$2,152
Percentage Points, 2003-2017	0.68	1.54
Per year	0.05	0.11
GDP-B Growth per year without Facebook (i.e. GDP growth)	1.83	1.83
GDP-B Growth per year with Facebook	1.87	1.91

Notes: w_0^1 = $506.04 (95% C.I.: [390.36; 653.64]), γ = 1 + Growth rate of CPI = 1.3, P^F = 1+ Growth rate of GDP Deflator[45] = 1.31, $\mathscr{P}^F$ = P^F/γ = 1.0078, Number of Facebook users in US in 2017 = 202 million, Nominal GDP for 2003[46] = $11.5 trillion; The reservation price is 12 times the intercept from a linear regression of monthly WTA on the corresponding share of users who keep Facebook, dropping the observations for the two extreme observations, E=$1 and E=$1000 (p-value = 0.0000, R^2=0.88). "Per year" estimates are calculated using the arithmetic mean of the percentage point difference over the period. "Growth per year" estimates are calculated using geometric means.

Next we consider the total income approach of equation (33) in Section 4. We need the total nominal income (T) for both 2003 and 2017, which we calculate as follows:

T^0 = nominal GDP in 2003 + $w_0^{0*}z_0^0$ = $11.51 trillion + 0 ≈ $11.51 trillion

T^1 = nominal GDP in 2017 + $w_0^1z_0^0$ = $19.39 trillion + $506.04 x No. of Facebook users in US in 2017 ≈ $19.49 trillion.

That is, total nominal income using GDP-B$_T$ is higher by $102 billion in 2017 since the value of Facebook to consumers is taken into account. Recall, from Section 4, that this can be interpreted as the amount that consumers in aggregate would need in compensation in order to attain the same level of utility if access to Facebook foregone in 2017. This is for the 2017 version of Facebook, including

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[45] GDP Implicit Price Deflator, annual, not seasonally adjusted, 2010=100: Growth for 2003 to 2017 = 112.05/85.69 = 1.31. https://fred.stlouisfed.org/series/USAGDPDEFAISMEI
[46] Gross Domestic Product, annual, not seasonally adjusted: https://fred.stlouisfed.org/series/GDPA. The beginning of year value for a 2004 product launch is the GDP of 2003.

all its characteristics, such as the size of the network. Hence, the result is independent of the changes in the characteristics of Facebook over the intervening years since its launch.

From equation (33), in our case GDP-B$_T$ = $(T^1/T^0)/P^F$ = $(19.49/11.51)/1.31$ ≈ 1.295. Thus GDP-B grew by 29.50% between 2003 and 2017 using the total income approach, whereas conventionally-measured real GDP grew by 28.82%, giving a percentage point difference of 0.68 over the entire period, or 0.05 per year on average.[47]

Compared with conventionally-measured real GDP growth of 1.83%, our estimates of average GDP-B growth per year range from 1.87% for the total income approach to 1.91% for the approach using our estimate of the reservation price.

b) Valuing Free Digital Goods Using Participants in a Laboratory

We conducted similar incentive compatible discrete choice experiments in a university laboratory in the Netherlands in order to evaluate additional free digital services.[48] While the online status on Facebook can be monitored remotely to make sure that participants did not use this service, other digital goods do not offer this functionality so that we needed another approach to make the decisions consequential. For services that require a password-protected login, we informed the participants that, if selected, they will have to change the password to a computer-generated code that would be kept in a sealed envelope afterwards. If

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[47] Recall that this is can be thought of as an underestimate of the additional growth from using GDP-B, as the deflator is not adjusted for the impact of new goods prices.
[48] These valuations are also reported in Brynjolfsson, Collis and Eggers (2019).

the seal was still intact and the password remained valid (not reset), we concluded that the participant in fact did not use this service. Additionally, we informed that we would check the usage statistics of the apps on the selected participants' devices. Therefore the laboratory setting was necessary in order to be able to contact participants in person after the study and make their decisions consequential.

We tested the valuation of the services Instagram, Snapchat, Skype, WhatsApp, digital Maps, Linkedin, Twitter as well as Facebook. We varied the monetary amount that we offered to participants to leave these services for one month within the range of €1 to €500. The respondents had to make decisions regarding each of these services, i.e., each respondent had to make eight decisions. One out of every fifty participants who completed the study got the chance to have their decision fulfilled. The specific service was determined randomly in this case.

The data collection took place at a large Dutch university in February and October 2017. Overall, 426 participants were available for the analysis, meaning that there were over 400 decisions for each digital service. The resulting estimated demand curves are given in Figure 2. The corresponding median WTA valuations and confidence intervals are given in Table 2.

We observe very high valuations for WhatsApp which all of the participants were using. No one was willing to give it up for €1, and the relative insensitivity of demand to price resulted in an estimated monthly median WTA of €535.73, far higher than for the other services. We interviewed participants after the study period to better understand these high valuations. They told us that WhatsApp had become a nearly indispensable focal platform for communicating with peers, co-workers and others in their community, leading to enormous disutility from lack

of access.[49] Of course, the disutility for an individual would likely be much less if all members of the community could coordinate on switching to an alternative communications platform and the values should be interpreted accordingly. Such network effects are observed with many other goods as well, and do not mean that the valuations should be discounted but it may affect the value of other substitute goods.[50] Hence, the net contribution to welfare should account for changes in both the value on the focal good, and such substitutes.

Facebook was used by almost all of the participants and had the next highest median WTA monthly valuation of around €100. The valuation for Facebook in this sample was thus significantly higher than that found for the US in the previous section ($42.17 ≈ €34.76). Maps (including Google, Bing, and Apple maps) were also highly valued, with WTA median values of almost €60 per month, followed by Instagram, Snapchat and LinkedIn.

For Skype and Twitter, we found very low median valuations of less than €1. Although 71% of the participants were using Skype, the majority were willing to give it up for one month for just €1, likely because other services offered very similar (video) calling possibilities and was not frequently used. Note that although Skype effectively provides access to a portion of the same network for 71% of sample, the valuation is massively different; €535.73 for WhatsApp and

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[49] Some quotes from our interviews: 1. "Whatapp is the only communication tool I use to contact my friends here. Without it, I can do nothing." 2. "WhatsApp is crucial. I use the app every hour of the day to keep in touch with friends and family but also to discuss group projects or things about my work. I really need to keep access to this app. There is also not a very suitable alternative."

[50] The fact that most people now use telephones to communicate rather than telegrams does not mean that the price people are prepared to pay for calls should be discounted in any way. That said, the value is partly due to network effects and partly due to intrinsic differences between the two goods.

€0.18 for Skype. This suggests that it is not simply a valuation of the network that is being captured.

Twitter is only used by 33% of the sample which explains the low value for the median user, i.e., the utility maximizing strategy for those who do not use Twitter is, of course, to accept any money that was offered, and this encompasses the majority of users in our sample.

These WTA estimates are converted to annual figures by simply multiplying by twelve to get the annual estimates, as per the previous section, and these figures are then used to calculate annual GDP-B growth for the Netherlands. We use the total income method of equation (33), and hence avoid having to estimate a reservation price for each good. The results are reported in Table 3.[51] Since our sample for these laboratory experiments is not representative of the national population of Netherlands, we provide these figures solely to gauge the approximate magnitude of potential underestimation in welfare inferred from conventional GDP growth figures from not accounting for popular free digital services.

Figure 2: WTA demand curves for popular digital goods measured in a laboratory

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[51] The welfare change estimates are available from the authors on request.
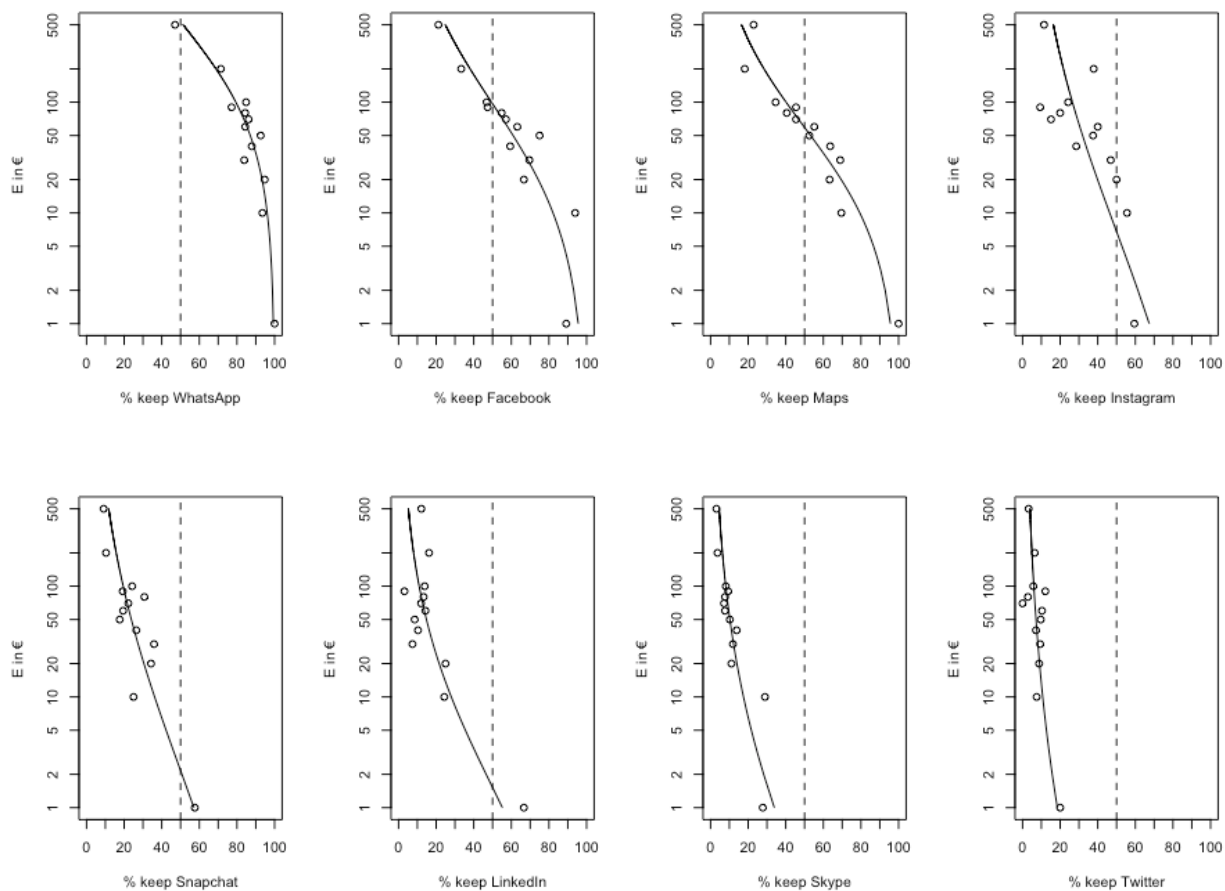
Table 2: Median Monthly WTA

Service	Launch Date	Median WTA	Lower CI	Upper CI
WhatsApp	January 2009	€535.73	€269.91	€1141.42
Facebook	February 2004	€96.80	€69.54	€136.68
Maps	February 2005	€59.16	€45.17	€78.31
Instagram	October 2010	€6.79	€2.53	€16.22
Snapchat	September 2011	€2.17	€0.41	€8.81

LinkedIn	May 2003	€1.52	€0.30	€5.84
Skype	August 2003	€0.18	€0.01	€2.58
Twitter	March 2006	€0.00	€0.00	€0.49

Table 3: Estimates of gross contributions of popular digital goods to real GDP-B growth in the Netherlands, percentage points, Total Income Method

Users	Average per year 10 million	Average per year 2 million
Service		
WhatsApp	4.10	0.82
Facebook	0.5	0.11
Maps	0.34	0.07
Instagram	0.07	0.01
Snapchat	0.02	0.00
LinkedIn	0.01	0.00
Skype	0.00	0.00
Twitter	0.00	0.00

Notes: Two alternative user populations are considered, 10 million and 2 million. The population in July 2017 was approximately 17 million, with around 2 million in the 15-24 age group (https://www.indexmundi.com/netherlands/demographics_profile.html), which is the age group of our laboratory sample. In January 2016, WhatsApp had 9.8 million (https://nltimes.nl/2016/01/25/dutch-people-leaving-twitter-en-masse-use-whatsapp-facebook). Quarterly data are used.[52] For products launched in the first half of the year, the period 0 values are taken to be those from quarter 4 of the preceding year. For products launched in the second half of the year, period 0 values are taken to be those of quarter 4 of the launch year. Per year estimates are calculated using arithmetic means of the percentage point difference in growth over the period that the respective goods were available.

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[52] CPI: https://fred.stlouisfed.org/series/NLDCPIALLMINMEI;
Real GDP: https://fred.stlouisfed.org/series/CLVMNACNSAB1GQNL;
Nominal GDP: https://fred.stlouisfed.org/series/CPMNACNSAB1GQNL
The GDP Implicit Price Deflator is calculated as the ratio of the nominal GDP series divided by the real GDP series. This is because the official deflator series is annual (an average over the four quarters of each year), and we need to ensure that price times quantity equals value.

From Table 3 we can see that WhatsApp, Facebook and digital maps contribute significantly towards GDP-B growth and hence conventional GDP estimates miss a great deal of value by not accounting for these goods. According to our estimates, if WhatsApp is used by only 2 million people in the Netherlands (the approximate population in the 15-24 years old age group in 2017 and the age group of our laboratory sample), its gross contribution to GDP growth over 2003 to 2017 would be 0.82 percentage points per year. This is large, especially when considering that (i) this is just one digital good, and (ii) that the actual using population of WhatsApp is likely to be much larger than 2 million. The actual Dutch number of users has been reported to be closer to 10 million, for both WhatsApp and Facebook.[53]

Hence, in Table 3 we report also report results for a user population of 10 million and find that, if accounted for, the annual average gross contribution of WhatsApp to GDP-B growth would have been a substantial 4.10 percentage points according to the total income method. It is important to note that if WhatsApp partially replaces conventional telephone calls and texting, then the traditional GDP captures the fall in disappearing value of these telephone services but misses the gains from WhatsApp. In contrast, the adjustment term to GDP-B growth due to WhatsApp could be very high because it captures these benefits from the introduction of WhatsApp relative to the counterfactual of lower valued telephone services.[54] This problem of GDP not reflecting benefits from free goods could

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[53] According to an NL Times story on January 25 2016, "Whatsapp is the largest social network in the Netherlands with 9.8 million users. Facebook came in second place with 9.6 million...." https://nltimes.nl/2016/01/25/dutch-people-leaving-twitter-en-masse-use-whatsapp-facebook. Given definitional uncertainty about what constitutes a "user", and the potential for rapid change in user numbers, we consider potential bounds of 2 million to 10 million users out of a population of 17 million.

[54] In other words, in an alternative world without WhatsApp, the counterfactual GDP-B would drop by somewhat less than our estimate because users would probably have relatively higher valuations for telephone services.

become increasingly severe as more and more free digital goods are used as substitutes for traditional paid goods, such as Wikipedia replacing encyclopedias and various smartphone apps replacing a variety of traditional goods.

6. Applying GDP-B to adjusting for new features in smartphone cameras

Smartphone cameras are now the primary devices for taking photos. From the 1997 to 2017, the dominant photographic technology shifted from analog cameras to digital cameras to smartphone cameras. The total number of digital cameras shipped worldwide dropped from 121 million units in 2010 to 24 million units in 2016,[55] while worldwide smartphone sales increased from 297 million in 2010[56] to 1.5 billion in 2016.[57] Moreover, the marginal cost of taking a photo has fallen to approximately zero with smartphones, compared with up to 50 cents per photo for developing film in the analog era. Just between 2010 and 2017, the number of photos taken worldwide has increased from 350 billion to an estimated 2.5 trillion.[58] Furthermore, a photo taken on a smartphone today is typically superior to a photo taken on an average camera twenty years ago, including its ability to be stored, shared or repurposed far more easily.

To illustrate the problem this change creates, we consider a simple case of two goods, each available in two periods: a digital camera and a feature phone[59] in period 0, and a smartphone with a digital camera in period 1.[60] Suppose that the value of the camera to the consumer is v_c, the value of the simple feature phone is

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[55] http://www.cipa.jp/stats/dc_e.html

[56] http://www.gartner.com/newsroom/id/1543014

[57] http://www.gartner.com/newsroom/id/3609817

[58] https://www.nytimes.com/2015/07/23/arts/international/photos-photos-everywhere.html

[59] A feature phone is a phone defined as a phone with no camera for the purposes of this example.

[60] We thank Hal Varian for sharing his notes on GDP and welfare which contained a version of this example.

v_f, and the value of the smartphone is $v_c + v_f$. Assume that a device fully depreciates in a time period, i.e., a consumer has to purchase new devices each period. Also assume that a consumer buys both the camera and the feature phone in period 0 and only the smartphone in period 1, and there are a total of x such consumers. Suppose that the price of the camera is p_c in period 0, the price of the feature phone is p_f in period 0, and the price of the smartphone is also p_f in period 1. Then we have the following consumer surplus measures, CS^0 and CS^1, for periods 0 and 1, respectively:

(34) $CS^0 = (v_c - p_c)x + (v_f - p_f)x \geq 0,$

(35) $CS^1 = (v_c + v_f - p_f)x \geq 0.$

Then the change in consumer surplus between periods 0 and 1 is $CS^1 - CS^0 = p_c x$. This is the cost saving of not buying the digital camera in period 1 because its functionality is now included in the smartphone. However, the contribution of these goods towards conventionally-measured GDP (i.e., the market price of final goods) is $(p_c + p_f)x$ in period 0 but only $p_f x$ in period 1. Hence the change in conventionally-measured GDP from period 0 to period 1 is $-p_c x$, which is exactly the opposite of the change in consumer surplus. Therefore, while conventionally-measured GDP goes down due to people not purchasing the digital camera, consumer surplus and GDP-B go up. The measured decrease in conventional GDP occurs because, even though it has the same market price (p_f) as the feature phone in this example, the smartphone is a higher quality product. That is, there is an implicit fall in price in shifting from the feature phone to the smartphone which is not being captured.

Hence, it is clear that GDP statistics should account for quality improvements in smartphones, including the introduction and improvements in smartphone

cameras. While GDP-B does this, until January 2018, the BLS only incorporated quality adjustments for data plans offered by mobile network operators in the CPI.[61] Starting from January 2018, there is now quality adjustment of the CPI for telephone hardware, calculators and other consumer information items using hedonic modelling of the value of characteristics;[62] this is used by the Bureau of Economic Analysis (BEA) to deflate Personal Consumption Expenditures for telephone and facsimile equipment in constructing real GDP; see BEA (2014, Chapter 5, Table 5.A). Therefore, even though GDP statistics capture paid goods such as smartphones, they have failed for many years to completely capture quality adjustments in the US, and most countries still do not make any quality adjusts for smartphones; see e.g. Wells and Restieaux (2014, Table 1). Even when they do attempt to adjust for quality improvements, Groshen et al. (2017) state that hedonic techniques are not suitable for products such as smartphones when the set of relevant characteristics frequently change. [63] Note that quality improvements, such as the addition of a camera feature to a smartphone, can also be thought of as additions of new goods as described in our framework.

To demonstrate the importance of quality change as can be captured by GDP-B, we elicit the value generated of smartphone cameras for participants in a university laboratory in the Netherlands and compare that with the approximate price paid for them.

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[61] https://www.bls.gov/cpi/factsheets/telephone-services.htm

[62] The methodology and characteristics used for the hedonic modelling are currently not published. https://www.bls.gov/cpi/factsheets/telephone-hardware.htm

[63] If we consider software features (including operating system and various apps) as part of the set of relevant characteristics for hedonic quality adjustments, then it is impossible to perform hedonic modelling because firms do A/B testing continuously and seek to improve these features as frequently as daily.

Specifically, we applied an incentive compatible BDM lottery (Becker, DeGroot, and Marschak 1964) in order to estimate the consumers' valuation of their smartphone camera. We asked participants to state the minimum amount of money they would request in order to give up their smartphone camera (both main camera and front camera) for one month. Participants were informed that this amount would serve as a bid in a lottery. If their minimum bid to forego their camera would be higher than a random price, drawn from a uniform distribution, they could keep access to their smartphone camera but would not receive any cash. If the random price exceeded their minimum requested amount, they would be paid the random price, provided that they would give up using the smartphone camera for one month. The utility-maximizing strategy of the participants in the BDM lottery is to provide a bid that matches their true valuation. Accordingly, we use the bids as measures of WTA to give up smartphone cameras.

In order to induce incentive compatibility and make the answers consequential, we provided further information that one out of fifty participants would be selected for the lottery and that if their bid was successful we would block their smartphone cameras with a special sealing tape (see Figure 3). The sealing tape would break if the participants tried to peel it off so that it was not possible to re-apply it. We also signed the tape so that it was not possible to buy the same type of seal and re-apply a seal. If, after the one month period, the seal was still intact participants were rewarded with the money and the seal could be removed.

The study was conducted in the laboratory of a large Dutch university in November/December 2017 (to not cover the holiday season, respondents were allowed to postpone giving up their camera until January 2018). In total, 213 students participated.

**Figure 3: Sealed smartphone camera (intact and broken)**

The sample was relatively balanced in terms of gender (54.5% were female) and represented the student population in terms of age (87.8% were between 18 and 24 years old). Participants reported that they use their smartphone cameras frequently and take, on average, 21.7 pictures (median = 10) and 2.3 videos (median = 1) per week. For 59% of the participants the smartphone camera is the only camera they possess. Only 16.4% own a separate point-and-shoot camera, and 18.8% a DSLR camera.

Directly eliciting monetary values in a survey leads to the observation of price thresholds, i.e., certain values that are stated more frequently. In our results, we observe that the bids 40, 50, 100, 150, 200 were each entered by more than 5% of the sample. The median bid that was given for the smartphone camera was €100. However, this median bid does not account for the price thresholds in the demand function. For example, the bids imply that 41% of the students would not give up their smartphone camera for €100, but 54% would at €100.01. To smooth the demand function, we therefore fitted a (multiplicative) function to the observed

shares of students willing to accept the offer. This function explains 87.7% of the variation in demand and is depicted in Figure 4.

According to the fitted values, the median WTA for giving up the smartphone camera for one month is €68.13, albeit having a wide confidence interval (95%-CI = [€33.53; €136.78]). This implies a median annual WTA of over €800 for smartphone cameras, at least for the students in our sample, a value that is not captured in conventional GDP statistics.

Figure 4: Demand function for the smartphone camera
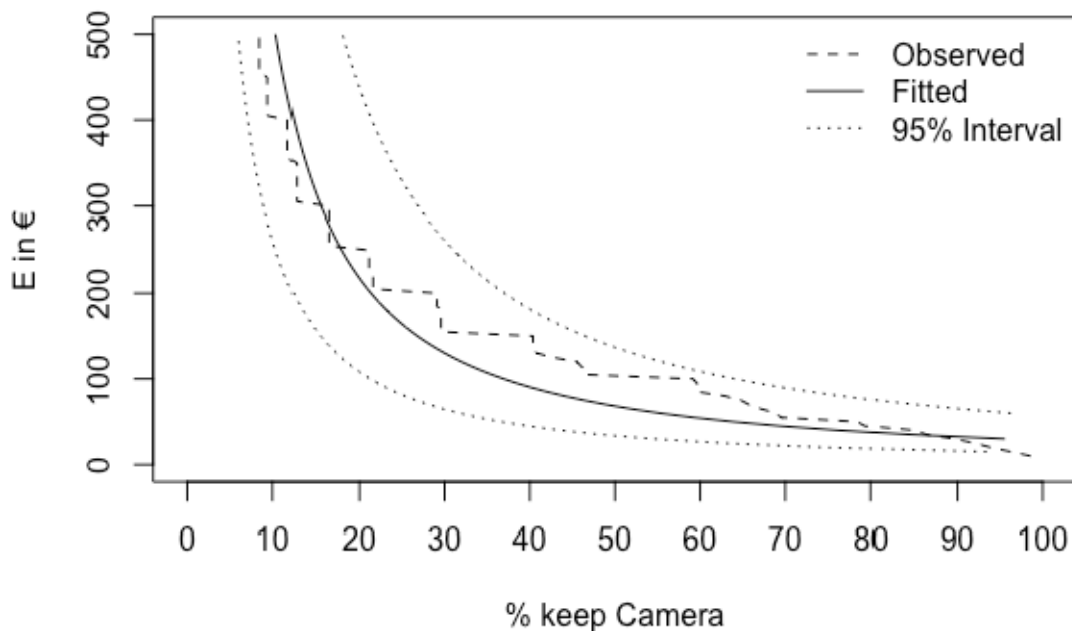
Analysts have estimated that it costs $20-$35 to manufacture the smartphone cameras present in current flagship models.[64] Similarly, a modular smartphone

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[64] E.g. http://www.techinsights.com/about-techinsights/overview/blog/cost-comparison-huawei-mate-10-iphone-8-samsung-galaxy-s8/, https://technology.ihs.com/595738/ihs-markit-teardown-reveals-what-higher-apple-iphone-8-plus-cost-actually-buys

sold in the Netherlands can add front and back cameras for an additional charge to consumers of €70.[65] This study provides strong evidence that consumers obtain a significant amount of surplus from using their smartphone cameras and this surplus is an order of magnitude larger than what they actually pay.[66] Hence, there has been a large implicit price decline arising from quality change; the services received from the smartphone have increased due to quality change but this is not reflected in the measured price. Therefore, even for paid goods such as smartphones, it is crucial to adjust for quality improvements before estimating GDP statistics. This might not be an issue if consumers derived an equally large surplus from what they actually paid for while using digital or analog cameras previously. However it is hard to reconcile this hypothesis with advancements in smartphone cameras and the reduction in costs of taking photos.

We can use our total income approach for GDP-B in equation (33), which does not require calculation of a reservation price for the good in the period before it appears, to calculate an estimate of the contribution of accounting for value of the smartphone camera to consumers; we estimate an average contribution of 0.62 percentage points per year to GDP-B.[67]

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[65] https://shop.fairphone.com/en/spare-parts (accessed January 2018)

[66] Of course, in a competitive market, most of the benefits from innovation go to consumers, not producers (Nordhaus, 2004)

[67] This is the arithmetic percentage point difference between the growth in GDP-B and official real GDP growth. It is calculated by assuming the following: (i) Smartphones with cameras appeared from July 2008, the date of the launch of the first iPhone in the Netherlands. Consistent with Table 3, period 0 is then taken to be Q4 of 2008. (ii) Based on EuroStat survey information on individuals who used a mobile or smartphone to access the internet (https://www.cbs.nl/en-gb/news/2018/05/the-netherlands-leads-europe-in-internet-access), the number of users of smartphones in 2017 was estimated to be 84% of the population of the Netherlands of age 15 and above (constituting 83.6% of the population). With a total population of 17 million this translates to approximately 12 million users in 2017. (iii) The annual median WTA is €817.56, and this is taken as the appropriate price for valuing the smartphone cameras; the purchase price of the camera component of the phone is assumed to be very small, so is treated as approximating zero for simplicity. With these assumptions, total income can be calculated for 2017 as nominal GDP plus the value of the smartphone cameras. The total income quantity index between the end of

7. Conclusion

This paper has developed a framework for measuring welfare change when there are new and free goods. This leads to a new measure, GDP-B, as well as its nested components, GDP-N and GDP-F. These measures provide a means by which to understand the potential mismeasurement that arises from not fully accounting for goods which are new, free or both new and free. This is of increasing relevance in the modern digital economy given the frequent introduction of new goods and growing presence of free goods.

Appropriately, we drew on both old and new literatures to define a framework for measuring welfare change. We were able to use this framework to derive an explicit term that is the marginal value of a new good on welfare change. That is, we get a measure of the contribution to welfare of a new good, and hence the extent of welfare change mismeasurement if it is omitted from statistical agency collections that rely on conventional measures of GDP and productivity.

We also showed how to use GDP-B to derive an estimate of the addition to real GDP growth that would be required to account for the welfare gains from the introduction of a new good, without having to recalculate GDP numbers published by national statistical offices.

We then introduced free goods into a standard microeconomic model of household cost minimization and re-worked our welfare change and real GDP

2008 and 2017 can then be calculated by deflating by the official GDP deflator, and the difference with official real GDP calculated: 1.152-1.095=0.0563. That is, the difference with official real GDP is 5.63 percentage points over the nine years, or an arithmetic average of 0.63 percentage points per year.

growth adjustments terms to allow for there to be "free" goods (with an implicit or imputable price). Accounting for new and free goods in GDP gives us a new metric, GDP-B, which is a contribution to the literature on expanding GDP beyond the traditional definitions. Two empirical implementations of GDP-B are proposed. One requires (the estimation of) reservation prices, while the other, based on the concept of "total income" avoids this necessity.

Hence, we have derived explicit adjustments for both welfare change and equivalent real GDP growth that account for new and free goods, both of which are new to the literature. Following Brynjolfsson et al. (2019), we proposed a way of implementing these adjustments using incentive compatible discrete choice experiments. We quantify this adjustment for the case of Facebook in the US using a representative sample of the US internet population. Under different assumptions, we provide two estimates for the impact of incorporating Facebook into GDP-B, ranging from 0.05 to 0.11 percentage points per year on average from 2004. What's more, since GDP is the numerator used to calculate both labor productivity and total factor productivity, both of these numbers would change by the same amount per year when accounting for new and free goods using GDP-B. These are significant changes, especially considering that Facebook is just one product in this very encompassing measure of economic activity.

Using laboratory experiments in the Netherlands, we also provide further evidence for the magnitude of consumer welfare and potential additions to GDP generated by the most popular digital goods. Finally, using another laboratory experiment for computing the welfare created by smartphone cameras, we also make a case for accounting for new features in smartphones and other products, to capture the reality of rapid quality change in the digital economy. To elicit the consumer valuations of quality attributes, the experimental approach proposed

here is to block certain features of the goods (e.g. cameras in smartphones), or even take away the entire good, in exchange for monetary compensation. This could be an attractive alternative way to estimate the valuations of product characteristics for adjusting price indexes, as opposed to hedonic techniques, especially when the set of characteristics of goods changes rapidly.

The high valuations for WhatsApp and Facebook raise a host of interesting questions that can be explored in further. In future work, it would be insightful to delve deeper into these individual apps and study the sources of these valuations. In addition to product quality, network effects and focal point effects are also contributing factors towards these valuations. Furthermore, many of these digital goods are also associated with externalities and a parallel stream of research is needed to explore these issues in greater detail (for example, Allcott et al. (2019) explore the impact of Facebook on subjective well-being, news consumption and political polarization).

GDP-B and the related metrics proposed in this paper enable a more thorough exploration of the impacts of new and free goods on welfare, with significant potential policy implications. As an example, given that real GDP growth is a key component of national productivity growth estimates, to the extent that the adjustments add to GDP growth they may go some way to explaining the much-documented and debated productivity growth slowdown experienced by industrialized countries since 2004.

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