# 1 Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not

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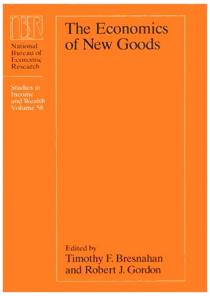

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## 1.1 The Achilles Heel of Real Output and Wage Measures

Studies of the growth of real output or real wages reveal almost two centuries of rapid growth for the United States and western Europe. As figure 1.1 shows, real incomes (measured as either real wages or per capita gross national product [GNP]) have grown by a factor of between thirteen and eighteen since the first half of the nineteenth century. An examination of real wages shows that they grew by about 1 percent annually between 1800 and 1900 and at an accelerated rate between 1900 and 1950.

Quantitative estimates of the growth of real wages or real output have an oft forgotten Achilles heel. While it is relatively easy to calculate nominal wages and outputs, conversion of these into real output or real wages requires calculation of price indexes for the various components of output. The estimates of real income are only as good as the price indexes are accurate.

During periods of major technological change, the construction of accurate price indexes that capture the impact of new technologies on living standards is beyond the practical capability of official statistical agencies. The essential difficulty arises for the obvious but usually overlooked reason that most of the goods we consume today were not produced a century ago. We travel in vehicles that were not yet invented that are powered by fuels not yet produced, communicate through devices not yet manufactured, enjoy cool air on the hot-

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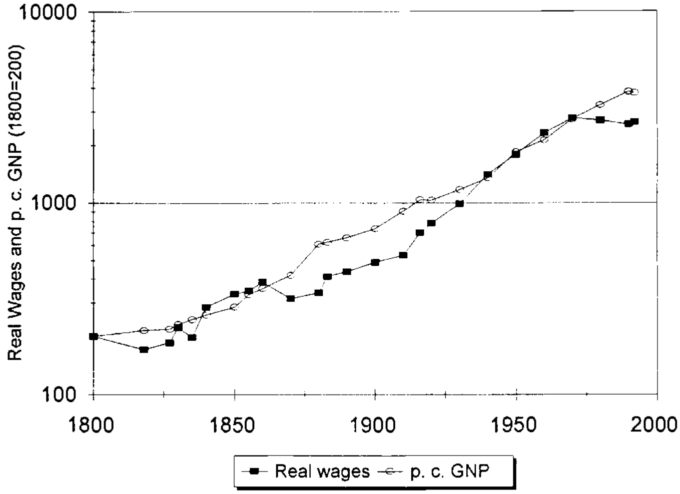

**Fig. 1.1 Real wages and per capita GNP**

test days,[1] are entertained by electronic wizardry that was not dreamed of, and receive medical treatments that were unheard of. If we are to obtain accurate estimates of the growth of real incomes over the last century, we must somehow construct price indexes that account for the vast changes in the quality and range of goods and services that we consume, that somehow compare the services of horse with automobile, of Pony Express with facsimile machine, of carbon paper with photocopier, of dark and lonely nights with nights spent watching television, and of brain surgery with magnetic resonance imaging.

Making a complete reckoning of the impact of new and improved consumer goods on our living standards is an epic task. The present study takes a small step in that direction by exploring the potential bias in estimating prices and output in a single area—lighting. This sector is one in which the measurement of "true" output is straightforward but where misleading approaches have been followed in the construction of actual price or output indexes. The bottom line is simple: *traditional price indexes of lighting vastly overstate the increase in lighting prices over the last two centuries, and the true rise in living standards in this sector has consequently been vastly understated.*

The plan of this paper is as follows: I begin with an analysis of the history of lighting, focusing particularly on the revolutionary developments in this field. I then use data on lighting efficiency to construct a "true" price of light and compare this with "traditional" price indexes that are constructed using traditional techniques. In the final section I engage in a *Gedankenexperiment* on the extent to which revolutionary changes in technology may lead to similar

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[1] The revolutionary implications of air-conditioning are considered in Oi, chap. 3 in this volume.

biases for other consumer goods and services and the consequent underestimation of the growth of real incomes over the last century.

## 1.2 Milestones in the History of Light

### 1.2.1 Basic Measurement Conventions

I begin with some simple conventions. What we call "light" is radiation that stimulates the retina of the human eye. Radiation in the visible spectrum comprises wavelengths between $4 \times 10^{-7}$ and $7 \times 10^{-7}$ meter. Light flux or flow is the name for the rate of emission from a source, and the unit of light flux is the lumen. A wax candle emits about 13 lumens, a one-hundred-watt filament bulb about 1200 lumens, and an eighteen-watt compact fluorescent bulb about 1290 lumens. The unit of illuminance (the amount of light per unit area) is the lux; one lux equals one lumen per square meter. Unobstructed daylight provides about ten thousand lux, while the level of illuminance of an ordinary home is about one hundred lux. In the candle age, a room lit by two candles would enjoy about five lux.

The efficiency of a lighting device can be measured in many ways, but for my purposes I am interested in the light output per unit of energy input. This is measured either as *lumen-hours per thousand Btu* (British thermal units), or alternatively today as *lumens per watt.*

### 1.2.2 Evolution

The first and in some ways most spectacular stage in the development of illumination is the eye itself, which evolved to exploit that part of the spectrum in which the sun (and moon) concentrate the greatest part of their radiated energy. Having adapted to daylight, the next stage for prehistoric humans was to devise means to illuminate the night, or dwellings like caves. The history of lighting reveals primarily the extraordinarily slow evolution in technology for the first few million years of human societies and then the extraordinarily rapid development from about the time of the Industrial Revolution until the early part of this century.

### 1.2.3 Open Fires

The first use of artificial or produced light probably coincided with the controlled use of fire. The first tool, known as the Oldowan chopper, has been dated from 2.6 million years ago, while the tentative identification of domesticated fire used by *Australopithecus* was discovered in Africa and dates from 1.42 million years ago. More definitive evidence of the controlled use of fire was found in the caves of Peking man (*Homo erectus*) dating from around 500,000 years ago. Presumably, open fires were used partially as illuminants in caves. It seems likely that sticks were used as torches in early times. (See table 1.1 for a brief chronology of the history of lighting.)

**Table 1.1** **Milestones in the History of Lighting**

| | |
|---|---|
| 1,420,000 B.C. | Fire used by *Australopithecus* |
| 500,000 B.C. | Fire used in caves by Peking man |
| 38,000–9000 B.C. | Stone fat-burning lamps with wicks used in southern Europe |
| 3000 B.C. | Candlesticks recovered from Egypt and Crete |
| 2000 B.C. | Babylonian market for lighting fuel (sesame oil) |
| 1292 | Paris tax rolls list 72 chandlers (candle makers) |
| Middle Ages | Tallow candles in wide use in western Europe |
| 1784 | Discovery of Argand oil lamp |
| 1792 | William Murdock uses coal-gas illumination in his Cornwall home |
| 1798 | William Murdock uses coal-gas illumination in Birmingham offices |
| 1800s | Candle technology improved by the use of stearic acid, spermaceti, and paraffin wax |
| 1820 | Gas street lighting installed in Pall Mall, London |
| 1855 | Benjamin Silliman, Jr., experiments with "rock oil" |
| 1860 | Demonstration of electric-discharge lamp by the Royal Society of London |
| 1860s | Development of kerosene lamps |
| 1876 | William Wallace's 500-candlepower arc lights, displayed at the Centennial Exposition in Philadelphia |
| 1879 | Swan and Edison invent carbon-filament incandescent lamp |
| 1880s | Welsbach gas mantle |
| 1882 | Pearl Street station (New York) opens with first electrical service |
| 1920s | High-pressure mercury-vapor-discharge and sodium-discharge lamps |
| 1930s | Development of mercury-vapor-filled fluorescent tube |
| 1931 | Development of sodium-vapor lamp |
| 1980s | Marketing of compact fluorescent bulb |

*Sources:* Stotz (1938), de Beaune and White (1993), Doblin (1982), and Encyclopedia Britannica 11th and 15th editions.

### 1.2.4 Lamps

Open fires are relatively inefficient, and *H. sapiens* not only developed the ability to start fires (dated as early as 7000 B.C.) but also invented capital equipment for illumination. The first known lighting tool was a stone, fat-burning lamp that was used in western Europe and found most abundantly in southern France. According to de Beaune and White (1993), almost two hundred fat-burning Paleolithic lamps dating from 40,000 to 15,000 B.C. have been identified. These lamps were made from limestone or sandstone and can easily be fashioned with shallow depressions to retain the melted fuel. Chemical analyses of residues of the fuel have shown that it was probably animal fat. De Beaune and White estimate that a Paleolithic lamp had the lighting power of a candle. Modern replicas are relatively easy to build, requiring but half an hour, suggesting that, like modern lights, most of the cost of early lighting devices was in the fuel rather than in the capital.

In Greece, lamps (from the Greek *lampas,* meaning torch) fashioned from pottery or bronze began to replace torches about 700 B.C. The Romans manufactured molded terra-cotta lamps, sometimes decorative and elaborate. The earliest markets for lighting fuel arose in early Babylonia around 2000 B.C. According to Dubberstein (1938), Babylonians used sesame oil as an illuminant in temples, although it was too expensive to employ in homes. The wage of a common laborer was approximately one shekel per month, which was also approximately the price of two *sutu* (ten liters) of sesame oil. I have performed a number of experiments with sesame oil and lamps purportedly dating from Roman times (see the appendix). These experiments provide evidence that an hour's work today will buy about 350,000 times as much illumination as could be bought in early Babylonia.[2]

As Europe declined into the Dark Ages, there was a clear deterioration in lighting technology, with lighting returning to the Paleolithic open saucer that performed more poorly than the wicked Roman lamps. Van Benesch (1909) describes the medieval peasant's practice of burning pine splinters. Sometimes the torch was held in the mouth to leave the hands free.[3] Virtually all historical accounts of illumination remark on the feeble progress made in lighting technology in the millennia before the Industrial Revolution.

### 1.2.5 Candles

Candles appeared on the scene several millennia ago, and candlesticks were recovered from Minoan Crete. From the Greco-Roman period until the nineteenth century, the most advanced and prestigious lighting instrument was the wax candle; indeed, the mark of nobility was to be preceded by a candle in the bedtime procession. Candle making was a respected profession in the Middle Ages, and some of the earliest labor struggles occurred between the wax and tallow chandlers of England in the fourteenth and fifteenth centuries. Students of international trade will recall the famous satirical "Petition of the Candle Makers" of Fredéric Bastiat:

> *To the Chamber of Deputies:*
>
> We are subjected to the intolerable competition of a foreign rival, who enjoys such superior facilities for the production of light that he can inundate our national market at reduced price. This rival is no other than the sun. Our petition is to pass a law shutting up all windows, openings and fissures through which the light of the sun is used to penetrate our dwellings, to the prejudice of the profitable manufacture we have been enabled to bestow on the country.
>
> *Signed:* Candle Makers. (quoted in Samuelson and Nordhaus 1992, 677)

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[2] I am particularly grateful to Alice Slotsky for tutoring me on the intricacies of Babylonian price and measure data. Analysis of Babylonian wage and price data are contained in Dubberstein (1938), Farber (1978), and Slotsky (1992). During the old Babylonian period of Hammurapi/ Samsuiluna (around 1750 B.C.), a common laborer earned about one shekel a month while a *sutu* (a measure equal to six *qa* or five liters) of sesame oil cost about half a shekel. Conversion of these to lighting efficiency and labor costs is discussed in the appendix.

[3] Details on the history of lighting are contained in many sources; the "mouth torch" is described in Gaster and Dow (1919).

Tallow gradually replaced wax as the former was much less costly, and in the eighteenth and nineteenth centuries whale-oil candles became the illuminant of choice.

### 1.2.6 Gas and Petroleum

One of the remarkable features of human history is how slow and meandering was the progress in lighting technology from the earliest age until the Industrial Revolution. There were virtually no new devices and scant improvements from the Babylonian age until the development of town gas in the late eighteenth century. By contrast, the nineteenth century was an age of tremendous progress in developing lighting technologies and reducing their costs (although, as we will see, you would have great difficulty discovering that from the price indexes on light).

A key milestone in illumination was the development of town gas, which was produced from coal and was used both in residences and for street lighting. There were a number of parallel attempts to introduce gas, but William Murdock is usually thought of as the father of gas lighting. As was often the case before the routinization of invention, he experimented on himself and his family in his home in 1792, and when they survived he started a commercial enterprise. The first quarter of the nineteenth century saw the great cities of Europe lit by gas.

The petroleum age was ushered in by the discovery of "rock oil" in Pennsylvania. We are fortunate that the first entrepreneurs had the good sense to hire as a consultant Benjamin Silliman, Jr., professor of general and applied chemistry at Yale and son of the most eminent American scientist of that period, to perform a thorough analysis of the possibilities of rock oil for illumination and other industrial purposes. (A thoroughly underpaid academic, Silliman served as a consultant for industrial interests and later lost his reputation when he predicted, to the contrary opinion and consequent displeasure of the head of the U.S. Geological Survey, that great quantities of oil were to be found in southern California.) For his report to the Pennsylvania oilmen, Silliman distilled the oil, ran a series of tests, and developed an apparatus he called a "photometer" to measure the relative illuminance of different devices. Silliman's 1855 report was suppressed on commercial grounds until 1870, but it is probably the best single source of data on both prices and efficiency available before this century (see his results in table 1.2).

Although energy consumption is the bête noire of today's environmental movement, it is interesting to contemplate how history would have unfolded if in 1850 technology had been frozen, by risk analysts or environmental impact statements, at the stage of coal gas and whale oil. One happy environmental effect of these new technologies, as Louis Stotz reminds us, was that "the discovery of petroleum in Pennsylvania gave kerosene to the world, and life to the few remaining whales" (1938, 6). After the development of the petroleum industry, kerosene became a strong competitor of gas, and the declining prices

**Table 1.2** **Silliman's Lighting Experiments, 1855**

| | | | | Efficiency | | Price of Illumination | |
|---|---|---|---|---|---|---|---|
| Fuel | Apparatus | Fuel Rate (per hour) | Fuel Price (cents per volume) | (candle-hours per hour) | (lumen-hours per 1,000 Btu) | (cents per candle-hour) | (cents per 1,000 lumen-hours) |
| Town gas (cu. ft.) | Scotch fish tail | 4 | 0.40 | 5.4 | 31.9 | 0.30 | 22.8 |
| | Scotch fish tail | 6 | 0.40 | 7.6 | 29.7 | 0.32 | 24.5 |
| | Cornelius fish tail | 6 | 0.40 | 6.2 | 24.4 | 0.39 | 29.8 |
| | Argand burner | 10 | 0.40 | 16.0 | 37.8 | 0.25 | 19.2 |
| Sperm oil (fl. oz.) | Carcel's lamp | 2 | 1.95 | 7.5 | 23.0 | 0.52 | 40.1 |
| Colza oil (fl. oz.) | Carcel's lamp | 2 | 1.56 | 7.5 | 23.0 | 0.42 | 32.1 |
| Camphene (fl. oz.) | Camphene lamp | 4 | 0.53 | 11.0 | 16.9 | 0.19 | 14.9 |
| Silvic oil (fl. oz.) | Diamond lamp | 4 | 0.39 | 8.1 | 12.4 | 0.19 | 14.8 |
| Rock oil (fl. oz.)[a] | Camphene lamp | 3.4 | 0.06 | 8.1 | 14.6 | 0.03 | 2.0 |

*Source:* Silliman (1871).

[a] Price for kerosene refers to 1870.

**Table 1.3** **Efficiency of Different Lighting Technologies**

| | | | Lighting Efficiency | |
|---|---|---|---|---|
| Device | Stage of Technology | Approximate Date | (lumens per watt) | (lumen-hours per 1,000 Btu) |
| Open fire[a] | Wood | From earliest time | 0.00235 | 0.69 |
| Neolithic lamp[b] | Animal or vegetable fat | 38,000–9000 B.C. | 0.0151 | 4.4 |
| Babylonian lamp[a] | Sesame oil | 1750 B.C. | 0.0597 | 17.5 |
| Candle[c] | Tallow | 1800 | 0.0757 | 22.2 |
| | Sperm | 1800 | 0.1009 | 29.6 |
| | Tallow | 1830 | 0.0757 | 22.2 |
| | Sperm | 1830 | 0.1009 | 29.6 |
| Lamp | Whale oil[d] | 1815–45 | 0.1346 | 39.4 |
| | Silliman's experiment: Sperm oil[e] | 1855 | 0.0784 | 23.0 |
| | Silliman's experiment: Other oils[f] | 1855 | 0.0575 | 16.9 |
| Town gas | Early lamp[g] | 1827 | 0.1303 | 38.2 |
| | Silliman's experiment[e] | 1855 | 0.0833 | 24.4 |
| | Early lamp[e] | 1875–85 | 0.2464 | 72.2 |
| | Welsbach mantle[e] | 1885–95 | 0.5914 | 173.3 |
| | Welsbach mantle[e] | 1916 | 0.8685 | 254.5 |
| Kerosene lamp | Silliman's experiment[e] | 1855 | 0.0498 | 14.6 |
| | 19th century[h] | 1875–85 | 0.1590 | 46.6 |
| | Coleman lantern[i] | 1993 | 0.3651 | 107.0 |
| Electric lamp | | | | |
| Edison carbon | Filament lamp[j] | 1883 | 2.6000 | 762.0 |
| Advanced carbon | Filament lamp[j] | 1900 | 3.7143 | 1,088.6 |
| | Filament lamp[j] | 1910 | 6.5000 | 1,905.0 |
| Tungsten | Filament lamp[j] | 1920 | 11.8182 | 3,463.7 |
| | Filament lamp[j] | 1930 | 11.8432 | 3,471.0 |
| | Filament lamp[j] | 1940 | 11.9000 | 3,487.7 |
| | Filament lamp[k] | 1950 | 11.9250 | 3,495.0 |
| | Filament lamp[k] | 1960 | 11.9500 | 3,502.3 |
| | Filament lamp[k] | 1970 | 11.9750 | 3,509.7 |
| | Filament lamp[k] | 1980 | 12.0000 | 3,517.0 |
| | Filament lamp[l] | 1990 | 14.1667 | 4,152.0 |
| Compact fluorescent | First generation bulb[m] | 1992 | 68.2778 | 20,011.1 |

*Note:* The modern unit of illumination is the lumen which is the amount of light cast by a candle at one foot.

[a] See appendix.

[b] From de Beaune and White (1993), assuming that the device is one-fifth as efficient as a tallow candle.

[c] A candle weighing one-sixth of a pound generates 13 lumens for 7 hours. Tallow candles are assumed to have three-quarters the light output of sperm candles.

[d] Whale oil is assumed to have the efficiency of a candle and one-half the caloric value of petroleum.

[e] See table 1.2.

[f] Other oils tested by Silliman included silvic oil, camphene, and colza oil. Here I choose camphene, largely wood alcohol, as the most cost effective.

**Table 1.3** (continued)

[g] From Stotz (1938, 7f). According to Stotz, expenditures of $30 per year on town gas at a price of $2 per 1,000 cubic feet would produce 76,000 candle-hours. After the introduction of the Welsbach mantle, efficiency improved from 3 candles per cubic foot to 20 candles per cubic foot; town gas had 500 Btu per cubic foot.

[h] According to Stotz (1938, 8f), expenditures of $25 per year on kerosene at a price of $0.135 per gallon would yield 90,000 candle-hours per year.

[i] Estimate on a Coleman kerosene lantern from Coleman Corp. (personal communication).

[j] Gaster and Dow (1919, 75, 79).

[k] Linear interpolation between 1940 and 1980.

[l] A standard incandescent bulb tested by *Consumer Reports.*

[m] According to *Consumer Reports*'s first test of compact fluorescent bulbs (Bright ideas in light bulbs 1992).

of both gas and kerosene led to a healthy competition which continues even to this day for heating.

### 1.2.7 Electric Lighting

The coup de grâce to both oil and gas for illumination came with the twin developments of electric power and Thomas Edison's carbon-filament lamp, discovered in 1879 and introduced commercially in New York in 1882. Although popular American legend elevates Edison above his peers, he did not in fact make any quantum leaps in this technology.

The first lighting by electricity took place with the electric-arc lamp as early as 1845. Michael Faraday's experiments were the decisive point in the development of electricity, and it was at his suggestion that the first trial of an electrically illuminated lighthouse took place at Dungeness in 1857. Electricity was used to light the Tuileries gardens in Paris in 1867. Filament lamps were made by Frederick de Moleyns in England in the 1840s, but the first practical "glow lamps" were simultaneously invented by J. W. Swan in England and Edison in the United States. Edison combined technical inspiration with commercial perspiration when he also generated electricity and distributed it from the Pearl Street substation in New York in 1882.

The first bulbs used carbon filaments that had short lifetimes and produced only 2.6 lumens per watt (see table 1.3). The major improvement in the efficiency of the lightbulb came from metal filaments, particularly tungsten, which raised the efficiency to almost 12 lumens per watt by 1919. Since that time, there has been very little improvement in the technology of the lightbulb itself, which reached an output of only 13–14 lumens per watt by the 1990s. In contrast, since the Edison bulb there have been great improvements in lamp technology for large users, and the efficiency of industrial or street lighting shows an even greater improvement than that of the residential-use lamps that I study here.

Until the last decade, the tungsten-filament lightbulb was both relatively unchanging and unchallenged for home uses. Arc, mercury-vapor, and other types of fluorescent lighting were understood at the beginning of this century, but they were more costly and complicated and made little progress in residential applications. Fluorescent bulbs were developed in the 1930s, but they were suitable only for specially installed fixtures. The most recent phase of the lighting revolution has been the introduction of compact fluorescent bulbs in the late 1980s and 1990s. The early compact fluorescent bulbs were expensive, bulky, and only marginally more efficient than the incandescent variety. The Compax bulb of the mid-1980s generated 47 lumens per watt, compared with 68 lumens per watt by 1992. Only in the last decade, with greatly improved technology and some promotion in poorly designed cross-subsidy schemes by electric utility companies, has the compact fluorescent bulb begun to replace the incandescent lamp in residences. The latest entry in the evolution of lighting has been the E-bulb, announced in 1994, which is the first electronic application and is about as efficient as other compact fluorescent bulbs.

### 1.2.8 Summary Data on Efficiency and Prices

Table 1.3 provides estimates of the efficiency of different devices back to the fires of Peking man. The estimates for both the Paleolithic lamps and open fires are extremely rough and are based on my measurements (see the appendix). The most reliable measurements are those of Silliman in 1855 and those from the modern era.

The overall improvements in lighting efficiency are nothing short of phenomenal. The first recorded device, the Paleolithic oil lamp, was perhaps a tenfold improvement in efficiency over the open fire of Peking man, which represents a 0.0004 percent per year improvement. Progression from the Paleolithic lamps to the Babylonian lamps represents an improvement rate of 0.01 percent per year; from Babylonian lamps to the candles of the early nineteenth century is an improvement at the more rapid rate of 0.04 percent per year. The Age of Invention showed a dramatic improvement in lighting efficiency, with an increase by a factor of nine hundred, representing a rate of 3.6 percent per year between 1800 and 1992.

Each new lighting technology represented a major improvement over its predecessor. What is striking, as well, is that in each technology there have been dramatic improvements. The Welsbach gas mantle improved the efficiency of gas lamps by a factor of seven, and another 100 percent improvement was seen between the kerosene lantern of the 1880s and today's Coleman lantern. There were marked improvements in the ordinary lightbulb in the four decades after Edison's first carbon-filament lamp, with most of the gain achieved by 1920. Overall, from the Babylonian sesame-oil lamp to today's compact fluorescent bulb, the efficiency of lighting has increased by a factor of about twelve hundred.

So much for the elementary physics. The questions for the economist are, what has happened to the true price of a lumen-hour, and have traditional price indexes captured the true price change?

## 1.3 Traditional Approaches to Measuring Prices

### 1.3.1 Introductory Considerations

My major concern here is whether traditional approaches to constructing price indexes capture the major technological changes of the last two centuries. I begin in this section by reviewing alternative approaches to the construction of price indexes and turn in the next section to a superior (if not superlative) technique. The major point will be to show that price indexes miss much of the action during periods of major technological revolution. They overstate price growth for three reasons: first, they may not capture quality changes; second, they measure the price of goods and services but do not capture the changes in efficiency of these goods and services; and, third, they do not capture the enormous changes in the efficiency of delivering services when new products are introduced. The present section begins with a simple analysis of the issue and then reviews the construction of traditional price indexes in practice.

### 1.3.2 Theoretical Considerations

It will be useful to lay out the fundamental issues.[4] For many practical reasons, traditional price indexes measure the prices of goods that consumers buy rather than the prices of the services that consumers enjoy. For purposes of measuring the true cost of living, we clearly should focus on the outputs rather than on the inputs. More precisely, we must distinguish between a goods price index that measures the price of *inputs* in the form of purchased goods and a characteristics price index that measures the (implicit) price of the *output* in the form of services.

The economics underlying the construction of the true price of light relies on the economics of hedonic prices, or more precisely on the calculation of the price of *service characteristics*. I will describe the theoretical background briefly.[5] Suppose that the underlying utility function is $U(C_1, C_2, \ldots)$, where $C_i$ is the quantity of characteristic $i$, which might be the number of lumens of light, the temperature of the dwelling, the fidelity of the sound reproduction, and so forth. Service characteristics are produced by purchased goods $(X_1, X_2, \ldots)$, which might be lighting devices, fuel, furnaces, or compact-disc players. Service characteristics are linked to goods by production functions. Generally, goods produce multiple service characteristics, and this often leads to difficulties in determining the implicit hedonic prices. I will simplify the analysis by assuming that each good is associated with a single characteristic, so that

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[4] The theory of index numbers is an ancient art, dating back at least to the Bishop of Ely in 1707 (see Diewert 1988 for an illuminating review). Modern treatments can be found in Deaton and Muellbauer (1980) or Diewert (1990).

[5] See Triplett (1987) for an excellent summary of the theory of characteristic prices.

$C_{it} = f_{jit}(X_{jt})$ is the production function by which good $j$ produces characteristic $i$ at time $t$. In the case of light, the $f_{jit}$ function is taken to be linear, so this means that at any time there will be a dominant technology and a unique implicit hedonic price of each characteristic.[6]

For the exposition I will suppress the time subscript. The consumer faces a budget constraint $I = p_1X_1 + \cdots + X_m p_m$, where $I$ is nominal income and $p_i$ is the price of good $i$. We can also associate hedonic prices (or shadow prices) with each of the service characteristics. These are actually the shadow prices of the utility maximization and can be derived as follows: Assuming identical consumers, maximizing utility subject to the production function and budget constraint yields first-order conditions

$$\lambda = (\partial U/\partial C_i)(\partial C_i/\partial X_j)/p_j \tag{1}$$

for all purchased goods $j$ that deliver characteristic $i$. Equation (1) shows the consumer's maximization in terms of purchases of goods. At a more fundamental level, however, we are interested in the trend in the characteristic prices. Therefore define the shadow price on characteristic $i(q_i)$ as

$$q_i = p_j/(\partial C_i/\partial X_j). \tag{2}$$

Substituting equation (2) into equation (1) we get the appropriate first-order condition in terms of service characteristics. In equation (2), $q_i$ is the shadow price of characteristic $i$ (its units for lighting are dollars per lumen-hour). The characteristic price is simply the price of the good $(p_j)$ divided by the efficiency of the good in delivering the characteristic $(\partial C_i/\partial X_j)$.

Using this approach, we can distinguish traditional price indexes from true price indexes. A *traditional* price index, $P_t$, measures (some index of) goods or input prices:

$$P_t = \sum_{j=1}^{n} p_{j,t}\zeta_{j,t}, \tag{3}$$

where $p_{j,t}$ are the prices of the goods and $\zeta_{j,t}$ are the appropriate weights on the goods. By contrast, a *true* price index, $Q_t$, measures the trend in the prices of the service characteristics:

$$Q_t = \sum_{i=1}^{m} q_{i,t}\omega_{i,t}, \tag{4}$$

where $q_{i,t}$ are the prices of the characteristics and $\omega_{i,t}$ are the appropriate weights on the service characteristics.

How can the traditional prices go wrong? There are three ways. (1) *Incorrect*

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[6] This assumption is oversimplified if the prices of the good or of complementary factors are different for different consumers. The most important exception would be the shadow price of the complementary capital, which would differ depending on whether the consumer had capital embodying an old technology or was buying a new capital good. I resolve this by calculating the "frontier hedonic price," which measures the price assuming that consumers are replacing their capital equipment.

*weights.* The first source of error arises if traditional price indexes use the wrong weights. This is probably relatively unimportant, for the shares are simply the expenditure weights and these can be directly observed and are not affected by use of traditional rather than true prices. (2) *Improvements in efficiency.* The second source of error comes because of changes in the efficiency of the production function for the service for a given good. If the production function is improving over time, this will lead to a decline in the service-good price ratio, $q_{j,t}/p_{i,t}$, which will be entirely missed by traditional price indexes. (3) *Incorrect linking of new goods.* Traditional price indexes can go astray in a third way if new goods are introduced for which the service-good price ratio is lower at the time that the new good is introduced. Hence, if good $(j+1)$ replaces good $j$, then a bias for the new good arises if the ratio $q_{j+1,t}/p_{i,t}$ is lower than the ratio $q_{j,t}/p_{i,t}$ at the time of introduction of the new good into the price index.

Two points emerge from this analysis, the first obvious and the second not. First, for the case where the good delivering the service does not change but where there are improvements in the efficiency of the production function f(·), the ratio $q_i/p_j$ will not change much as long as the efficiency does not change much over time. We need to examine a good's efficiency in producing the service to determine whether there is a significant bias in traditional price measures.

The second point relates to new goods. Say that the good delivering a particular characteristic changes: good $(j+1)$ replaces good $j$ in delivering characteristic $i$, so equation (2) drops out of the consumer equilibrium and is replaced by the equation for the new good, $q_i = p_{j+1}\ (\partial C_i/\partial X_{j+1})$. *For new products, the price index will be accurate if the shadow price of the service characteristic for the new good, $j + 1$, is the same as that for the old, $j$, at the date when the new good is introduced into the price index.* Because shadow prices tend to be equal very early in the life cycles of new goods, this suggests that early introduction of new goods is the appropriate treatment.

My procedure in what follows will be to calculate the true price of the service characteristic of lighting ($q_i$ being the lumen-hour) as a replacement for the traditional price index of fuel ($q_j$ being the price of candles, town gas, or electricity).

### 1.3.3 Treatment of Quality Change in Practice

Before World War II, little attention was paid to the problem of quality change and new products. Since that time, however, it has been increasingly recognized that adjusting for quality change is a major issue in constructing price indexes. The common presumption among most economists is that price indexes fail to deal adequately with quality change and new products; furthermore, it is generally presumed that there is an upward bias of prices (or inflation) over time. It is useful to review the current practices so as to understand the way quality is treated today.

Those who construct price indexes are, of course, quite aware of the quality-change issue (see, e.g., Armknecht, Lane, and Stewart, chap. 9 in this volume). There are three techniques for dealing with quality change or new products. (1) *Direct comparison.* One approach is simply to divide the second-period price by the first-period price. This technique implicitly assumes that the quality change is insignificant and is the technique followed for the preponderance of goods and services. (2) *Linking.* In this approach, prices are adjusted by factoring out price differences in a base time period where prices for both commodities exist. This method assumes that the relative prices in the base period fully reflect quality differences. (3) *Adjusting for quality differences.* A final method is to adjust the price to reflect the estimated value of the quality difference. For example, car prices might be adjusted on the basis of horsepower, fuel economy, and size; computer prices might be adjusted by assuming that the quantity of output is a function of speed and memory. To be accurate, this method requires both reliable estimates of the service characteristics of old and new products and an appropriate imputation of the economic value of the change in service characteristics. As of 1990, only two adjustments were routinely used in the official price indexes of the United States: for computer prices and for housing prices.

In analyzing traditional techniques, it is useful to start with the simplest case, which involves quality improvement of existing products or the introduction of new products for the same service characteristic. For this class of new or improved products, the problems arise primarily in calculating the quantity of service characteristics delivered by old and new products. Typically, the statistician will simply assume that the products deliver the same quantity of service characteristics per dollar of spending at a given date and will then use the method of linking to splice together the prices of the new and old products. Two problems are likely to arise with new products. First, new goods are likely to be introduced into price indexes relatively late in their product cycle; late introduction leads to an upward bias in price indexes because the relative prices of the service characteristics of old and new goods begin to diverge markedly after the introduction of a new good into the market. Second, many new goods experience rapid improvement in efficiency of delivering service characteristics, so the bias from using goods prices rather than service-characteristic prices may be particularly severe for goods in the early stages of the life cycle.

For a relatively small number of products, the services are genuinely new and in essence expand the range of service characteristics spanned by available commodities. For example, when the first artificial lighting was produced half a million years ago, or when anesthetics or space travel were first introduced in the modern age, or if we really could visit Jurassic Park, these service characteristics would be genuinely novel and we could find no market benchmarks for creation of hedonic prices. However, such genuinely novel commodities are quite rare because most new products are in reality new combinations of old wines in redesigned bottles.

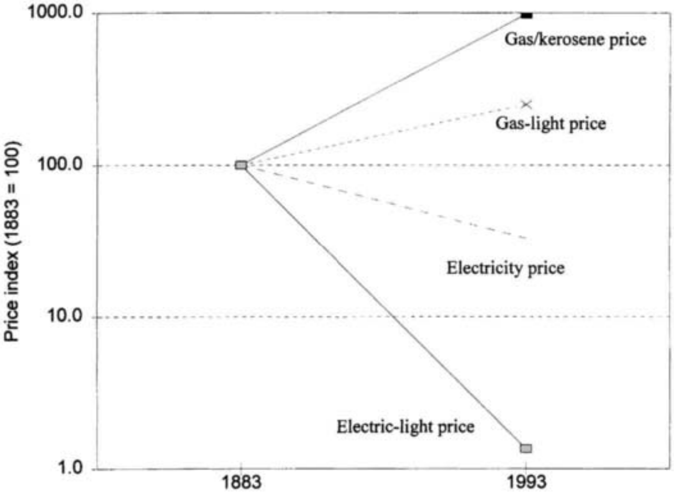

**Fig. 1.2 Bias in price indexes**

Construction of price indexes for products that represent new service characteristics requires greater knowledge about preferences than the other two cases. Current thinking suggests that the appropriate technique is to estimate the value of the new-characteristic commodity by determining the reservation income at which consumers would be indifferent to the choice between the budget set without the new-characteristic commodity and the actual income with the new-characteristic commodity. In considering the true price of light, this problem does not arise and is not considered further in this study.

### 1.3.4 An Illuminating Example of the Bias in Lighting Prices

Before I turn to the actual construction of traditional and true price indexes, I can make the point with a simple example of lighting prices over the century from 1883 to 1993. I take this period because Edison priced his first electric light at an equivalent price to gaslight, so the prices per unit of light output for gas and electricity were equal in 1883. Since the 1883 price of kerosene light was also reasonably close to that of town gas during this period, I will compare the prices of electric light with that of gas/kerosene light over the last century.

Figure 1.2 shows the result. Over the last century, the prices of the fuels (which are from traditional price indexes and are shown by the dashed lines) rose by a factor of 10 for kerosene and fell by a factor of 3 for electricity. If an ideal traditional (frontier) price index were constructed, it would use late weights (following electricity prices) since this is the frontier technology. Hence the ideal traditional (frontier) price index using the price of inputs would show a fall in the price of light by a factor of 3 over the last century. If the price index were incorrectly constructed, say using 1883 consumption weights and tracking gas/kerosene prices, it would show a substantial upward increase by a factor of 10.

A true (frontier) price index of output or illumination, by contrast, would track the lowest solid line in figure 1.2, which shows a decline by a factor of 75 over the last century. This shows a steeper decline in price relative to the price of electricity because of the vast improvements in the efficiency of electric lighting.

Hence if we compare the worst traditional price index (the gas/kerosene price) to the true price, we see an overstatement by a factor of 750 in this simple example. The overstatement comes, first, from incorrect weighting of the different fuels and, second, because of the improvements in the efficiency in production of the services. It is instructive to note that even the most superlative price index can only correct for the first of these defects, and I must turn to estimation of characteristic production functions to determine the magnitude of the second bias.

### 1.3.5 Traditional Price Indexes for Light

The first step in the comparison is to obtain a "traditional" or conventional estimate of the price of light. Actually, the U.S. Bureau of Labor Statistics (BLS) does not currently calculate a price of light or lighting. The closest thing to that concept is the price of energy, which is broken down into different fuels (gas, electricity, and oil). Earlier indexes sometimes did include the price of "fuel and light," either in wholesale or in consumer price indexes. The other component of the price of light is the prices of lighting devices, which are not included as a separate index.

To construct the traditional price of light, I patched together the most closely related series. The earliest data, for the period 1790–1851, was the wholesale price of "fuel and light" from Warren and Pearson (1933). There is a short period, 1851–80 for which I constructed consumer prices using the index of the price of "fuel and light" from Hoover (1960). Then for the period 1880–90, I returned to the Warren and Pearson index of fuel and light. For the period 1890–1940, I used the BLS wholesale price index of fuel and light (U.S. Bureau of the Census 1975). From 1940 on, there are two variants available. The first links the earlier series with the U.S. Consumer Price Index series on gas and electricity, which is the closest component to a price index of lighting costs in the current index; I call this series "Light I."

A second series reflects the fact that since 1940 virtually all lighting has been powered by electricity, so I have constructed a price series for electricity from the composite price of electricity used in residences; this second series is called "Light II" and rises less rapidly than Light I because of the rapid fall in electricity prices over the last half century. For comparative purposes, I also use a consumer price index for all commodities recently prepared by McCusker (1991). All three series are shown in table 1.4.

It is clear that the traditional indexes that have been constructed are only rough proxies for what might have been used as a price of lighting if the official statistical agencies actually had set about trying to measure the price of light. But this traditionally measured price of light is probably representative of the approach taken for most commodities at any particular time. It should be recalled that as of 1990 there were only two hedonic price indexes included in all the price calculations of the U.S. government (these being for housing and computers), so we can think of this audit of the reliability of the traditional price of light as a representative (albeit small) sample of prices.

## 1.4 *Lux et Veritas:* Construction of the "True Price of Light"

### 1.4.1 Theoretical Background

In constructing an ideal or true price, we want to employ the price of the service characteristic as defined in equation (2) rather than that of the good (just as we want to measure the price of the output rather than the price of the input). The true price index is then constructed according to the formula in equation (4) rather than by the traditional goods price index defined in equation (3). It is clear that in principle the characteristics approach is superior, but because of the labor involved in constructing characteristics prices, statisticians almost always collect goods prices, and price indexes rely almost entirely on the price of goods.

### 1.4.2 Implementation

*Measurement*

In this section I describe the actual calculations of the true price of light. Unlike many estimates of hedonic price indexes, the true price of light is conceptually very simple in that there are laboratory measurements of light flux and illuminance, as discussed above. As with all goods, light has a number of different service characteristics: (1) illumination or light flux (measured in lumens), (2) wavelength (usually proximity to wavelength of sunlight), (3) reliability (in terms of constancy and lack of flicker), (4) convenience (ease of turning off and on, low maintenance), (5) safety (from electrocution, burns, ultraviolet radiation),[7] and (6) durability (lifetime and ease of replacement or fueling).

In practice, the true price of light is constructed with a number of simplifying assumptions. For the present purpose, I restrict the calculation in a number of respects: (1) The only characteristic that I analyze is the first, illumi-

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[7] It is easy for those living in the modern age to overlook the terrifying dangers of earlier technologies. Early lighting devices, especially lamps and candles, were serious threats to life. A number of eminent women, such as Fanny Longfellow and Lady Salisbury, burned to death when their dresses caught fire from candles. One-third of New York tenement fires in 1900 were due to lamps or candles. See Lebergott (1993).

**Table 1.4** **Basic Data on the True Price of Light**

| | True Price of Light | | | Light Price in Terms of Labor (hours of work per 1,000 lumen-hours) | Official Price Indexes | | | Price Ratio (true to official price) | |
|---|---|---|---|---|---|---|---|---|---|
| | Per 1,000 Lumens | | Index, Real Prices (1800 = 100) | | | | | | |
| Date | (current prices) (1) | (1992 prices) (2) | (3) | (4) | CPI (1800 = 100) (5) | Light I (1800 = 100) (6) | Light II (1800 = 100) (7) | Light I (8) | Light II (9) |
| ca. 500,000 B.C. | | | | 58 | | | | | |
| 38,000–9000 B.C. | | | | 50 | | | | | |
| 1750 B.C. | | | | 41.5 | | | | | |
| 1800 | 40.293 | 429.628 | 100.000 | 5.387 | 100.0 | 100.00 | 100.00 | 1.00 | 1.00 |
| 1818 | 40.873 | 430.117 | 100.114 | 6.332 | 101.3 | 93.71 | 93.71 | 0.92 | 0.92 |
| 1827 | 18.632 | 249.985 | 58.186 | 3.380 | 79.5 | 86.16 | 86.16 | 1.86 | 1.86 |
| 1830 | 18.315 | 265.659 | 61.835 | 2.999 | 73.5 | 72.96 | 72.96 | 1.61 | 1.61 |
| 1835 | 40.392 | 596.089 | 138.745 | 7.569 | 72.3 | 69.81 | 69.81 | 0.70 | 0.70 |
| 1840 | 36.943 | 626.774 | 145.888 | 5.057 | 62.8 | 66.04 | 66.04 | 0.72 | 0.72 |
| 1850 | 23.199 | 397.362 | 92.490 | 2.998 | 62.3 | 59.75 | 59.75 | 1.04 | 1.04 |
| 1855 | 29.777 | 460.980 | 107.298 | 3.344 | 68.9 | 64.15 | 64.15 | 0.87 | 0.87 |
| 1860 | 10.963 | 176.505 | 41.083 | 1.152 | 66.2 | 61.64 | 61.64 | 2.27 | 2.27 |
| 1870 | 4.036 | 41.390 | 9.634 | 0.330 | 104.0 | 84.28 | 84.28 | 8.41 | 8.41 |
| 1880 | 5.035 | 65.907 | 15.340 | 0.489 | 81.5 | 57.86 | 57.86 | 4.63 | 4.63 |
| 1883 | 9.228 | 122.791 | 28.581 | 0.750 | 80.1 | 55.97 | 55.97 | 2.44 | 2.44 |
| 1890 | 1.573 | 23.241 | 5.410 | 0.133 | 72.2 | 45.28 | 45.28 | 11.60 | 11.60 |

|  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
| 1900 | 2.692 | 42.906 | 9.987 | 0.2204 | 66.9 | 55.03 | 55.03 | 8.24 | 8.24 |
| 1910 | 1.384 | 19.550 | 4.550 | 0.0921 | 75.5 | 56.57 | 56.57 | 16.47 | 16.47 |
| 1916 | 0.346 | 4.282 | 0.997 | 0.0154 | 86.1 | 88.31 | 88.31 | 102.92 | 102.92 |
| 1920 | 0.630 | 4.228 | 0.984 | 0.0135 | 158.9 | 194.56 | 194.56 | 124.40 | 124.40 |
| 1930 | 0.509 | 4.098 | 0.954 | 0.0104 | 132.5 | 93.30 | 93.30 | 73.86 | 73.86 |
| 1940 | 0.323 | 3.092 | 0.720 | 0.00549 | 111.3 | 85.22 | 65.78 | 106.44 | 82.16 |
| 1950 | 0.241 | 1.350 | 0.314 | 0.00188 | 190.7 | 84.28 | 62.61 | 140.66 | 104.49 |
| 1960 | 0.207 | 0.940 | 0.219 | 0.00102 | 234.4 | 102.28 | 70.89 | 199.45 | 138.24 |
| 1970 | 0.175 | 0.608 | 0.142 | 0.00055 | 307.3 | 111.50 | 75.01 | 256.26 | 172.39 |
| 1980 | 0.447 | 0.730 | 0.170 | 0.00068 | 652.3 | 313.43 | 179.34 | 282.82 | 161.83 |
| 1990 | 0.600 | 0.618 | 0.144 | 0.00060 | 1,035.1 | 479.80 | 275.57 | 322.31 | 185.12 |
| 1992 | 0.124 | 0.124 | 0.029 | 0.00012 | 1,066.3 | 503.94 | 281.09 | 1,631.55 | 910.03 |

(1) From table 1.5.

(2) Col. (1) reflated into 1992 prices using the consumer price index in col. (5).

(3) Index of col. (2) using 1800 = 100.

(4) From table 1.6.

(5) From McCusker (1991).

(6) A chain index was constructed as follows: Warren and Pearson's (1933) index of wholesale prices of fuel and light was used for the period up to 1850. Hoover's (1960) index of consumer prices for fuel and light was used for the period 1850–80. Warren and Pearson (1933) was used for the period 1880–90. BLS's wholesale price index was used for the period 1890–1940 (U.S. Bureau of the Census 1975). The U.S. CPI for the price of gas and electric fuels was used for the period 1940–92.

(7) Same data as col. (6) through 1929. From 1929 to 1992, the Bureau of Economic Analysis implicit deflator for consumer purchases of electricity was used as the price of light (U.S. Dept. of Commerce 1986).

(8) Ratio of the index of Light I to the true price of light.

(9) Ratio of the index of Light II to the true price of light.

nation. For the most part, the other service characteristics are of modest importance and can be tuned to optimal specifications inexpensively. (2) Because of the lack of data on the actual use of different technologies, I construct a frontier price index, which estimates the cost of the best available technology. This obviously would not apply to the backwoods farmer but is likely to apply to city dwellers. (3) I consider only the marginal cost of lighting in terms of fuel. Other costs, including capital, risk, labor, and environmental costs, are omitted primarily because of lack of data. It should be noted, however, that the traditional price indexes also consider only fuel costs.

### *Data and Reliability*

The major contribution of this study is to provide estimates of the price and efficiency of different lighting devices. The procedure begins with estimates of the light output (in lumen-hours) for different lighting devices. A summary of these efficiencies is shown in table 1.3. The data have varying levels of reliability. Estimates from Silliman (1871) and twentieth-century sources are probably quite reliable, while those for other years (particularly for the earliest periods) should be regarded with considerable caution.

Estimates of the prices of fuel come from a variety of sources. Prices for the modern era were drawn either from national data or from local quotations. For the historical periods, Stotz's 1938 history of the gas industry provided most of the data on prices of candles, town gas, kerosene, and electricity. Silliman gathered data on the major fuels for his 1855 experiment. Edison priced electricity in terms of its gas equivalent, writing in 1883: "Our charge for light . . . is at the rate of 1 and 1/5th cents per lamp-hour. . . . A lamp of 16 candlepower was the equivalent of a gas burner supplied with 5 [cubic] feet of gas."[8] This works out to approximately twenty-four cents per kilowatt-hour at the dawn of the electric age, or about three dollars per kilowatt-hour when reflated by McCusker's consumer price index.

### *Prices in Terms of Goods*

The estimates of the true price of lighting are shown in tables 1.4 and 1.5 as well as in figures 1.3 and 1.4. Table 1.4 and figure 1.4 show the nominal price as well as the price in terms of the traditionally measured basket of consumer goods and services.

### *Prices in Terms of Labor*

An alternative measure of the price of light, derived in table 1.6, measures the amount of labor time that would be required to purchase a certain amount of light. This measure is seldom used, so its rationale will be given. It is

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[8] Quoted in Doblin (1982, 20). I am particularly grateful to Clair Doblin for first pointing out many of the sources on lighting efficiency.

**Table 1.5** **Price of Lighting for Different Lighting Technologies**

| Device | Stage of Technology | Approximate Date | Price (cents per 1,000 lumen-hours) |
|---|---|---|---|
| Open fire | Wood | From earliest time | |
| Neolithic lamp | Animal or vegetable fat | 38,000–9000 B.C. | |
| Babylonian lamp | Sesame oil | 1750 B.C. | |
| Candle[a] | Tallow | 1800 | 40.293 |
| | Sperm oil | 1800 | 91.575 |
| | Tallow | 1830 | 18.315 |
| | Sperm oil | 1830 | 42.125 |
| Lamp | Whale oil | 1815–45 | 29.886 |
| | Silliman's experiment: Sperm oil[b] | 1855 | 160.256 |
| | Silliman's experiment: Other oils[b] | 1855 | 59.441 |
| Town gas | Early lamp[c] | 1827 | 52.524 |
| | Silliman's experiment[b,d] | 1855 | 29.777 |
| | Early lamp[c] | 1875–85 | 5.035 |
| | Welsbach mantle[c] | 1885–95 | 1.573 |
| | Welsbach mantle[c] | 1916 | 0.346 |
| Kerosene lamp | Silliman's experiment[e] | 1855 | 4.036 |
| | 19th century[c] | 1875–85 | 3.479 |
| | Coleman lantern[f] | 1993 | 10.323 |
| Electric lamp | Edison carbon lamp[g] | 1883 | 9.228 |
| | Filament lamp | 1900 | 2.692 |
| | Filament lamp | 1910 | 1.384 |
| | Filament lamp[h] | 1920 | 0.630 |
| | Filament lamp[h] | 1930 | 0.509 |
| | Filament lamp[h] | 1940 | 0.323 |
| | Filament lamp[h] | 1950 | 0.241 |
| | Filament lamp[h] | 1960 | 0.207 |
| | Filament lamp[h] | 1970 | 0.175 |
| | Filament lamp[h] | 1980 | 0.447 |
| | Filament lamp[i] | 1990 | 0.600 |
| | Compact fluorescent bulb[i] | 1992 | 0.124 |

[a] Price from Bezanson, Gray, and Hussey (1936). Tallow candles generate 0.75 candles; sperm-oil candles generate 1 candle.

[b] See table 1.2. Price from Silliman (1871).

[c] Price from Stotz (1938).

[d] Gas price is in New Haven, Connecticut.

[e] See table 1.2. Price of kerosene is from 1870.

[f] Price in southern Connecticut, November 1993.

[g] See text under *Data and Reliability*.

[h] Average price of residential use from U.S. Bureau of the Census (1975, S116).

[i] Price of electricity as of 1992.

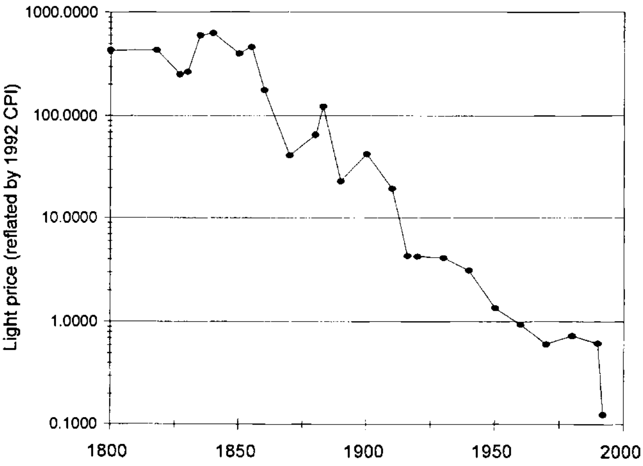

Fig. 1.3 Deflated price of light (cents per 1,000 lumen-hours)

customary to measure the increase in productivity in an industry by the total factor productivity in that industry. This approach is incomplete when we are examining productivity growth of service characteristics. When the service characteristic is produced by a number of different stages (lighting device, fuel, etc.), the impact of all the stages of production must be considered.

In a world where there are $k$ primary factors of production $(L_1, L_2, \ldots, L_k)$, where all goods and characteristics are produced by constant-returns-to-scale production functions, and where we can invoke the nonsubstitution theorem, we can determine the hedonic prices of the service characteristics $(q_1, q_2, \ldots, q_m)$ as unique functions of the factor prices $(w_1, w_2, \ldots, w_k)$. These functions can be written as $q = (q_1, q_2, \ldots, q_m) = Q(w_1, w_2, \ldots, w_k; t)$, where $t$ is a time index that represents the various technological changes that are occurring in the different sectors. The labor cost of a service characteristic, $q_i/w_1$, with labor's price being $w_1$, is defined as the inverse of the index of overall technological change. If labor is the only primary factor of production, then the ratios of $q_i/w_1$ are exact measures of the total increase in productivity for the service characteristic $C_i$. To the extent that there are other primary factors (such as land), the measure used here will misstate the correct input cost index. Given the dominant share of labor in primary input costs, it seems likely that the labor deflation is a reliable measure of total characteristic productivity.

As an example, one modern one-hundred-watt incandescent bulb burning for three hours each night would produce 1.5 million lumen-hours of light per year. At the beginning of the last century, obtaining this amount of light would have required burning seventeen thousand candles, and the average worker would have had to toil almost one thousand hours to earn the dollars to buy the candles.

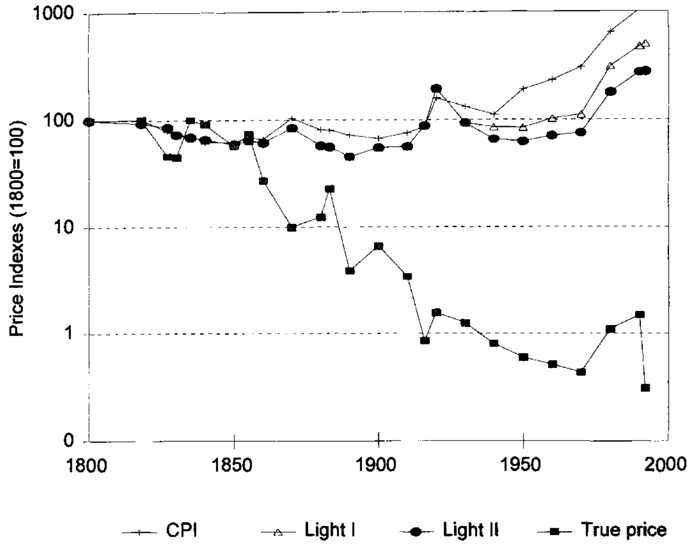

**Fig. 1.4 Alternative light prices**

In the modern era, with a compact fluorescent bulb, the 1.5 million lumen-hours would need twenty-two kilowatt-hours, which can be bought for about ten minutes' work by the average worker. The trend in the labor requirements to buy our daily light is shown in figure 1.5, where the true index is compared with the trend in the required labor according to a traditional index. Figure 1.6 extends the estimates to the labor time required by a Babylonian to fuel the sesame lamps of that period.

## 1.5 Comparison of True and Traditional Prices

Figures 1.4 and 1.7 compare the traditional and true price indexes of light as well as the overall consumer price index. The traditional price of light has risen by a factor of between three and five in nominal terms since 1800. This is not bad compared to all consumer prices (again, the traditional version), which have risen tenfold over the same period.

The true price of light bears little resemblance to the traditional indexes. As can be seen in the tables and figures, the traditional price has risen by a factor of between nine hundred and sixteen hundred relative to the true price. The squared correlation coefficient between the changes in the logarithms of the true price and those of either traditional light price is around .07. For Light II, which is probably the more reliable of the traditional indexes, the average annual bias (the rise in the traditional price relative to the true price) is 3.6 percent per year.

**Table 1.6** **Labor Price of Light**

| Device | Stage of Technology | Approximate Date | Wage Rate (cents per hour) | Labor Price (hours of work per 1,000 lumen-hours) | Price (cents per 1,000 lumen-hours) |
|---|---|---|---|---|---|
| Open fire | Wood | From earliest time | | 58[a] | |
| Neolithic lamp | Animal or vegetable fat | 38,000–9000 B.C. | | 50[b] | |
| Babylonian lamp | Sesame oil | 1750 B.C. | 1 shekel per month | 41.50[a] | |
| Candle | Tallow | 1800 | 7.5[c] | 5.37 | 40.293 |
| | Sperm | 1800 | 7.5[c] | 12.21 | 91.575 |
| | Tallow | 1830 | 6.1[c] | 3.00 | 18.315 |
| | Sperm | 1830 | 6.1[c] | 6.91 | 42.125 |
| Lamp | Whale oil | 1815–45 | 6.1[c] | 4.90 | 29.886 |
| | Silliman's experiment: Sperm oil | 1855 | 10[d,c] | 16.03 | 160.256 |
| | Silliman's experiment: Other oils | 1855 | 10[d,e] | 5.94 | 59.441 |
| Town gas | Early lamp | 1827 | 7.1[c] | 7.398 | 52.524 |
| | Silliman's experiment | 1855 | 10[d,e] | 2.978 | 29.777 |
| | Early lamp | 1875–85 | 15.4[f] | 0.326 | 5.0345 |
| | Welsbach mantle | 1885–95 | 19.0[g] | 0.083 | 1.573 |
| | Welsbach mantle | 1916 | 28.3[h] | 0.012 | 0.346 |
| Kerosene lamp | Silliman's experiment | 1855 | 17.5[c,i] | 0.2306 | 4.036 |
| | 19th century | 1875–85 | 15.4[e] | 0.2253 | 3.479 |
| | Coleman lantern | 1993 | 1,058.0[j] | 0.0098 | 10.323 |

| | | | | | |
|---|---|---|---|---|---|
| Electric lamp | Edison carbon lamp | 1883 | 12.3[k] | 0.750239 | 9.228 |
| | Carbon filament | 1900 | 12.2[l] | 0.220431 | 2.692 |
| | Carbon filament | 1910 | 15.0[l] | 0.092096 | 1.384 |
| | Filament lamp | 1920 | 46.6[l] | 0.013538 | 0.630 |
| | Filament lamp | 1930 | 49.0[l] | 0.010396 | 0.509 |
| | Filament lamp | 1940 | 58.8[l] | 0.005490 | 0.323 |
| | Filament lamp | 1950 | 128.2[j] | 0.001883 | 0.241 |
| | Filament lamp | 1960 | 203.3[j] | 0.001016 | 0.207 |
| | Filament lamp | 1970 | 318.4[j] | 0.000551 | 0.175 |
| | Filament lamp | 1980 | 658.6[j] | 0.000678 | 0.447 |
| | Filament lamp | 1990 | 992.2[j] | 0.000605 | 0.600 |
| | Compact fluorescent | 1992 | 1,049.6[j] | 0.000119 | 0.124 |

*Source:* All data are from earlier tables except wage rates and calculations for the three earliest periods. Sources for wage data are given in specific notes.

[a] See appendix.

[b] The calculation assumes that the Paleolithic lamp is one-third as efficient as the Babylonian lamp. It further assumes that each kilogram (equal to one liter) of animal fat requires 8 hours to catch and prepare (see Pospisil 1963, 227, 254; and Lebergott 1993, 64).

[c] Average monthly earnings of farm workers from U.S. Bureau of the Census (1975, D705) at 250 hours per month. For 1830, this corresponds exactly to the wage rate calculated according to the methodology used in note e.

[d] From table 1.2.

[e] Wages are those paid to a common laborer on the Erie Canal calculated by assuming that the daily work day was 10 hours long. Data are from U.S. Bureau of the Census (1975, D718).

[f] Average annual earnings of nonfarm employees from U.S. Bureau of the Census (1975, D735), assuming 2500 hours per year of work for 1880.

[g] Same as note f for 1890.

[h] Same as note f, but for all workers (U.S. Bureau of the Census 1975, D779).

[i] Wages are from 1870.

[j] Average hourly earnings for private nonfarm industries (Council of Economic Advisers 1993, 396).

[k] Same as note e for 1883.

[l] Same as note f using U.S. Bureau of the Census (1975, D723).

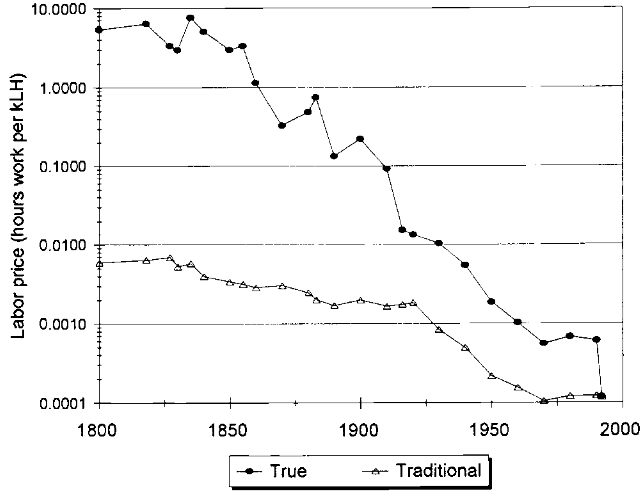

Fig. 1.5 Labor price of light: true and traditional

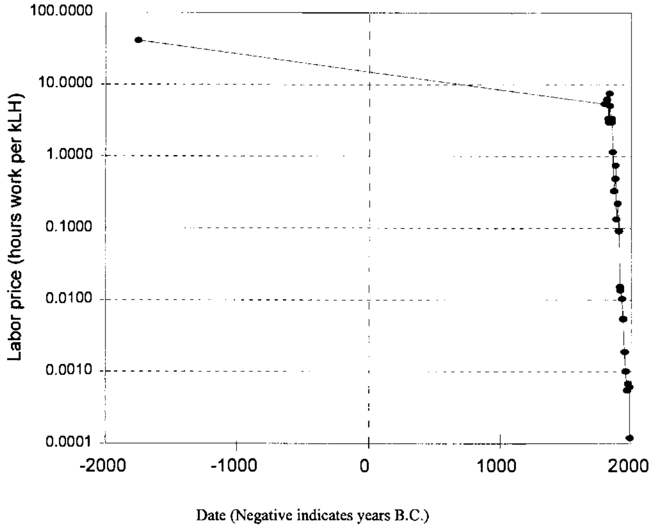

Fig. 1.6 Labor price of light: 1750 B.C. to present

## 1.6 Do Real-Wage and -Output Indexes Miss All the Action?

Having seen how far the price of light misses the truth, we might go on to ask whether light might be a representative slice of history. In other words, is it possible that by the very nature of their construction, price indexes miss the most important technological revolutions in economic history? I suggest that

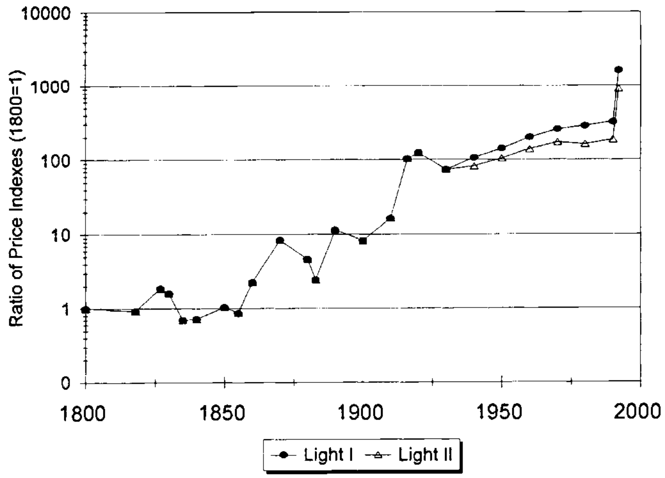

**Fig. 1.7 Bias in price index: ratio of conventional to true price**

the answer might well be yes. By design, price indexes can capture the small, run-of-the-mill changes in economic activity, but revolutionary jumps in technology are simply ignored by the indexes. What is surprising is how pervasive the range of revolutionary products is. In this section I look at how price indexes treat quality change, examine the treatment of selected inventions, estimate the range of poorly measured consumption, and then hazard an estimate of the potential bias in real wage and real output measures.[9]

## 1.6.1 Treatment of Quality Change and Inventions in Practice

### *Traditional Long-Term Estimates of Consumer Prices*

In constructing estimates of either real wages or real output, I begin with the relatively firm data of nominal wages or output and deflate them with an estimate of a price index of the consumption bundle or of outputs produced. The measurement of real wages over the last two centuries uses a series of consumer price indexes that have been built by the painstaking research of generations of economic historians including Ethel Hoover, Alvin Hansen, Paul Douglas, Stanley Lebergott, and Paul David.[10] A review of these studies indicates three features: First, most of the early indexes were heavily weighted toward foods. For example, Alvin Hansen's estimates of the cost of living from 1820 to 1840 used prices of twelve foods and three clothing items. Second, most of the early indexes relied upon wholesale prices and assumed that con-

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[9] The question of the bias in traditional price measures and the consequent bias in real incomes has been considered in many studies. See, for example, Baily and Gordon (1988) and Gordon (1990, 1993).

[10] See a recent survey in McCusker (1991).

sumer prices changed proportionally with wholesale prices. This is particularly the case for the subject of this study. For example, the Douglas estimates of the cost of living used wholesale prices for "fuel and light" for the period 1890–1926, with the wholesale prices being adjusted to retail prices on the basis of an assumed uniform markup.

The third and most important point is that until the modern age, all "cost-of-living" indexes were in reality indexes of "prices of goods bought by consumers." Collecting goods prices was itself a Herculean task, but we must recognize that these indexes did not measure the trend in the efficiency or *services* delivered by the purchased goods. Hence, the fact that one Btu of gas bought in the nineteenth century delivered a quantity of heat or light quite different from one Btu of electricity bought in the twentieth century never entered into the construction of the price indexes.

The inattention to the services delivered by the purchased good would not matter much if goods changed little or if new products or processes were absent. But during this period, as was seen clearly in the case of lighting and as is suggested below for other goods and serices, there were profound changes in the very nature of virtually all goods and services. Given the inattention to measurement of quality change, it is questionable whether the entire range of qualitative changes is correctly captured today, and there can be no question that it was completely ignored in the period before World War II.

### *Traditional Treatment of Major Inventions*

For revolutionary changes in technology, such as the introduction of major inventions, traditional techniques simply ignore the fact that the new good or service may be significantly more efficient. Consider the case of automobiles. In principle, it would be possible to link automobiles with horses so as to construct a price of travel, but this has not been done in the price statistics for just the reasons that the true price of light was not constructed. Similar problems arise as televisions replace cinemas, air travel replaces ground travel, and modern pharmaceuticals replace snake oil.

The omission of quality change and particularly revolutionary technological change does raise the possibility that most of the action of the Age of Invention was simply missed in our traditional real-product and real-wage measures. Table 1.7 presents a selection from Jewkes, Sawers, and Stillerman's list of the one hundred great inventions (1969). Note how little of the impact of these great inventions was captured in traditional price indexes.

This discussion leads to the thought that the standard methodology of price indexes may be destined to capture the small changes but to miss the revolutionary improvements in economic life. The last century has seen massive changes in transportation, communications, lighting, heating and cooling, and entertainment. Indeed, the tectonic shocks of changing technologies have occurred in virtually every area. Food is perhaps an exception in that the products are superficially the same. Indeed, the relative stability of food products suggests the reason food is the fixed star in all long-term consumer price indexes;

**Table 1.7 Treatment of the Great Inventions**

| Invention | Treatment in Price Indexes |
|---|---|
| Aeronautics, helicopter | Except for lower costs of transportation of intermediate goods, lower prices not reflected in price indexes |
| Air-conditioning | Outside of refrigerated transportation and productivity increases in the workplace, amenities and health effects not captured in price indexes |
| Continuous casting of steel | A process innovation that showed up primarily in lower costs of intermediate goods and thus was reflected in price indexes of final goods |
| DDT and pesticides | Some (now questionable) benefits probably included in higher yields in agriculture and therefore included in price indexes; health benefits and ecological damages largely excluded from price indexes |
| Diesel-electric railway traction | A process innovation that showed up primarily in the price of goods and services |
| Insulin, penicillin, streptomycin | Improved health status not captured in price index |
| Internal combustion engine | Except for lower costs of transportation of intermediate goods, lower prices not reflected in price indexes |
| Long-playing record, radio, television | Major product inventions that are completely omitted from price indexes |
| Photo-lithography | Largely reflected in reduced printing costs |
| Radar | A wide variety of improvements, some of which might have shown up in lower business costs and prices (such as lower transportation costs or improved weather forecasting) |
| Rockets | A wide variety of implications: major application in telecommunications showed up in consumer prices; improvements in television not captured in price indexes; improved military technology and nuclear-war risk not reflected in prices |
| Steam locomotive | Reduced transportation costs of businesses reflected in price indexes; expansion of consumer services and nonbusiness uses not reflected |
| Telegraph, telephone | Improvements over Pony Express or mail largely unreflected in price indexes |
| Transistor, electronic digital computer | As key inventions of the electronic age, impacts outside business costs largely omitted in price indexes |
| Xerography | Major process improvement: some impact showed up in reduced clerical costs; expansion of use of copied materials not captured in price index |
| Zipper | Convenience over buttons omitted from price indexes |

*Note:* Inventions are selected from Jewkes, Sawers, and Stillerman (1969).

in addition, the omnipresence of food is a tip-off that the price indexes are misleading.

## *A Classification of Consumption Changes*

The last section suggested that existing price indexes—and perforce existing measures of real output and real incomes—fail to capture the major shifts in technologies and therefore underestimate long-term economic trends. How pervasive are these major shifts? This is an awesomely difficult question, and in this section I present a *Gedankenexperiment* that suggests the importance of qualitative change in economic life.

The approach taken here is to examine *today's consumption bundle,* and then to divide it into three categories. In each case, the question is how great the change in the good or service has been since the beginning of the nineteenth century:

1. *Run-of-the-mill changes.* This category of good is one where the changes in technology have been relatively small and where price indexes are likely to miss relatively little of the quality change or impact of new goods. This category includes primarily home consumption of food (such as potatoes), most clothing (such as cotton shirts), personal care (such as haircuts), furniture, printed materials (such as books), and religious activities (such as going to mass). In these areas, there are to be sure some categories where life has improved in ways that are not captured, such as more timely news, pasteurized milk, and high-tech running shoes. But the overall underestimate of quality change is likely to be much less than that which we uncovered for light.

2. *Seismically active sectors.* A second category is one where there have been both major changes in the quality of goods and provision of new goods, but where the good or service itself is still recognizably similar to its counterpart at the beginning of the nineteenth century. Examples in this category are housing (such as high-rise apartments), watches (which still tell time but do it much more accurately while simultaneously taking your pulse and waking you up), personal business (including financial services and the information superhighway), space-age toys, and private education and research.

3. *Tectonic shifts.* The final area is the category in which lighting is placed. It is one where the entire nature of the production process has changed radically. In these sectors, the changes in production and consumption are so vast that the price indexes do not attempt to capture the qualitative changes. This category includes household appliances (such as refrigerators and air conditioners), medical care, utilities (including heating, lighting, and other uses of electricity), telecommunications, transportation, and electronic goods (such as radio and television). In each of these cases, there is virtually no resemblance between the consumption activity today and that in the early nineteenth century. Indeed, in many cases, the basic science or engineering that underpins the technology was undiscovered or poorly understood in the earlier age.

Clearly, this categorization is extremely rough, and refinements would probably shift some of the sectors to different categories. It is unlikely, however, that the size of the category experiencing tectonic shifts would shrink. Because of the aggregation, it is likely that many tectonic shifts are buried in run-of-the-mill or seismically active sectors. For example, the lowly toilet is classified as furniture but delivers a service that would delight a medieval prince.

Table 1.8 shows the basic breakdown for 1991. According to this categoriza-

**Table 1.8** **Consumption by Extent of Qualitative Changes, 1991 ($ billion)**

| Sector | Run-of-the-Mill Sectors | Seismically Active Sectors | Tectonically Shifting Sectors |
|---|---|---|---|
| Food | | | |
| Home consumption | 419.2 | | |
| Purchased meals | | 198.5 | |
| Tobacco | | 47.8 | |
| Clothing | | | |
| Apparel | 208.9 | | |
| Cleaning and services | | 21.1 | |
| Watches and jewelry | | 30.6 | |
| Personal care | | | |
| Toilet articles | | 38.2 | |
| Services | 24.0 | | |
| Housing | | | |
| Dwellings | | 574.0 | |
| Housing operation | | | |
| Furniture and utensils | 116.3 | | |
| Appliances | | | 25.5 |
| Cleaning and polishing | | 52.8 | |
| Household utilities | | | 143.2 |
| Telephone and telegraph | | | 54.3 |
| Other | 49.6 | | |
| Medical care | | | 656.0 |
| Personal business | | | |
| Legal and funeral | 60.3 | | |
| Financial and other | | 257.5 | |
| Transportation | | | 438.2 |
| Recreation | | | |
| Printed | 42.9 | | |
| Toys | | 32.3 | |
| Electronics and other goods | | | 84.2 |
| Other | 51.7 | 51.2 | 27.4 |
| Private education and research | | 92.8 | |
| Religious and welfare | 107.7 | | |
| Total | 1,080.6 | 1,396.8 | 1,428.8 |
| Percent of total | 27.7 | 35.8 | 36.6 |

*Source:* Prepared by the author based on U.S. Department of Commerce (1986), with updates from BEA's *Survey of Current Business.*

*Note:* "Run-of-the-mill" sectors are ones in which the goods or services have changed relatively little or in which price indexes can measure quality change relatively easily. "Seismically active" sectors are ones in which the goods or services are recognizable from the early 19th century but for which there is likely to have been major changes in quality and great difficulty in measuring quality change accurately. Industries subject to "tectonic shifts" are ones in which the nature of the good or service has changed drastically (as in lighting) or for which the good or service did not exist at the beginning of the 19th century (as in antibiotics).

tion, about 28 percent of current consumption has experienced minor changes over the last two centuries, 36 percent has been seismically active, and 37 percent has experienced tectonic shifts. In other words, almost three-quarters of today's consumption is radically different from its counterpart in the nineteenth century. As a result, it is likely that estimates of the growth of real consumption services is hampered by significant errors in the measurement of prices and that for almost two-fifths of consumption the price indexes are virtually useless.

### 1.6.2 Measuring True Income Growth

#### *Theoretical Background*

How badly biased might our measures of real wages and real incomes be? The measurement of true income growth obviously depends crucially on the correct measurement of both nominal incomes and true price indexes. Measurement of nominal incomes is probably subject to relatively modest error for marketed commodities, but the measurement of true prices may be far off the mark. We can obtain an exact estimate of the bias in measurement of real income and real wages as follows.

I assume that the appropriate measure of real income, $R(t)$, is a smooth utility function of the form $U[C_1(t), C_2(t), \ldots]$, where $C_i(t)$ is the flow of service characteristic $i$ at time $t$. I do not assume any particular form for $R$. All that is needed is the customary assumption that the utility function is locally constant returns to scale. Under this assumption, I can in principle construct Divisia indexes of real-income changes by taking the weighted average growth of individual components.

It will be more convenient to transform the direct utility function into a *characteristic indirect utility function* of the following form:

$$R = V(q_1/I, q_2/I, \ldots, q_n/I). \tag{5}$$

(In this discussion, I suppress the time dimension where it is unnecessary.) This utility function has all the properties of the standard indirect utility function except that the prices are characteristics prices rather than traditional goods prices. $R$ in equation (5) is a measure of real income in that it represents the utility that can be obtained with market prices and income.

I would like to estimate the *bias in the measurement of real income due to the mismeasurement of the prices of service characteristics.* For simplicity, assume that the only price that is incorrectly measured is the first (say, the price of light). Assume that $q_1^*$ is the measured price of the characteristic and $q_1$ is the true price; then rewrite the utility function as

$$R = V[(q_1/q_1^*)(q_1^*/I), q_2/I, \ldots, q_n/I]. \tag{6}$$

The ideal measure of real income is the measure of utility in equation (6). Further, the growth in real income can be calculated as the growth in $R$ over time. Let $g_Z$ be the rate of growth of variable $Z$. Then, because the $V$ function is locally linearly homogeneous, the growth in utility (equal to the growth of real income) is given by

$$(7) \qquad g_R(t) = g_I(t) - [\sigma_1(t)g_{q_1}(t) + \sigma_2(t)g_{q_2}(t) + \dots],$$

where $\sigma_i(t)$ equals the (local) share of spending on service characteristic $i$ in total spending at time $t$. Note that because the share of income devoted to spending on characteristic $i$ is unaffected by the bias in the calculated price, the calculated share can be estimated without any hedonic correction. This implies that the bias in the calculation of real income or real output, $g_R(t)^* - g_R(t)$, is simply equal to

$$(8) \qquad \text{Bias in measuring real income growth} = g_R(t)^* - g_R(t)$$
$$= \text{Bias from good 1} = \sigma_1(t)\,[g_{q_1}(t) - g_{q_1^*}(t)].$$

In words, the bias in the growth rate of real income or real output is equal to the share of the service in total consumption times the bias in the growth rate of the service in question.

### *Bias for Lighting*

I calculate the bias in real income using the data in the tables and the formula in equation (8). According to my calculations, the average annual bias for lighting is 3.6 percent per year. The share of lighting in total consumer expenditures is difficult to estimate (see table 1.9). It probably consisted of slightly above 1 percent of budgets in the last century but has declined to less than 1 percent today; I assume that light's share averaged 1 percent over the last two hundred years. This suggests that the real-wage and -output growth using Light II has been underestimated by 0.036 percent per year because of the misestimate of lighting's price alone.

Using the formula in equation (8), and assuming a constant share, I find the

**Table 1.9** **Budget Studies on Lighting**

| Period | Household Income ($/year) | Spending on Lighting ($/year) | Spending on Lighting (% of spending) | Total Lighting (1,000 kilolumen-hours) |
|---|---|---|---|---|
| 1760s | £48 | £0.45 | 0.94 | 28 |
| 1815–55 | 180 | 22.0 | 12.2 | 117 |
| 1875 | 333 | 2.2 | 0.7 | 48 |
| 1880 | 309 | 30.0 | 9.7 | 988 |
| 1890 | 354 | 25.0 | 7.1 | 1,170 |
| 1960 | 7305 | 23.5 | 0.3 | 13,241 |

*Sources:* For 1760s, for a Berkshire family, from Burnett (1969, 167); for 1815–55, 1880, and 1890 from Stotz (1938); for 1875 from Hoover (1960, 183) from a survey of 397 families; for 1960 from Darmstadter (1972) for electricity from lighting.

total bias in the growth of real income or real wages for Light II to be 0.01 × log(0.036 × 192) = 0.068 (or 0.074 for Light I). In other words, just correcting for light adds 7 percent to the total growth of real wages over the period 1800–1992. In terms of dollar values, the bias in the measurement of the price of lighting (using Light II) would increase the value of consumption by about $275 billion in 1992 relative to 1800. This is approximately equal to the consumer's surplus equivalent of the unmeasured quality change in lighting.

### *A* Gedankenexperiment *for All Consumption*

To calculate the potential bias for all consumption requires assumptions about how much the bias in the measurement of the true price of different categories might be. There are few proxies to use. One measure is that for light, where I determined that the true price of light fell 3.6 percent per year relative to the traditionally measured price of light. Other hedonic indexes include that for computers, where the estimated bias is close to 15 percent per year, and that compiled by Robert Gordon for capital goods, where the bias is estimated to be 3 to 4 percent per year (see Gordon 1990).

For the thought experiment, I assume a "high" and a "low" estimate for the bias. For the low estimate, I assume that there has been no bias in the run-of-the-mill sectors, a bias in the seismically active areas that is one-fourth the estimated bias for light, and a bias in the tectonic sectors that is one-half that of light. (See table 1.8 for a list of the different industries in each category.) For the high-bias estimate, I assume a bias of 0.5 percent per year in the run-of-the-mill category, a bias one-half that of light in the seismically active areas and a bias equal to that of light in tectonically shifting sectors. More specifically, the bias rates are 0, 0.93, and 1.85 percent annually for sectors 1, 2, and 3 in the low case and 0.5, 1.85, and 3.7 percent annually for the same sectors in the high case. In addition, I have taken the shares of the different sectors in 1929 from the same sources used for table 1.8 and made rough estimates from budget studies of the budget shares over the last century. By this reckoning, the share of the run-of-the-mill sectors has decreased from about 75 percent of total consumption at the beginning of the last century to 28 percent today.[11]

The base estimate of the rate of growth of real wages from 1800 to 1992 is 1.4 percent per year using traditional price indexes. The estimated growth rate is 1.9 percent per year with the low assumption about the bias in price indexes and 2.8 percent per year with the high assumption. In terms of living standards,

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[11] The calculation of the bias for consumption was constructed as follows. I calculated from the National Income and Product Accounts for 1929 the same breakdown of consumption between the three innovation categories (run-of-the-mill, seismically active, tectonically shifting) as shown in table 1.8. For each major consumption sector (food, clothing, etc.), I then estimated for 1929 the share of each of the three innovation categories. The next step was to obtain budget studies for the years 1874, 1890, 1901, and 1918 (from U.S. Bureau of the Census 1975), with an extrapolation back to 1800 using English data from Burnett (1969), shown in table 1.9. I then constructed a Törnqvist index of the bias by taking the within-period shares of each of the major consumption sectors and multiplying them by the estimated bias for each sector, using the estimated low or high bias as stated above and the proportion of each of the three innovation categories.

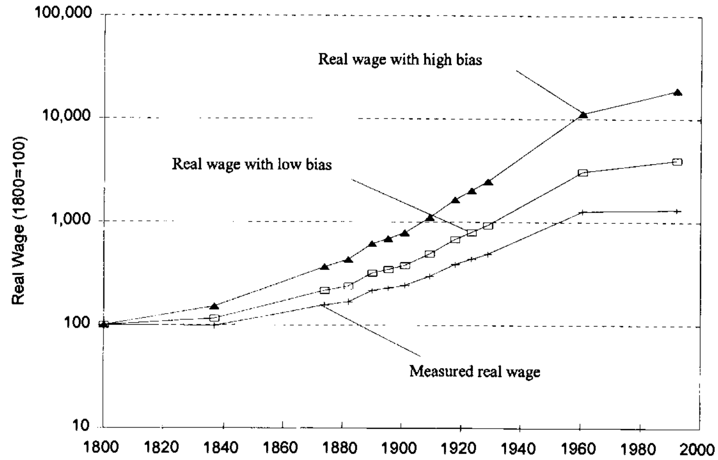

Fig. 1.8 **Traditional and true real wages**

the conventional growth in real wages has been by a factor of 13 over the 1800–1992 period. For the low-bias case, real wages have grown by a factor of 40, while in the high-bias case real wages have grown by a factor of 190. Figure 1.8 shows the trends in real wages according to the measured real-wage series along with the estimated true real wages with the high and the low estimate of the bias in measuring consumer prices.

Note as well that because the composition of consumption has evolved over the last two centuries from predominantly run-of-the-mill sectors to more technologically active sectors, the degree of bias or underestimate of real-wage increases has probably increased over this period. Under the methodology for estimating bias used here, the bias has more than doubled from 1800 to 1992 according to the low-bias assumption and has slightly less than doubled according to the high-bias assumption.

Clearly, the alternative estimates of real-wage growth provided by the thought experiment are highly speculative. On the other hand, they are consistent with an emerging set of estimates in the literature on hedonic prices that suggests that we have greatly underestimated quality improvements and real-income growth while overestimating inflation and the growth in prices.

## 1.7 Conclusion

I have shown that for the single but extraordinarily important case of lighting traditional price indexes dramatically overstate the true increase in prices as measured by the frontier price of the service characteristic. This finding implies that the growth in the frontier volume of lighting has been underestimated by a factor of between nine hundred and sixteen hundred since the beginning of the industrial age.

If the case of light is representative of those products that have caused tectonic shifts in output and consumption, then this raises the question of whether the conventional measures of real-output and real-wage growth over the last two centuries come close to capturing the true growth. Of today's consumption, perhaps one-quarter has undergone only modest changes since the mid-nineteenth century (locally grown foods, clothing, some types of personal care). More than one-third of consumption takes place in tectonically shifting industries and in ways that were virtually unimaginable at that time—including medical care, transportation, recreation, and much of household operation. If the half of consumption that takes place in tectonically shifting industries shows even a small fraction of the unmeasured growth that we have uncovered in lighting, then the growth of real wages and real incomes in conventional estimates might be understated by a very large margin.

While this point may get lost in the details of national income accounting, it was obvious to Adam Smith even before the Age of Invention:

> Compared with the extravagant luxury of the great, the accommodation . . . of the most common artificer or day-labourer . . . must no doubt appear extremely simple and easy; and yet it may be true, perhaps, that the accommodation of a European prince does not always so much exceed that of an industrious and frugal peasant, as the accommodation of the latter exceeds that of many an African king, the absolute master of lives and liberties of ten thousand. (1776, 12)

# Appendix

## *Estimates for Babylonian Lamps and Peking-Man Fires*

For early technologies, no references were found on either lighting efficiency or costs. To provide rough data on these, I undertook measurements for sesame oil and firewood. All measurements of illumination were taken using a Minolta TL-1 illuminance meter.

For fire, 21 pounds of firewood were burned in a standard home fireplace. This provided measurable illumination for 3.4 hours with an average level of illumination of 2.1 foot-candles. The zone of illumination is less than a candle because of the floor and walls, so the average illumination is assumed to be 5 lumens per foot-candle, for a total illumination of 1.7 lumen-hours per pound. At an energy content of 5 million Btu per ton, this yields 0.69 lumen-hours per thousand Btu. I have no reliable data on prehistoric labor costs of obtaining firewood. It is assumed that 10 pounds of firewood could be foraged, trimmed, and dried in 1 hour. This yields 58 hours of work per one thousand lumen-hours.

For sesame-oil lamps, I purchased a Roman terra-cotta lamp supplied by Spirits, Inc., of Minneapolis, Minnesota. It was certified as dating from Roman times and closely resembled museum artifacts from Roman times that I viewed, but its age could not be independently verified. This lamp was fueled by 100 percent Hunza pure cold-pressed sesame oil with a wick extracted from a modern candle. This proved a remarkably efficient device, with an efficiency very close to that of a modern candle. One-quarter cup (60 ml) burned for 17 hours with an average intensity of 0.17 foot-candles. The zone of illumination is less than a candle's and is estimated to be 10 lumens per foot-candle. The total illumination was therefore 28.6 lumen-hours, for an efficiency of 17.5 lumen-hours per thousand Btu. This represents a major improvement in efficiency over firewood.

To obtain the labor price of Babylonian illumination, I assume that Babylonian lamps are reasonable represented by the Roman terra-cotta lamp and that the measurements are representative. Wages were around 1 shekel per month during the period investigated, while sesame oil sold for approximately 0.1 shekel per liter. Using the data on illumination, this yields 42 hours of work per one thousand lumen-hours. Note that while this is no major improvement over the estimated labor price of firewood, the quality of the light from the lamps is far superior and the lamp is much more easily controlled.

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# Comment

## Charles R. Hulten

It is hard to imagine a more appropriate place than Colonial Williamsburg in which to discuss a paper on historical living standards. Step outside the conference center and you enter the life of the late eighteenth century. Stroll down the main street of Williamsburg and you see the techniques used to make can-

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dles, wigs, barrels, and other items of eighteenth-century life. Enter a tavern or private dwelling and you have a window on the daily life of that era. At some point during the visit, you will probably ask yourself, "What would my life have been like had I been born two hundred years earlier?"

According to Bill Nordhaus, you would have been quite a bit poorer—far poorer than indicated by official statistics and very much poorer than the casual experience of Williamsburg would probably suggest. Working with what is undoubtedly the longest time series in econometric history—from Peking man to the present—Nordhaus argues that "traditional price indexes of lighting vastly overstate the increase in lighting prices over the last two centuries, and the true rise in living standards in this sector has consequently been vastly understated." The magnitude is truly remarkable: according to the estimates of this paper, "the traditional price has risen by a factor of between nine hundred and sixteen hundred relative to the true price." This leads to the conclusion that it is possible "that by the very nature of their construction, price indexes miss the most important technological revolutions in economic history."

An attempt to quantify the magnitude of the "miss" is presented in section 1.6. A *Gedankenexperiment* is performed there which leads to the conclusion that, when quality improvements are taken into account, real wages may have increased by a factor that ranges from 40 (the low-bias case) to 190 (the high-bias case) over the period 1800–1992. The conventional (non–Nordhaus corrected) growth of real wages has been a factor of 13–18 over this period. This is clearly a very large miss.

The magnitude of this result may incline some readers to skepticism. However, the size of the quality correction for lighting should evoke no surprise from those familiar with the paper by Cole et al. (1986) on adjusting the price of computers for quality change. That paper implied that quality improvements in computing equipment have proceeded at double-digit rates (10 to 20 percent per year) for several decades. In light of the Cole paper, a major contribution of the current paper is to show that the computer result is not an isolated phenomenon.

Indeed, the two papers together virtually force the debate over appropriateness of the conventional goods approach of standard economic theory. Textbook treatments of supply and demand are based on the market transaction of well-defined goods like candles, oil lamps, and electric lightbulbs. This is the paradigm that is found wanting when improvements in quality take the form of new goods—lamps replacing candles, for example. The alternative offered by Nordhaus, Cole et al., and many others (including Robert Gordon, Zvi Griliches, Robert Hall, Sherwin Rosen, and Jack Triplett) is to organize the analysis by the characteristics delivered by goods, rather than by the goods themselves. In this paradigm, the principal characteristic linking candles, oil lamps, and lightbulbs is the amount of light that they produce.

The two paradigms are not necessarily incompatible. Goods can be seen as "packages" of characteristics, so that statements that apply to one must also apply to the other. Ideally, the issue under consideration should dictate which form of analysis is most useful. For example, when the main issue is about market structure, the goods approach may be preferred, because goods are the unit of market transaction. On the other hand, when new goods that embody old characteristics appear in the market place, the use of the characteristics technique may be a more useful way to measure the contribution to growth or welfare. And, according to Nordhaus, the alternative goods approach in this context can be highly misleading.

It is now clear that economic historians, productivity specialists, and just about everyone else in the economics profession must recognize that quality change is an important source of welfare improvement that is almost certainly missed by conventional measurement techniques. However, it must also be recognized that even if the goods approach does give the wrong answer, it does not follow that the characteristics approach in its current incarnation necessarily gives the right answer. Indeed, the following extension of Nordhaus's *Gedankenexperiment,* which asks what level of per capita income is implied by the Nordhaus results, suggests that the characteristics answer may *overstate* the true amount of welfare gain: When 1991 disposable personal income per capita in the United States (approximately $17,200) is adjusted by the conventionally measured wage-deflation factor of 13 cited by Nordhaus for the period 1800–1992, the result is a real disposable income of around $1,300 in 1800; on the other hand, if Nordhaus's low-bias deflator is used, the resulting 1800 income in the United States is only about $430; the high-bias deflator yields an estimate of 1800 real disposable income of $90.

Taken literally, these comparisons imply that a person possessing the average disposable income in America today should be willing to accept a massive reduction in spending power—from $17,200 to the $90–430 range—in order to avoid being sent back in time to an equivalent status in colonial America. Alternatively, it suggests that the average colonial should prefer living in the America of today, with as little as $90 per year, to staying put in the late eighteenth century. It is hard to imagine anyone wanting to live in modern America with an income of $90; it is only just imaginable that anyone would want to live with an income at the upper end of the Nordhaus range.

This extension of the Nordhaus *Gedankenexperiment* is obviously rather loose. It compares living standards across vastly different cultural and economic milieus, and it does not include other types of purchasing power parity adjustments that tend to narrow income differentials between rich and poor economies (i.e., the PPP corrections that raise real per capita income in Mozambique from $60 to $570). However, while it is certainly possible that the average American colonial was about as well-off as the average resident of the poorest contemporary countries, the size of the Nordhaus adjustment invites the speculation that there may be upward biases in the characteristics approach to valuing new goods.

A full treatment of this issue is beyond the scope of this comment and, since

I agree with the thrust of Nordhaus's results, if not with their magnitude, I will only offer the following illustration of how the characteristics approach might yield misleading results. Consider a characteristic, X, for which the process of innovation is essentially serendipitous and costless. X is packaged with another characteristic, Y, into a good Z. Suppose, now, that a run of good luck and inspiration yields a surge of technical improvements that increases the effective quantity of X, first from an index of 100 to 200, then from 200 to 300; Y remains unchanged. Suppose, finally, that the marginal value of the second increment of 100 units of X is far less than the marginal value of the first increment because Y is fixed, though both exceed the marginal cost, which we take to be zero. Let us also assume that the first improvement in X for fixed Y translates into a marginal change in value in the good Z from an index of 100 to 150, and the second improvement in X yields a change in Z from 150 to 160.

In this scenario, an analysis which focused on the characteristic X in isolation would suggest a threefold improvement in welfare, whereas the effective increase is only 60 percent. In other words, there is an upward bias in the characteristics approach. On the other hand, a purely goods-based approach leads to the opposite bias. Since the improvement in X is essentially costless, the price per unit of Z is unchanged even though it embodies more of the characteristic X. A statistician using conventional goods-oriented techniques would thus attribute a zero effect to the innovation in X.

This is a stylized example, but it may apply in some degree to real-world cases. The replacement of horses by cars, for example, obviously brought on a major revolution in transportation that is certainly understated by a simple comparison of horsepower. However, once the new technology became established, further increases in power were far less significant given the other characteristics of the transportation package (the basic nature of cars, roads, and drivers). The fact that cars can now be propelled to speeds in excess of three hundred miles per hour by hugely powerful engines is important to only a handful of race-car drivers and enthusiasts. A simple characteristics index that focused only on the characteristic "maximum available horsepower" would not pick up these nonlinearities and would assign the same weight to the five fold increase from one hundred to five hundred horsepower that it assigned to the increase from one to five horsepower.

There may be a similar problem with the use of the characteristic "maximum available lumens" to measure the progress in providing light, and with the use of an index like "million instructions per second" (MIPS) to measure increases in computing power. As with horsepower, there is probably some level of both lumens and MIPS at which most users are satiated (particularly when other characteristics are held equal or change gradually).

The example set out above applies to the case in which the costs of innovation are small relative to the benefits. Some attention must also be given to those situations in which the costs and benefits of innovation are fully arbitraged. If, for example, a new type of lightbulb is four times more efficient but also costs four times as much to put in the light socket, then there is no net improvement in welfare ("better" investment is equivalent to more investment in this case). Something like this seems to have happened with the new generation of high-efficiency lightbulbs, which cost a great deal more than their less-efficient predecessors. In this case, a characteristics index based solely on the saving of energy (i.e., one that does not pick up the full cost dimension) will overstate the welfare improvement.

These caveats should not, however, deflect attention from the contribution made by this ingenious and highly original paper. While there is no characteristics index of the value of scientific ideas—no index of *veritas* to match the Nordhaus index of *lux*—the contribution of this paper to the goods versus characteristics debate is undoubtedly very large. Although much more remains to be done on the "technology" of the characteristics approach, Nordhaus, by demonstrating that the Cole et al. finding on computers is not an isolated case, has established the presumption that the chararacteristics approach to new technologies is the most promising way of treating the difficult and important problem of new goods.

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