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

by

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Abstract

Historical studies of the growth in real wages and output depend upon the accurate measurement of the price trends of goods and services. Over long periods of time, the consumption bundle has changed profoundly, and most of today's consumption includes items that were not produced, and in some cases not even conceived, at the beginning of the 19th century. This paper tackles the issue of the quantitative significance of the qualitative change in consumption by choosing a single service -- lighting -- for which the service characteristic -- illumination -- is invariant. We estimate changes in lighting efficiency and construct a "true" price index back to Babylonian times, with the major emphasis on changes over the last two centuries. A comparison of the true price of light with a traditional light price indicates that traditional price indexes overstate price growth, and therefore understate output growth, by a factor between 900 and 1600 since the beginning of the nineteenth century. This finding suggests that the "true" growth of real wages and real output may have been significantly understated during the period since the Industrial Revolution.

Do Real Income and Real Wage Measures Capture Reality? The History of Lighting Suggests Not

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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 shows, real incomes (measured either as real wages or per capita GNP) have grown by a factor of between 13 and 18 since the first half of the 19th century. An examination of the growth in real wages indicates that real wages grew around 1 percent annual for three of the half-centuries and much faster for the first half of the 20th century.

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 need to construct 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 that we consume today were not produced a century ago. We travel in vehicles that were not yet invented, powered by fuels not yet produced, talk on devices not yet manufactured, enjoy cool air

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[1] Helpful comments on economics, physics, and the index-number practices were given by Ernst Berndt, William Brainard, Carole Cooper, William English, Robert J. Gordon, Zvi Griliches, Tim Guinnane, Charles Hulten, Stanley Lebergott, Michael Lovell, Joel Mokyr, Sherwin Rosen, Alice Slotsky, Robert Solow, T. N. Srivivasan, and Jack Triplett. Robert Wheeler brought the diary and experiments of B. Silliman Jr. to my attention. All errors and flights of fancy are my responsibility.

on the hottest days,[2] 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 recognize the vast change in the quality and range of goods and services that we consume, that somehow compare the services of horse and automobile, or facsimile machine and Pony Express, of Xerox machine and carbon paper, of television with dark and lonely nights, of magnetic resonance imaging with brain surgery.

A complete reckoning of the impact of new and improved consumer goods on our living standards is at best an epic task and at worst infeasible. 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 where 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 the following: We begin with an analysis of the history of lighting focussing our attention particularly on the revolutionary developments in this field. We 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 we engage in a *Gedankenexperiment* on the extent to which revolutionary changes in technology may lead to similar biases for other consumer goods and services and the consequent underestimate of the growth of real incomes over the last century.

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[2]The revolutionary implications of air conditioning are considered in Oi [1994].

2. Milestones in the History of Light

2.1. Basic Measurement Conventions

Begin with some simple conventions. What humans call "light" is radiation that stimulates the retina of the human eye. This occurs in what is called the visible spectrum, which occurs for wavelengths between 4×10^{-7} and 7×10^{-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 100-watt filament bulb about 1200 lumens, and an efficient 18-watt compact fluorescent about 1290 lumens. The unit of illuminance (the amount of light per unit area) is defined as the lux, and one lumen per square meter provides 1 lux. Unobstructed daylight provides a lux of about 10,000 while the level of illuminance of an ordinary home is about 100 lux. In the candle age, a room lit by two candles would enjoy about 5 lux.

The efficiency of a lighting device can be measured in many ways, but for our purposes we generally measure it by *lumenhours per thousand Btus*. An alternative measure often used today is *lumen per watt*.

2.2. Evolution

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

2.3 Open fires

The first use of artificial or produced light almost surely coincided with the controlled use of fire. The first tool, known as the Oldowan chopper, has been dated from 2.6 million ybp (years before present), while the tentative identification of domesticated fire used by *h. australopithecus* were discovered in Africa and date from 1.42 million ybp. More definitive evidence of the controlled use of fire was found in the caves of Peking man (*h. erectus*) around 500,000 ybp. 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 for a brief chronology of the history of light.)

2.4. Lamps

Open fires are relatively inefficient, and *h. sapiens* not only developed the ability to start fires (dated as early as 9000 ybp) but also to develop capital equipment for illumination. The first known lighting tool was a stone, fat-burning lamp, used in Western Europe, and found most abundantly in southern France. According to de Beaune and White [1993], almost 200 fat-burning Paleolithic lamps dating from 42,000 to 17,000 ybp have been identified. These lamps were made from limestone or sandstone and can easily be fashioned with shallow depressions to retain the melted fuel. Using chemical analyses, the residues of the fuel have been found to resemble animal fat. De Beaune and White estimate that the Paleolithic lamps had the lighting power of a candle. Modern replicas are relatively easy to build, requiring but a half-hour, suggesting that, like modern lights, most of the costs of early lighting devices were in the fuel rather than in capital costs. Such a device has been employed by the author using a candle wick, a shallow bowl, and duck fat.

In Greece, lamps (from the Greek *lampas*, meaning torch) fashioned from pottery or bronze began to replace torches about 2700 ybp. The Romans manufactured molded terra cotta lamps, sometimes decorative and elaborate. The earliest markets for lighting fuel came in early Babylonia around 4000 ybp. According to Dubberstein [1938], Babylonians used sesame oil as an illuminate in temples, although this was too expensive to employ in homes. The wage of a common laborer was approximately 1 shekel per month, which was also approximately the price of 2 *sutu* (10 liters) of sesame oil. A rough calculation indicates that an hour's work today will buy about 300,000 times as much illumination could be bought in early Babylonia.[3]

[3] 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

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 describes medieval practices, in which pine splinters were habitually burned by peasants. Sometimes, the torch was held in the mouth so as to leave the hands free.[4] Virtually all historical accounts of illumination remark on the feeble progress made in lighting technology in the millennia before the Industrial Revolution.

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 19th century, the most advanced and prestigious lighting instrument was the wax candle; the mark of nobility, indeed, was to be preceded by a candle in the bedtime procession. Candles were 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 14th and 15 centuries. Students of international trade will recall the famous satirical "Petition of the Candlemakers" of Frederic Bastiat:

[1938], Farber [1978], and Slotsky [1992]. During the old Babylonian period of Hammurapi/Samsuiluna (around 1750 BC), a common laborer earned about 1 shekel a month while a *sutu* (measure, equal to 6 *qa* or 5 liters) of sesame oil cost about ½ shekel. Assuming that, either on a volumetric or weight basis, sesame oil burned in Babylonian lamps had one-half the luminosity of candles or whale-oil lamps, a Babylonian hour's work would buy .0272 kilolumenhours (klh) of light. In 1992, as we will see below, an hour's work would buy about 8500 klh of light. This growth in the social productivity of lighting over this period is therefore about 300,000.

[4]Details on the history of lighting are contained in many sources, and the "mouth torch" is described in Gaster and Dow [1919].

> *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.

Tallow gradually replaced wax as the former was much less costly, and in the 18th and 19th century whale-oil candles became the illuminant of choice.

2.6. Gas and petroleum

As mentioned above, and will be demonstrated below, 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 18th century. By contrast, the nineteenth century was the 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 the progress in illumination was the development of town gas (produced from coal), used both in residences and for street lighting. There were a number of parallel attempts to introduce gas, but William Murdoch is usually thought of as "the father of gas lighting." He experimented, as was often the case before the routinization of invention, on himself and his family in his home in 1792, and when they survived he started a commercial enterprise. The first quarter of the 19th century saw the great cities of Europe lit by gas.

The petroleum age was ushered in by the discovery of "Rock Oil" (now called petroleum) in Pennsylvania. We are fortunate that the first entrepreneurs had the good taste to hire as consultant Benjamin Silliman, Jr., Professor of General and Applied

Chemistry at Yale and son of the most eminent American scientist of that age, 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. In his report for the Venango County, 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 is probably the best single source of data on both prices and efficiency available before this century (see his results in Table 2).

Although modern energy systems are the betes noires of the environmental movement, it is interesting to contemplate how history would have evolved if technology had been frozen in 1850 by risk analysts or environmental impact statements. One happy environmental effect of the new technologies, as Louis Stotz reminds us, is that "the discovery of petroleum in Pennsylvania gave kerosene to the world, and life to the few remaining whales."[5] After the development of the petroleum industry, kerosene became a strong competitor to gas, and the declining prices of both gas and kerosene led to a healthy competition which continues even to this day for heating.

2.7. Electric lighting

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

The first lighting by electricity took place with the electric-arc lamp as early as 1845. Faraday's experiments were the decisive point in the development of electricity, and it was at his suggestion that the first trial of electrically illuminated lighthouse took

[5] Stotz [1938], p. 6.

place at Dungeness in 1857. Electricity was used to light the Tuileries gardens in Paris in 1867. Filament lamps were made by Moleyns and King 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 the 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 3). The major improvement in the efficiency of the light bulb was metals filaments, particularly tungsten, which raised the efficiency by 1919 to almost 12 lumens per watt. From that time, there has been very little improvement in the technology of the light bulb itself, which reached only 13-14 lumen per watt by the 1990s. Since the Edison bulb, there have been great improvements in lamp technology for large users, and the efficiency for industrial or street lighting show an even greater improvement than that of the residential uses that we study here.

Until the last decade, the tungsten-filament light bulb was both relatively unchanging and unchallenged for home uses. Arc, mercury vapor, and other 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 as compared to 68 lumens per watt by 1992. Only in the last decade, with a greatly improved technology and sometimes pushed with poorly designed cross-subsidy schemes of electric utilities, 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 appears to have an efficiency about the same as compact fluorescent bulbs.

2.8. Summary Data on Efficiency and Prices

Table 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. The most reliable measurements are those of Silliman of 1855 and those from the modern era.

The overall improvements in lighting efficiency are nothing short of phenomenal. The first recorded device of the Paleolithic oil lamp are perhaps a twenty-fold improvement in efficiency over the open fire of Peking man, which represents a 0.0006 percent per year improvement in efficiency; from the Paleolithic lamps to the Babylonian lamps represented an improvement rate of 0.004 percent per year; from Babylonia to the candles of the early 19th century we calculate an improvement at the more rapid rate of .04 percent per year. The Age of Invention shows a dramatic improvement in lighting efficiency, with an increase of efficiency from 1800 to 1992 by a factor of 900, representing an annual rate of 3.6 percent per year.

Note that each technology represented a major improvement over its predecessor. What is striking, as well, is that even within a given technological paradigm there have been dramatic improvements. The Welsbach gas mantle improved the efficiency of gas lamps by a factor of 7, and another 100 percent improvement was seen from the 1880s to today's Coleman lantern. There were dramatic improvements in the ordinary light bulb 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 to today's compact fluorescent, the efficiency of light use has increased by a factor of about 2000.

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

3. Traditional Approaches to Measuring Prices

3.1. Introductory Considerations

The major question addressed in this study is whether traditional approaches to constructing price indexes capture the major technological changes of the last two centuries. We 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 revolutions. They overstate price growth for three reasons: first, for the widely recognized reason that they may not capture quality changes; second, because they measure the price of goods but do not capture the changes in efficiency of these goods and services; and thirdly because they do not capture the sometimes-enormous changes in the efficiency in 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,

3.2. Theoretical considerations[6]

It will be useful to lay out the fundamental issues. 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. 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 the calculation of the price of *"service*

[6] The theory of index numbers is an ancient art, dating at least back 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])

characteristics." We will describe the theoretical background briefly.[7] Say 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 record 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. We will simplify the analysis by assuming that each good is associated with a single characteristic, so that $C_{it} = f_{jit}(X_{jt})$ 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.[8]

For the exposition we will suppress the time subscript. The consumer faces a budget constraint $I = p_1 X_1 + \ldots + X_m p_m$, 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:

(1) $\lambda = [\partial U/\partial C_i][\partial C_i/\partial X_j] / p_j$

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:

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[7] See Triplett [1987] for an excellent summary of the theory of characteristic prices.

[8] This assumption is oversimplified if the prices of the good or of complimentary 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. We resolve this by calculating the "frontier hedonic price," which measures the price assuming that consumers are replacing their capital equipment.

(2) $q_i = p_j / [\partial C_i / \partial X_j]$.

Substituting (2) into (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 the dollars per lumenhour). 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:

$$(3) \quad P_t = \sum_{i=1}^{n} p_{i,t} \ \zeta_{i,t}$$

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

$$(4) \quad Q_t = \sum_{j=1}^{m} q_{j,t} \ \omega_{j,t}$$

where $q_{j,t}$ are the prices of the characteristics and $\omega_{j,t}$ are the appropriate weights on the characteristic services.

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

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 $f(\ )$, then 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 characteristic service 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 at the very early stage of the life cycle of new goods, this suggests that early introduction of new goods is the appropriate treatment.

Our procedure in what follows will be to calculate the true price of the characteristic service of lighting (q_i being the lumenhour) as a replacement for the traditional price index of fuel (p_j being the price of candles, town gas, or electricity).

3.3. Treatment of Quality Change in Practice

Before World War II, there was little attention to the problem of quality change and new products. Since that time, however, it has become 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 the bias is in the direction of upward bias of prices (or inflation) over time. It will be 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.[9] 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 followed for the preponderance of goods and services. (2) *Linking.* In a second 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 comprises adjusting the price to reflect the estimated value of the quality difference. For example, cars 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 imputation of the economic value of the change in service characteristics. As of 1990, only two adjustments were used in the official price indexes of the United States: for computer prices and for housing prices.

In analyzing traditional techniques, it will be 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 product. Two problems are likely to arise with new products: First, new goods are likely to be introduced 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 first introduction of a new good. In addition, many new goods experience rapid improvement in efficiency of delivering service characteristics, so the bias from using goods prices rather than service-characteristic

[9]See for example Armknecht et al. [1994].

prices may be particularly severe for goods in the early stages of their 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 introduced half a million years ago, or when anesthetics or space travel were first produced in the modern age, or if we really could visit *Jurassic Park*, these characteristic services would genuinely be novel and we could find no market benchmark for creation of hedonic prices. However, such commodities are probably quite rare because most new products are in reality new combinations of old wines in redesigned bottles.

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 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.

3.4. A Simple Example of the Bias in Lighting Prices

Before we turn to the actual construction of traditional and true price indexes, we can make the point with a simple example of lighting prices over the century from 1883 to 1993. We take this period because Edison priced his first electric light at an equivalent price to gas light, so the price 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, we will compare the prices of electric light with that of gas-kerosene light over the last century.

Figure 2 shows the result. Over the last century, the prices of the fuels (which are used for traditional price indexes and are shown by the dashed lines) have risen by a factor of 10 for kerosene have fallen by a factor of three 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. Even the ideal traditional (frontier) price index would have shown a fall in the price of light by a factor of only 3 over the last century. If the price index were incorrectly constructed, say using early consumption weights and tracking gas-kerosene prices, it would have shown a substantial upward increase by a factor of 10.

A true (frontier) price index would have tracked the lowest solid line in Figure 2, which shows a decline by a factor of 75 over the last century. This shows a steeper decline in price relative to the traditional 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 we must turn to estimation of characteristic production functions to determine the magnitude of the second bias.

3.5. Traditional Prices Indexes on Light

The first step in our comparison is to obtain a "traditional" or conventional estimate of the price of light. Actually, the U. S. Bureau of Labor Statistics 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 that of lighting devices, which are not separately included as an index.

To construct the "traditional price of light," I patched together the most closely related series. The earliest data, from 1790 to 1851, was the wholesale price of "fuel and light" from Warren and Pearson [1933]. There is a short period, from 1851 to 1880, for which we can construct consumer prices, using the index of the price of "fuel and light" from Hoover [1960]. Then from 1880 to 1890, we return to the Warren and Pearson index of fuel and light. For the from 1890 to 1940, we use the Bureau of Labor Statistics wholesale price index of "fuel and light." From 1940 on, there are two variants available. The first is to link the earlier series with the 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 fueled 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 growth in productivity in electricity over the last half century. For comparative purposes, we can also use a consumer price index for all commodities recently prepared by McCusker [1991]. All three series are shown in Table 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 in this respect, 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 for 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.

4. Lux et Veritas

4.1. Construction of the "true price of light": theoretical background

In constructing an ideal or true price, we would want to employ the price of the service characteristic as defined in (2) rather than 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 (4) rather than the traditional goods-price index defined in (3). It is clear that in principle the characteristics approach is superior, but because of the labor involved in constructing characteristic prices, statisticians almost always collect goods prices, and price indexes rely almost entirely on the price of goods.

4.2. Construction of the "true price of light:" implementation

4.2.1. Measurement

In this section I describe the actual calculations of the "true price of light." Unlike many estimates of hedonic price index, the true price of light is conceptually very simple in that there are objective measures of light flux and illuminance, as discussed above. As with all goods, "light" has a number of different service characteristics: (a) *illumination* or light flux (measured in lumens); (b) *wavelength* (usually, proximity to wavelength of sunlight); (c) *reliability* (in terms of constancy and lack of flicker); (d) *convenience* (ease of off-on, low maintenance); (e) *safety* (from electrocution, burns, UV radiation);[10] and (f) *durability* (lifetime and ease or replacement or fueling).

In practice, the "true" price of light is constructed with a number of simplifying assumptions: For the present purpose, we restrict the calculation in a number of respects: (1) The only characteristic that will be analyzed is the first, the illumination. 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) We 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.

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[10] 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].

4.2.2. 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 lumenhours) for different lighting devices. A summary of the efficiencies is shown in Table 3. The data have varying levels of reliability. Estimates of Silliman and the 20th century 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 are drawn either from national data or from local quotations. For the historical data, a history of the gas industry by Stotz [1938] provides most of the data on prices of candles, town gas, kerosene, and electricity. Silliman gathered data on the major fuels for his 1855 experiment. Electricity is an interesting historical footnote. At first, the unit was the "Weber," which is a unit of magnetic flux. By 1884, rates were quoted in Amperes, and the current unit of kilowatt-hour was adopted in the United States in 1889. Edison, however, priced his lamp 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 candle-power was the equivalent of a gas burner supplied with 5 [cubic] feet of gas."[11] This works out to approximately 24 cents per kilowatthour (kwh) at the dawn of the electric age, or about $3 per kwh when reflated by the consumer price index.

4.2.3. Prices in terms of goods

The estimates of the true price of lighting are shown in Table 5 as well as in Figure 3. This shows the nominal price as well as the price in terms of the traditionally measured basket of consumer goods and services.

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[11] Quoted in Doblin [1982].

4.2.4. Prices in terms of labor

An alternative measure of the price of light, derived in Table 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 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 characteristic services. When the characteristic service 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 non-substitution theorem, we can determine the hedonic prices of the characteristic services ($q_1, q_2, \ldots, q_m$) 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. We define the labor cost of a characteristic service, q_i / w_1, with labor's price being w_1, 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 characteristic service 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 100-watt incandescent bulb burning for three hours each night would produce 1.5 million lumenhours of light per year. At the beginning of the last century, to obtain this amount of light would require burning 17,000 candles, and the average worker would need to toil almost 1000 hours to earn the dollars to buy the candles.

By the modern era, with a compact fluorescent bulb, the 1.5 million lumenhours would need 22 kilowatt hours, which can be bought for about 10 minute's work by the average worker. The trend in the labor requirements to buy our daily light is shown in

Figure 4, where the true index is compared with the trend in the required labor according to a traditional index; Figure 5 extends the estimates to the labor time required by a Babylonian to fuel the sesame lamps of that period.

5. Comparison of True and Traditional Prices

Figures 6 and 7 compare the traditional and true price indexes of light along with the overall consumer price index. The traditional price of light has risen somewhere between three and five times in nominal terms since 1800. This is not bad compared to all consumer prices (again, the traditional version), which have risen ten-fold 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 between 900 and 1600 relative to the true price. The squared correlation coefficient between the changes in the logarithms of the true price and that 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 (rise in the traditional price relative to the true price) is 3.6 percent per year.

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? We suggest that 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 consumption. In this section we 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.[12]

6.1. Treatment of Quality Change and Inventions in Practice

6.1.1. Traditional long-term estimates of consumer prices

In constructing estimates of either real wages or real output, we 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.[13] A review of these studies indicate three features: First, most of the early indexes are 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 consumer prices moved 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 to 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 "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 a Btu of gas bought in the 19th century delivered quite a different quantity of heat or light from a Btu of electricity bought in the 20th century never entered into the construction of the price indexes.

[12] 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], Gordon [1990], and Gordon [1993].

[13] See a recent survey in McCusker [1991].

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 we saw clearly in the case of lighting and suggest below for other goods and services, 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 are correctly captured today, and there can be no question that they were completely ignored in the period before World War II.

6.1.2. Conventional treatment of major inventions

For revolutionary changes in technology, such as when major inventions are introduced, 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 medicine replaces snake oil.

The omission of quality change and particularly revolutionary technological changes 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 7 considers a selected bundle from the Jewkes, Sawers, and Stillerman list of the 100 great inventions [1969]. Note how little of the impact of the great inventions would be 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 most of the revolutionary improvements of 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 why food is the fixed star in all long-term consumer price indexes; in addition, the omnipresence of food is a tip-off that the price indexes are misleading.

6.1.3. 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 19th century:

I. *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 we uncovered for light.

II. *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 that at the beginning of the 19th century. Examples in this category are housing (with 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.

III. *Tectonic shifts*. The final area is the sector 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 sector includes household appliances (such as refrigerators and air conditioners); utilities, including heating, lighting, and use 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 of the early 19th 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 categories around. It is unlikely, however, that the size of those sectors experiencing tectonic shifts would shrink. Because of the aggregation, it is likely that many tectonic shifts are buried in the run-of-the-mill or seismically active sector. For example, the lowly toilet is classified in furniture but delivers a service that would delight a medieval prince.

Table 8 shows the basic breakdown for 1991. According to this categorization, 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 19th 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.

6.2. Measuring True Income Growth

6.2.1. 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. Measuring 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.

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

It will be more convenient if we transform the direct utility function into a *characteristic indirect utility function* (or *CIUF*) of the following form:

(5) $R = V(q_1/I, q_2/I, ..., q_n/I)$

(In this discussion, we suppress the time dimension where that is unnecessary.) This utility function has all the properties of the standard indirect utility function except that the prices are characteristic 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 the market prices and income.

We 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 we can rewrite the utility function as:

(6) $R = V[(q_1/q_1^*)(q_1^*/I), q_2/I, ..., q_n/I]$

Our ideal measure of real income is the measure of utility in (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 linear homogeneous, the growth in utility (equal to the growth of real income) is given by:

(7) $g_R(t) = g_1(t) - \{ \sigma_1(t)\, g_{q1}(t) + \sigma_2(t)\, g_{q2}(t) + \ldots \}$

where $\sigma_i(t)$ = the (local) share of spending on characteristic service 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, $g_R^* - g_R$, is simply equal to:

(8) Bias in measuring real income growth = $g_R^*(t) - g_R(t)$

= Bias from good 1 = $\sigma_1(t)\, [\, g_{q1}(t) - g_{q1^*}(t)]$

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.

6.2.2. Bias for lighting

We can calculate the bias in real income using the data in the tables and the formula in (8). According to our calculations, the average annual bias for lighting is 3.6 percent per annum. The share of lighting in total consumer expenditures is difficult to estimate (see Table 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 200 years. This suggests that the real wage and output growth using Light II has been underestimated by .036 percent per annum on the account of the misestimate of lighting's price alone.

Using the formula in (8), and assuming a constant share, the total bias in the growth of real income or real wages for Light II would be .01 × log(.036 × 192) = .068 (or .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 surplus equivalent of the unmeasured quality change in lighting.

6.2.3. 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. We have few proxies to use. One measure is that for light, where we 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 computers, where the estimated bias is close to 15 percent per year, and work of Robert J. Gordon on capital goods, where the bias is estimated to be 3 to 4 percent per year.[14]

For the thought experiment, we assume a "high" and "low" estimate for the bias. For the low estimate, we assume that there has been no bias in the run-of-the-mill sectors, a bias in the seismically active areas that is one-third the estimated bias for light, and a bias in the tectonic sectors that is two-thirds that of light . (See Table 8 for a list of the different industries in each category.) For the high estimate, we assume a baseline bias of ½ percent per annum plus a bias in seismically active areas equal to one-half of that of light and a bias in tectonic industries that is equal to that of light. More specifically, the bias rates are (0,1.2, 2.5) percent annually for sectors (I, II, III) in the low case and (1.7, 2.4, 4.2) percent annually for the same sectors in the high case. In addition, we have made rough estimates of the shares in the different sectors taking the shares of the different sectors in 1929 from the same sources as that in Table 8 and making rough estimates from budget studies of the 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.[15]

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[14] See Gordon [1990].

[15] The calculation of the bias for consumption was constructed as follows. We calculated for 1929 the same breakdown of consumption between the three innovation categories (run-of-the-mill, seismically active, tectonically shifting) as shown in Table 8. For each major consumption sector (food, clothing, etc.), we 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 Historical Statistics [1975]), with an extrapolation back to 1800 using English data from Burnett [1969] shown in Table 9. We then constructed a Divisia index of the bias by taking the within period shares of each of the major consumption sectors and multiplying these by the estimated bias for each sector using the estimated low or high bias from this paragraph and the

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 2.1 percent annually with the low assumption about the bias in price indexes and 3.6 percent per year in the case of the high assumption about the bias in price indexes. In terms of living standards, the conventional growth in real wages has been a factor of 13 over the 1800-1992 period. For the low-bias case, real wages have grown by a factor of 58, while in the high-bias case real wages have grown by a factor of 970. Figure 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.

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.

7. Conclusion

We 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 characteristic service. This finding implies that the growth in the frontier volume of lighting has been underestimated by a factor of between 900 and 1600 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-19th century (locally grown foods, clothing, parts of personal care). More than one-third of consumption takes place in seismically active industries and in ways that were virtually unimaginable at that time --

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proportion of each of the three innovation categories.

including medical care, transportation, recreation, and much of household operation. If the half of consumption that takes place in tectonically active 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 might well be off 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....[16]

16 Smith [1776], p. 12.

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Table 1. Milestones in the History of Lighting

1,420,000 ybp:	Fire used by *homo austropithecus*
500,000 ybp:	Fire used by Peking man.
42,000-13,000 ybp:	Stone fat-burning lamps with wicks used in Southern Europe.
5000 ybp:	Candlesticks recovered from Egypt and Crete.
1292:	Paris tax rolls list 72 "chandlers" (or candlemakers)
Middle Ages:	Tallow candles in wide use in Western Europe
1784:	Discovery of Argand oil lamp
1792:	William Murdoch uses coal-gas illumination in his Cornwall home.
1798:	William Murdoch uses coal-gas illumination in Birmingham offices.
1820:	Gas street lighting installed in Pall Mall, London.
19th C	Improvement of candle technology with use of stearic acid, spermaceti, and paraffin wax.
1855:	Silliman's experiments with "rock oil."
1860s:	Development of kerosene lamps.
1860:	Demonstration of electric discharge lamp by Royal Society of London.
1876:	Centennial Exposition (Philadelphia)-William Wallace's 500-candlepower arc lights.
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 lamp.
1930s:	Development of mercury-vapor-filled fluorescent tube
1931:	Development of sodium-vapor lamp
1980s:	Marketing of compact fluorescent bulb.

Source: Stotz [1938], de Beaune and White [1993], Doblin [1982], Encyclopedia Britannica [1981, 1993].

Table 2
Silliman's Lighting Experiments, 1855

Fuel	Apparatus	Fuel rate	Fuel price (cents)		Efficiency CH/hr	Efficiency LH/mbtu	Price of illumination [cents\CH]	Price of illumination [cents per 1000LH]
			per cu ft.					
Town Gas	Scotch fish tail	4 cu ft/hour	0.40		5.40	31.91	0.30	22.8
	Scotch fish tail	6 cu ft/hour	0.40		7.55	29.74	0.32	24.5
	Cornelius fish tail	6 cu ft/hour	0.40		6.20	24.42	0.39	29.8
		10 cu ft/hour	0.40		16.00	37.82	0.25	19.2
			per oz	per gal				
Sperm oil	Carcel's lamp	2 oz/hour	1.95	250	7.50	22.99	0.52	40.1
Colza oil	Carcel's lamp	2 oz/hour	1.56	200	7.50	22.99	0.42	32.1
Camphene	Camphene lamp	4 oz/hour	0.53	68	11.00	16.86	0.19	14.9
Silvic Oil	Diamond lamp	4 oz/hour	0.39	50	8.10	12.41	0.19	14.8
Rock oil (a)	Camphene lamp	3.4 oz/hour	0.06	8	8.10	14.61	0.03	2.0

Source: Silliman [1871].
(a) Price for kerosene refers to 1870.

Table 3

Efficiency of Different Lighting Technologies

	Fuel	Device	Approximate Date	Lighting Efficiency [lumen/watt]	Lighting Efficiency [lumen-hours/mBtu]
1	Wood	Open fire	From earliest time	0.00065	0.2
2	Neolithic lamp	Animal or vegetable fat	40-15,000 B. C.	0.0151	4.4
3	Babylonian lamp	Sesame oil	1750 B. C.	0.0341	10.0
4	Candle	Tallow	1800	0.0757	22.2
4		Sperm	1800	0.1009	29.6
4		Tallow	1830	0.0757	22.2
4		Sperm	1830	0.1009	29.6
5	Lamp	Whale oil	1815-45	0.1346	39.4
6		Silliman: Sperm oil	1855	0.0784	23.0
7		Silliman. Other oils	1855	0.0575	16.9
8	Town Gas	Early lamp	1827	0.1303	38.2
9		Silliman's experiment	1855	0.0833	24.4
10		Early lamp	1875-85	0.2464	72.2
11		Welsbach mantle	1885-95	0.5914	173.3
12		Welsbach mantle	1916	0.8685	254.5
13	Kerosene lamp	Silliman's experiment	1855	0.0499	14.6
14		19th century	1875-85	0.1590	46.6
15		Coleman lantern	1993	0.3651	107.0
	Electric lamp				
16	Edison carbon lamp	Filament lamp	1883	2.6000	762.0
17	Advanced carbon	Filament lamp	1900	3.7143	1088.6
17		Filament lamp	1910	6.5000	1905.0
17	Tungsten filament	Filament lamp	1920	11.8182	3463.7
17		Filament lamp	1930	11.8432	3471.0
18		Filament lamp	1940	11.9000	3487.7
19		Filament lamp	1950	11.9250	3495.0
19		Filament lamp	1960	11.9500	3502.3
19		Filament lamp	1970	11.9750	3509.7
19		Filament lamp	1980	12.0000	3517.0
20		Filament lamp	1990	14.1667	4152.0
21	Compact fluorescent bulb	First generation bulb	1992	68.2778	20011.1

Notes to Table 3:

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

1 Rough estimate based on open fire fueled with wood.
2 From de Beaune [1993] assuming that device is one-fifth as efficient as a tallow candle.
3 See discussion in text. Assumes that sesame oil has one-half efficiency of whale oil.
4 Candle weighing one-sixth of pound generates 13 lumens for 7 hours. From Hayward [1927], p. 75. Tallow candles are assumed to have three-quarters the light output of sperm candle.
5 Whale oil assumed to have efficiency of candle and one-half caloric value of petroleum
6 See Table 2.
7 Other oils tested by Silliman included Silvic oil, Camphene, and Colza oil. This chooses Camphene, largely wood alcohol, as most cost-effective.
8 From Stotz [1938], p. 7f. According to Stotz, expenditures of $30 per year on town gas at a price of $2 per 1000 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.
9 See Table 2.
10 See 8.
11 See 8.
12 See 8.
13 See Table 2.
14 According to Stotz [1938], p. 8f., expenditures of $25 per year on kerosene at a price of 13.5 cents per gallon would yield 90,000 candle-hours per year.
15 Estimate from Coleman on Coleman kerosene lantern.
16 Gaster and Dow [1919], p. 75.
17 Gaster and Dow [1919], p. 79.
18 Interview with lighting engineer.
19 Linear interpolation between 1940 and 1980.
20 A standard incandesent bulb tested by Consumer Reports.
21 Consumer Reports [1992] first test of compact fluorescent bulbs. October 1992.

Table 4

Basic Data on the True Price of Light

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	True Price of Light			***Light Price in Terms of Labor***	*Official Price Indexes*			*Price Ratio* ***[True to official price]***	
	Per kilolumenhour		***Index, real prices***	[hours of work per kilolumenhour]	**CPI**	**Light-I**	**Light-II**		
Date	[current prices]	[1992 prices]	[1800 = 100]		[1800 = 100]	[1827 = 100]	[1827 = 100]	**Light I**	**Light II**
500,000 BC				100.00000					
20,000 BC				80.00000					
1750 BC				36.76471					
1800	40.293	429.628	100.000	5.38677	100.0	100.00	100.00	1.00	1.00
1816	40.873	430.117	100.114	6.33193	101.3	93.71	93.71	0.92	0.92
1827	18.632	249.985	58.186	3.37991	79.5	86.16	86.16	1.86	1.86
1830	18.315	265.659	61.835	2.99870	73.5	72.96	72.96	1.61	1.61
1835	40.392	596.089	138.745	7.56682	72.3	69.81	69.81	0.70	0.70
1840	36.943	626.774	145.889	5.05676	62.8	66.04	66.04	0.72	0.72
1850	23.199	397.362	92.490	2.99771	62.3	59.75	59.75	1.04	1.04
1855	29.777	460.980	107.295	3.34382	66.9	64.15	64.15	0.87	0.87
1860	10.963	176.505	41.083	1.15166	65.2	61.64	61.64	2.27	2.27
1870	4.036	41.390	9.634	0.32996	104.0	84.28	84.28	8.41	8.41
1880	5.035	65.907	15.340	0.48922	81.5	57.85	57.85	4.63	4.63
1883	9.228	122.791	28.581	0.75024	80.1	55.97	55.97	2.44	2.44
1890	1.573	23.241	5.410	0.13346	72.2	45.28	45.28	11.60	11.60
1900	2.692	42.906	9.987	0.22043	66.9	55.03	55.03	8.24	8.24
1910	1.364	19.550	4.550	0.09210	75.5	56.57	56.57	16.47	16.47
1916	0.346	4.282	0.997	0.01540	86.1	88.31	88.31	102.92	102.92
1920	0.630	4.228	0.984	0.01354	158.9	194.56	194.56	124.40	124.40
1930	0.509	4.098	0.954	0.01040	132.5	93.30	93.30	73.86	73.86
1940	0.323	3.092	0.720	0.00549	111.3	85.22	65.76	106.44	82.16
1950	0.241	1.350	0.314	0.00188	190.7	84.26	62.61	140.66	104.49
1960	0.207	0.940	0.219	0.00102	234.4	100.25	70.83	199.45	133.24
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	0.00066	652.3	313.43	179.34	282.82	161.83
1990	0.600	0.616	0.144	0.00060	1035.1	479.80	275.57	322.31	185.12
1992	0.124	0.124	0.029	0.00012	1066.3	503.94	281.09	1631.55	910.03

Notes to Table 4:

(1) From Table 5.

(2) Column (1) reflated into 1992 prices using the consumer price index in column (4).

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

(4) From Table 6.

(5) From McCusker [1993]

(6) Chain index constructed as follows: Warren and Pearson index of wholesale prices of fuel and light used for period up to 1850. Hoover index of consumer prices for fuel and light used from 1850 to 1880. Warren and Pearson used for period from 1880 to 1890. BLS wholesale price index used for period from 1890 to 1940. BLS index of price of gas and electric fuels used from 1940 to 1992.

(7) Uses the same data for period through 1929. Then from 1929 to 1992, uses the BEA implicit deflator for consumer purchases of electricity as the price of light.

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

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

Table 5

Price of Lighting for Different Lighting Technologies

	Fuel	*Device*	*Approximate Date*	*Price [cents per 1000 lumen hours]*
1	Wood	Open fire	From earliest time	na
2	Neolithic lamp	Animal or vegetable fat	40-15,000 B. C.	na
3	Babylonian lamp	Sesame oil	1750 B. C.	na
4	Candle	Tallow	1800	40.293
4		Sperm	1800	91.575
5		Tallow	1830	18.315
5		Sperm	1830	42.125
5	Lamp	Whale oil	1815-45	29.886
6		Silliman: Sperm oil	1855	160.256
6		Silliman: Other oils	1855	59.441
5	Town Gas	Early lamp	1827	52.524
7		Silliman's experiment	1855	29.777
5		Early lamp	1875-85	5.035
8		Welsbach mantle	1885-95	1.573
9		Welsbach mantle	1916	0.345
10	Kerosene lamp	Silliman's experiment	1855/1870	4.036
11		19th century	1875-85	3.479
12		Coleman lantern	1993	10.323
	Electric lamp			
13	First electric devices	Edison carbon lamp	1883	9.228
14		Filament lamp	1900	2.692
		Filament lamp	1910	1.384
14		Filament lamp	1920	0.630
14		Filament lamp	1930	0.509
14		Filament lamp	1940	0.323
14		Filament lamp	1950	0.241
14		Filament lamp	1960	0.207
14		Filament lamp	1970	0.175
14		Filament lamp	1980	0.447
15		Filament lamp	1990	0.600
15	Compact fluorescent bulb	First generation bulb	1992	0.124

Notes to Table 5:

4 Price from Bezanson et al. [1936]. Tallow candles generate .75 candles; sperm candles generate 1 candle.
5 Price from Stotz [1938].
6 See Tables 2 and 3. Price from Silliman [1871].
7 See Tables 2 and 3. Price from Silliman [1871]. Gas price is in New Haven, Connecticu
8 Price from Stotz [1938].
9 Price from Stotz [1938].
10 See Table 3. Price is 1870 price of kerosene.
11 Price from Stotz [1938].
12 Price in southern Connecticut, November 1993.
13 See text.
14 Average price of residential electricity use from Historical Statistics [1975], S116.
15 Price of electricity as of 1992.

Table 6

How Hard Would You Have to Work for Your Light?

	Fuel	*Device*	*Approximate Date*	*Wage rate* [cents per hour]	*Labor Price* [hours of work per 1000 lumen hours]
1	Wood	Open fire	From earliest time		100.00
2	Neolithic lamp	Animal or vegetable fat	40-15,000 B. C.		80.00
3	Babylonian lamp	Sesame oil	1750 B. C.	1 sh/month	36.76
4	Candle	Tallow	1800	7.5	5.37
4		Sperm	1800	7.5	12.21
5		Tallow	1830	6.1	3.00
5		Sperm	1830	6.1	6.91
6	Lamp	Whale oil	1815-45	6.1	4.90
7		Silliman: Sperm oil	1855	10	16.03
7		Silliman: Other oils	1855	10	5.94
8	Town Gas	Early lamp	1827	7.1	7.398
7		Silliman's experiment	1855	10	2.978
9		Early lamp	1875-85	15.4	0.326
10		Welsbach mantle	1885-95	19.0	0.083
11		Welsbach mantle	1916	28.3	0.012
12	Kerosene lamp	Silliman's experment	1855/1870	17.5	0.2308
13		19th century	1875-85	15.4	0.2253
14		Coleman lantern	1993	1059.0	0.0098
	Electric lamp				
15	First electric devices	Edison carbon lamp	1883	12.3	0.750239
16		Carbon filament	1900	12.2	0.220431
16		Carbon filament	1910	15.0	0.092096
16		Filament lamp	1920	48.6	0.013535
16		Filament lamp	1930	49.0	0.010396
16		Filament lamp	1940	58.6	0.005490
14		Filament lamp	1950	128.2	0.001893
14		Filament lamp	1960	203.3	0.001016
14		Filament lamp	1970	318.4	0.000551
14		Filament lamp	1980	655.6	0.000678
14		Filament lamp	1990	992.2	0.000605
14	Compact fluorescent bulb	First generation bulb	1992	1049.6	0.000119

Notes to Table 6:

All data are from earlier tables except wage rates and calculations for two earliest periods.

Notes that follow explain sources for wages.

1 Assumes that need 10 kg of fuel per hour to produce 10 useable lumens and that such foraging requires 60 minutes to gather 10 kg of fuel.

2 Assumes that lamp can produce 100 lumen-hours per kg of animal fat and that each kg of animal fat requires 8 hour to catch and prepare (see Pospisil [1963], pp. 227, 254and Lebergott [1993] p. 64).

3 See text. Assumes heating value of sesame oil is one-half that of candle on a weight basis.

4 From Table 5 and wage data as in 5.

5 Average monthly earnings of farm workers for 1830 from Historical Statistics ([1975], D705) at 250 hours per month. This corresponds closely to the wage rate calculated according to the methodology used in 7.

6 Same as 5.

7 Wages for 1855 are those paid to common labor on the Erie Canal calculated by assuming that the daily work day was 10 hours. Data from Historical Statistics ([1975], D718).

8 Same as 5.

9 Average annual earnings of nonfarm employees from Historical Statistics ([1975], D735), assuming 2500 hours per year of work for year 1880.

10 Same as 9 for 1890.

11 Same as 9, but for all workers (Historical Statistics ([1975], D779)

12 Same as 7. Wages are from 1870.

13 Same as 9

14 Average hourly earnings, private non-farm industries (ERP [1993], p. 396).

15 Same as 9 for 1883

16 Same as 9 using Historical Statistics ([1975], D723).

newtab1.D

Table 7
Treatment of the Great Inventions

Invention	Treatment in Price Indexes
Aeronautics, helicopter	Except for lower transportation of intermediate goods, lower prices not reflected in price indexes.
Air conditioning	Outside of refrigerated transportation and productivity increases in the work place, amenity and health effects are not captured in price indexes.
Continuous casting of steel	A process innovation that would show up primarily in lower costs of intermediate goods and thus would be reflected in price indexes of final goods.
DDT and pesticides	Some of (now questionable) benefits probably included in higher yields in agriculture and therefore included in price indexes; health benefits largely excluded from price indexes.
Diesel-Electric Railway Traction	A process innovation that would show up primarily in the price of goods and services.
Insulin, Penicillin, Streptomycin	Improved health status not captured in price index.
Internal Combustion Automobile	Except for lower transportation of intermediate goods, lower prices not reflected in price indexes.
Long Playing Record, Radio, Television	Major product invention that are completely omitted from price indexes.
Photo-Typesetting	Largely reflected in reduced printing costs.

Radar	Wide variety of improvements. Some might show up in lower business costs and prices (such as lower transportation costs or improved weather forecasting).
Rockets	Wide variety of implications. Major application in telecommunications would show 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 are reflected in price indexes, while expansion of consumer services and non-business uses are not.
Telegraph, Telephone	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 would show 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 et al [1969].

Table 8

Consumption by Extent of Qualitative Changes, 1991

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		
Housing			
Dwellings		574	
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
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	27.44
Private education and research		92.8	
Religious and welfare	107.7		
TOTAL	1080.6	1396.8	1428.84
Percent of total	27.7	35.8	36.6

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 there is likely to be 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).

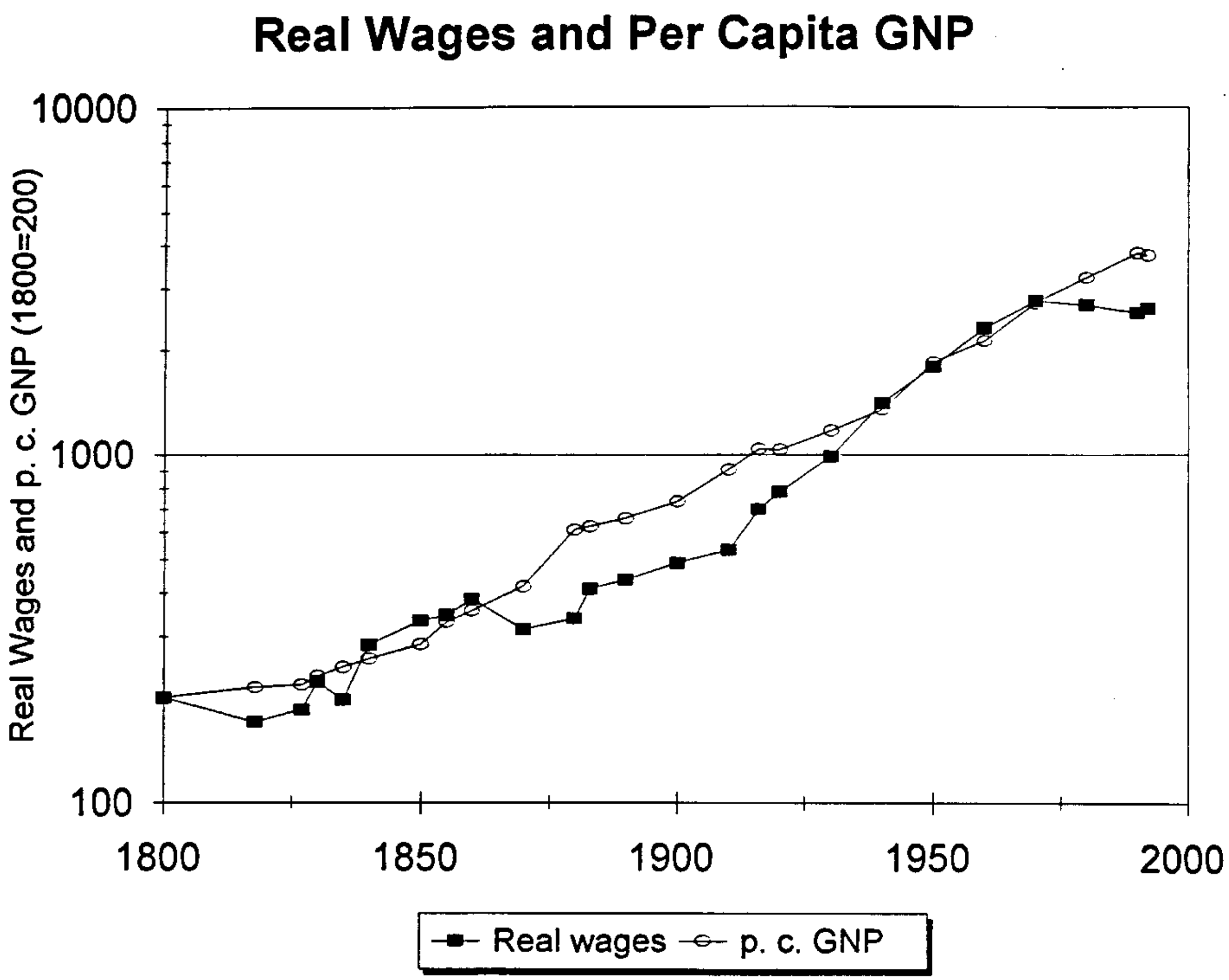
Table 9

Budget Studies on Lighting

Period	*Household Income* [$/year]	*Spending on Lighting* [$/year]	[percent of spending]	*Total Lighting* [thousand kilolumenhours]
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

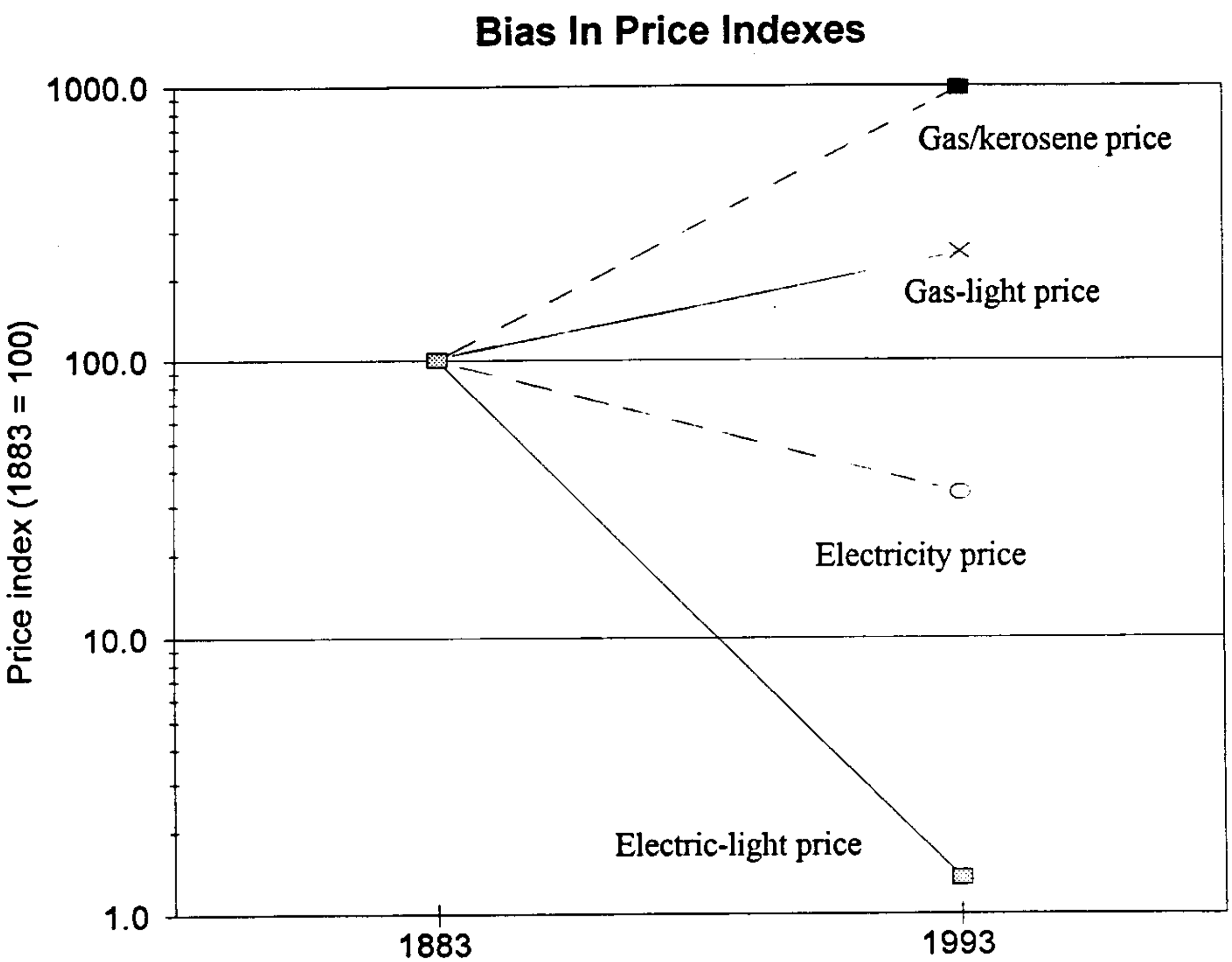
Sources: 1760s for a Berkshire family from Burnett [1969], p. 167; 1815-55, 1880, and 1890 from Stotz [1938]; 1875 from Hoover [1960], p. 183 from a survey of 397 families; 1960 from Darmstadter [1972] for electricity from lighting.

Figure 1



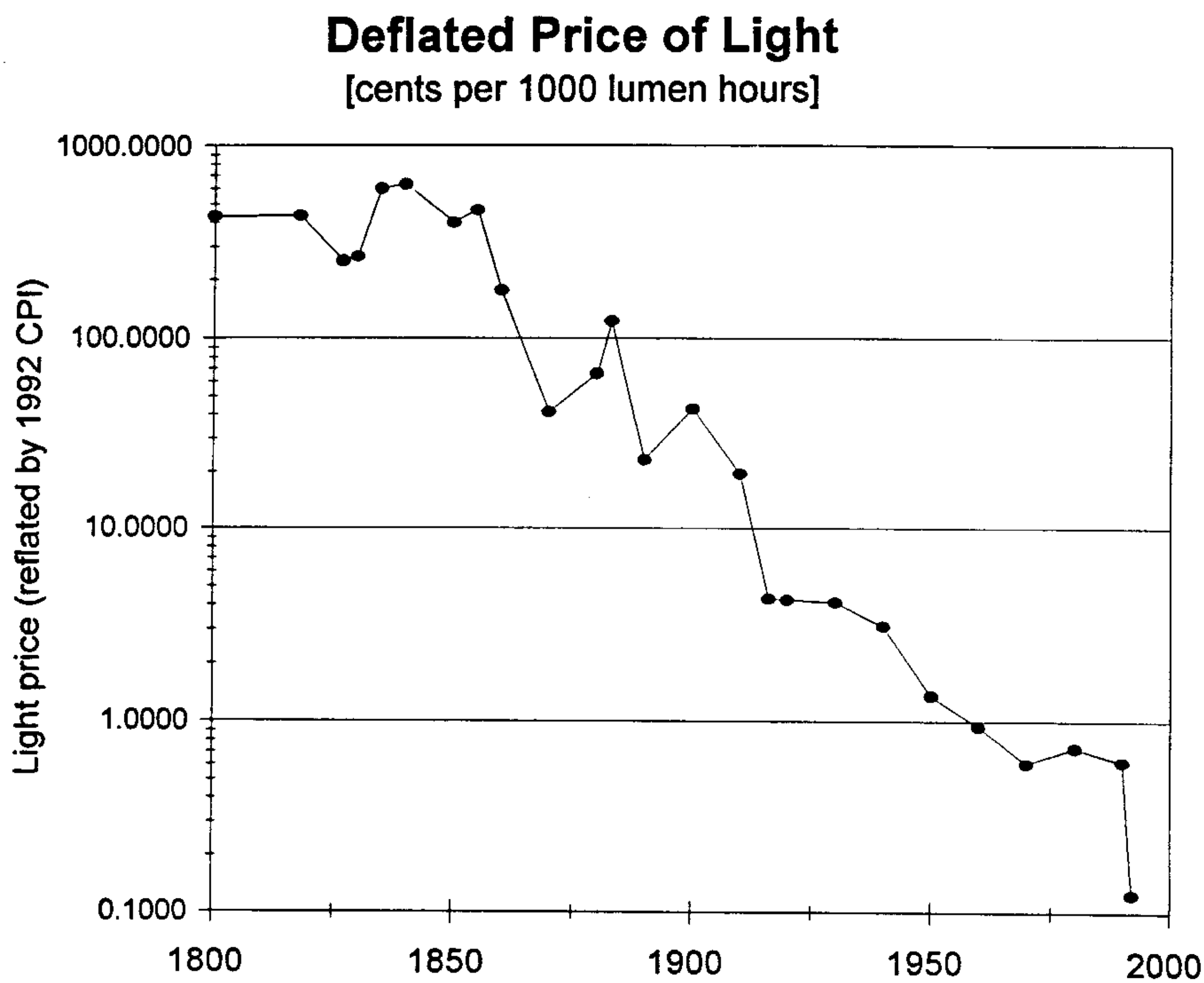
Real Wages and Per Capita GNP
10000
1000
100
Real Wages and p. c. GNP (1800=200)
1800
1850
1900
1950
2000
Real wages
p. c. GNP

Figure 2



Bias In Price Indexes
1000.0
100.0
10.0
1.0
Price index (1883 = 100)
Gas/kerosene price
Gas-light price
Electricity price
Electric-light price
1883
1993

Figure 3



Deflated Price of Light
[cents per 1000 lumen hours]
Light price (reflated by 1992 CPI)
1000.0000
100.0000
10.0000
1.0000
0.1000
1800
1850
1900
1950
2000

Figure 4

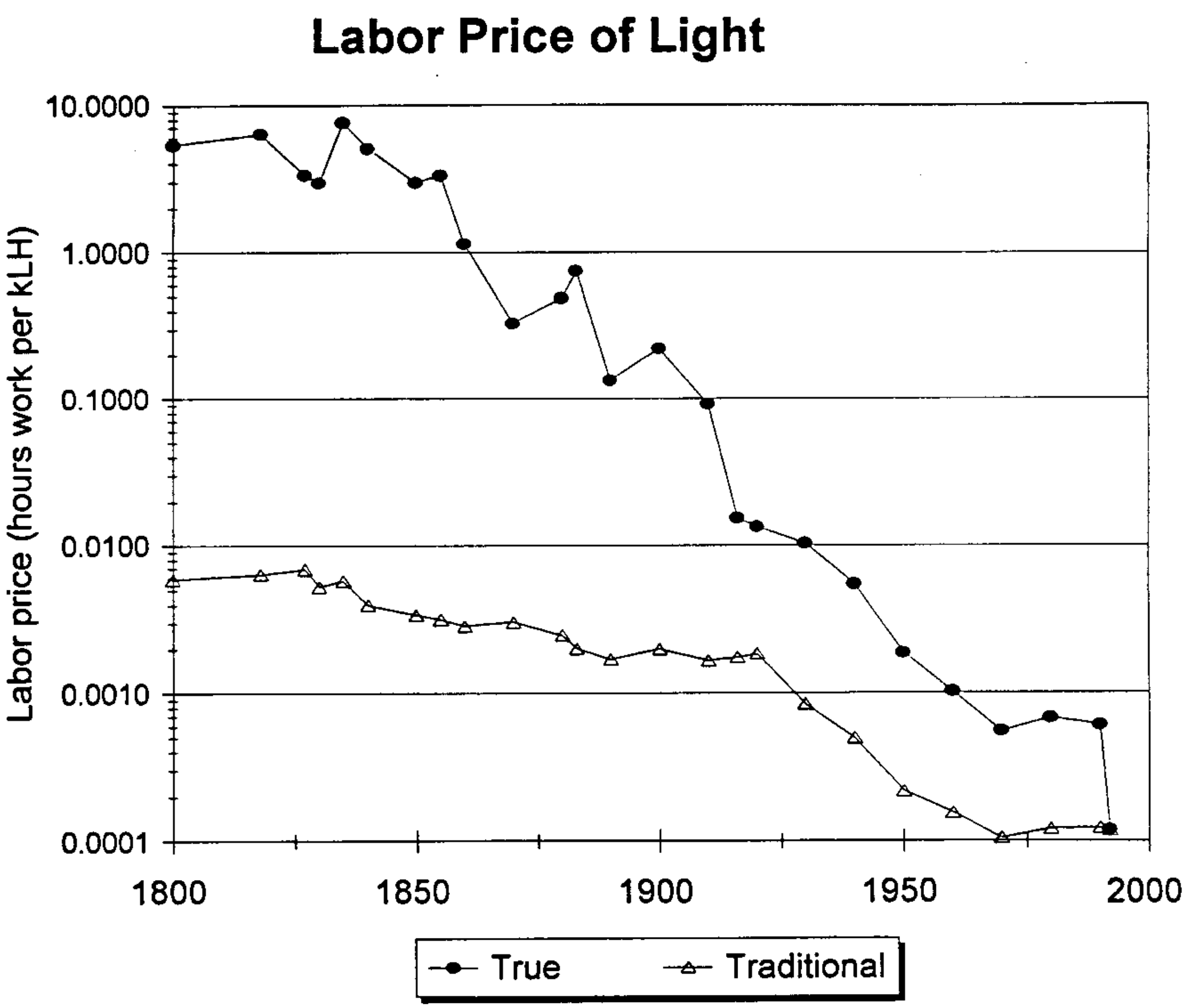
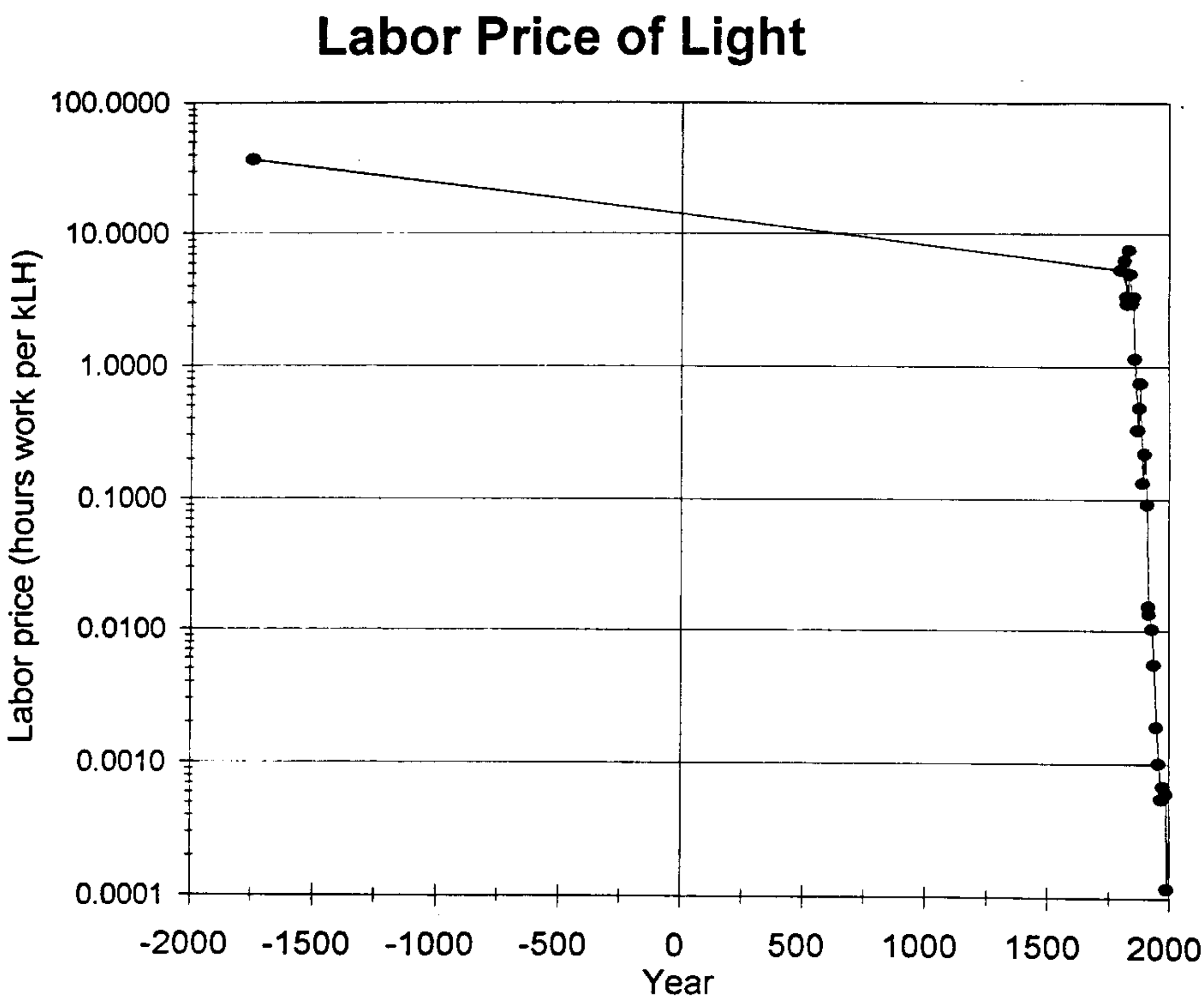
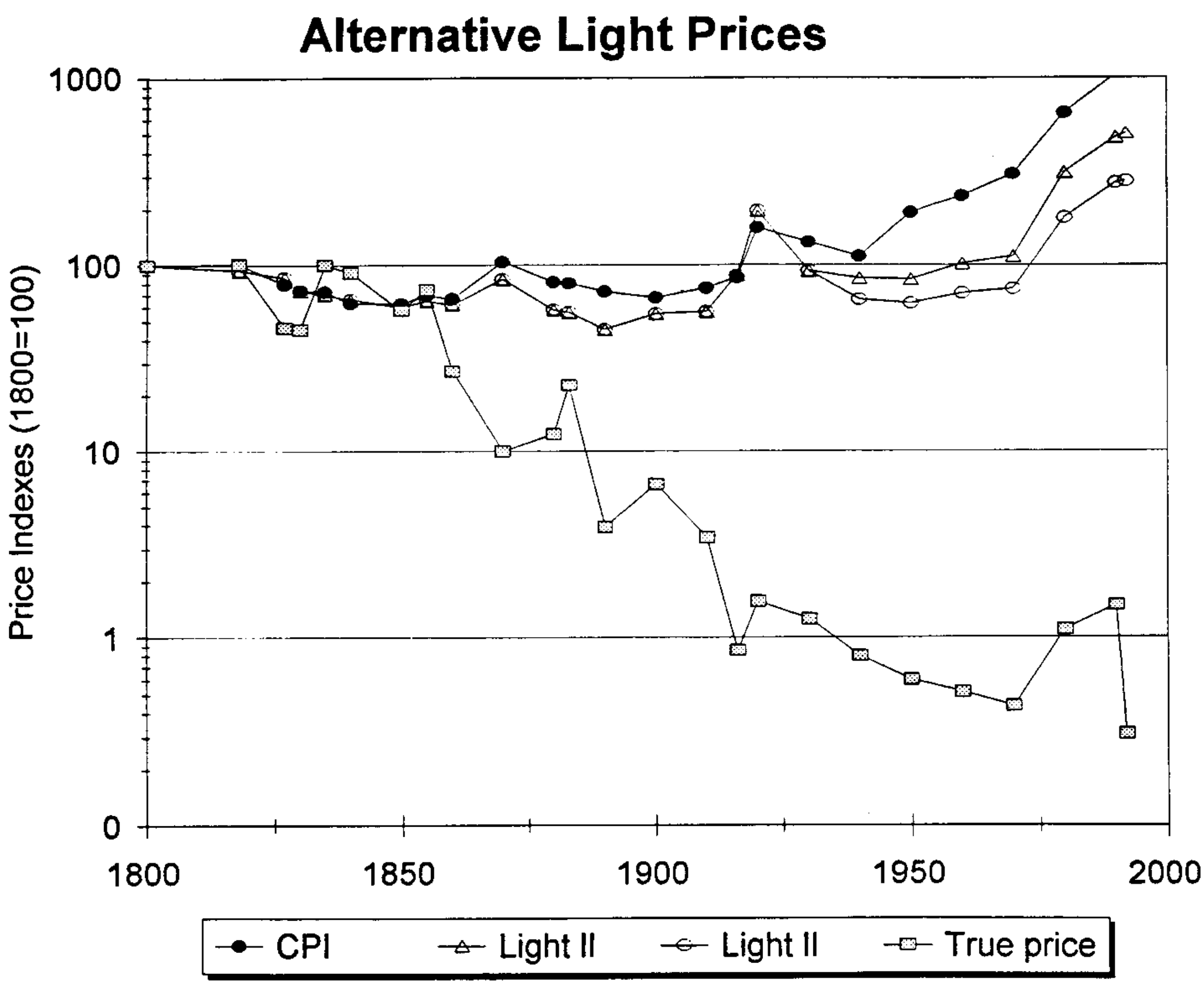

Labor Price of Light
10.0000
1.0000
0.1000
0.0100
0.0010
0.0001
Labor price (hours work per kLH)
1800
1850
1900
1950
2000
True
Traditional

Figure 5



Labor Price of Light
Labor price (hours work per kLH)
100.0000
10.0000
1.0000
0.1000
0.0100
0.0010
0.0001
-2000
-1500
-1000
-500
0
500
1000
1500
2000
Year

Figure 6



Alternative Light Prices
1000
100
10
1
0
Price Indexes (1800=100)
1800
1850
1900
1950
2000
CPI
Light II
Light II
True price

Figure 7

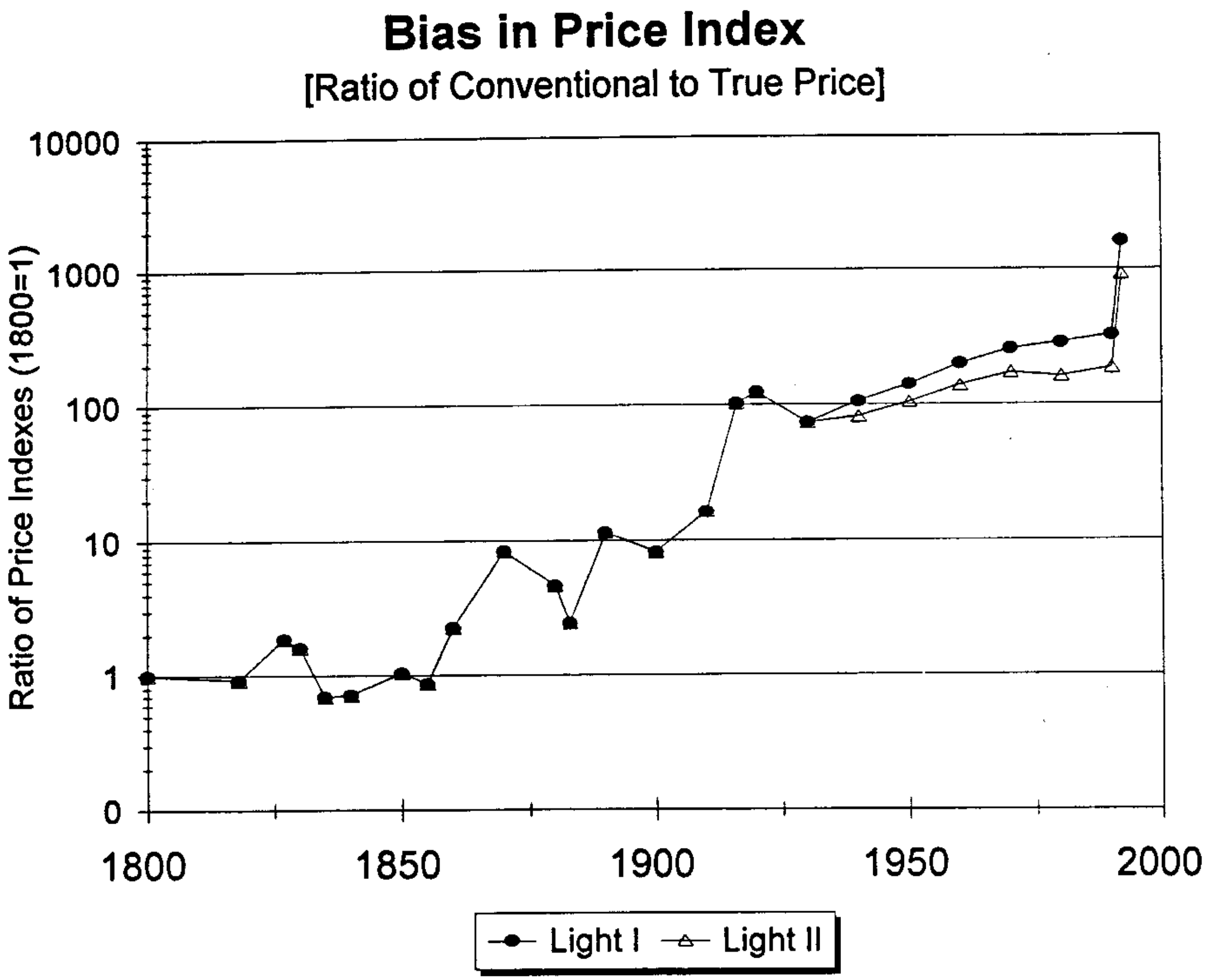
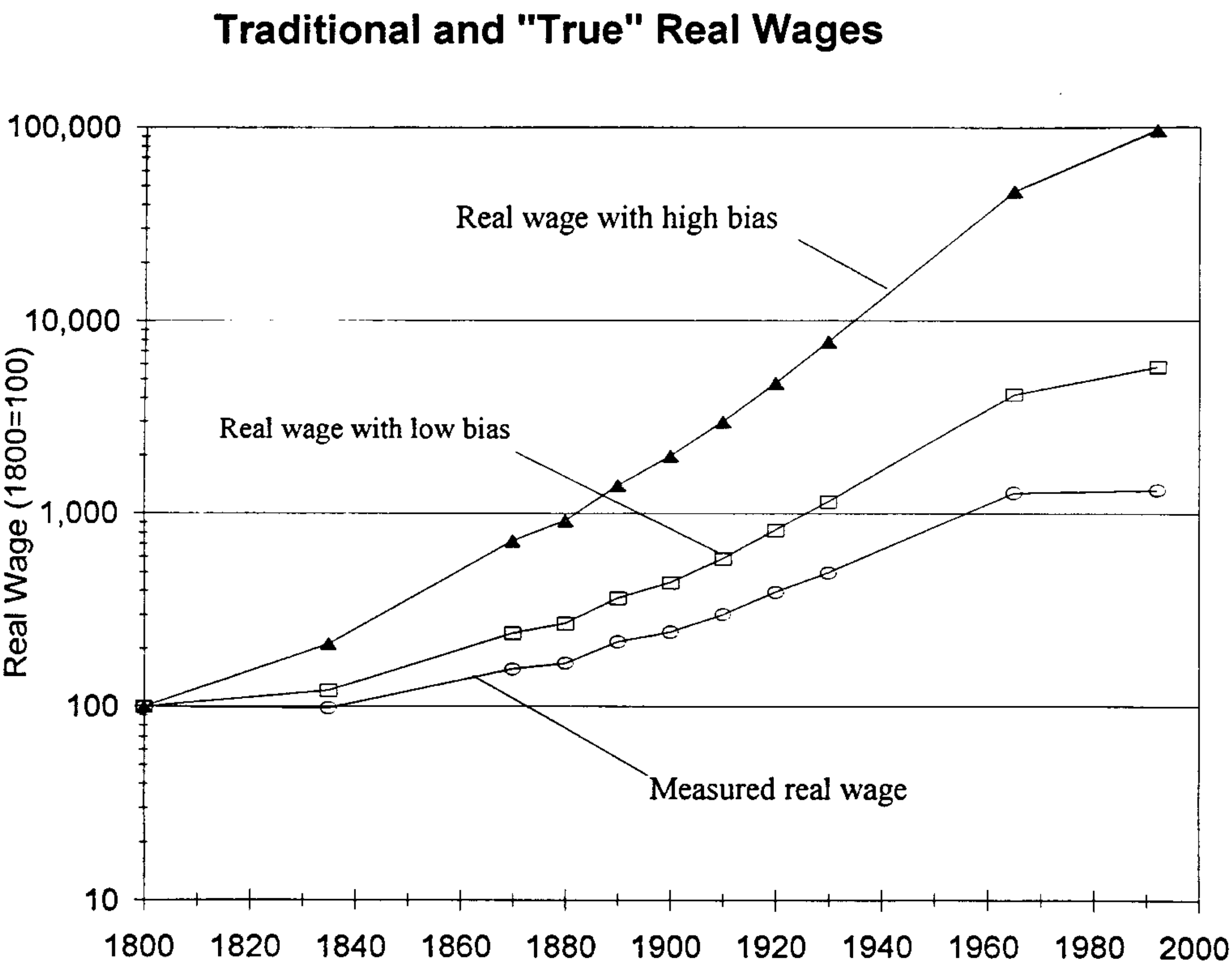

Bias in Price Index
[Ratio of Conventional to True Price]
10000
1000
100
10
1
0
Ratio of Price Indexes (1800=1)
1800
1850
1900
1950
2000
Light I
Light II

Figure 8



Traditional and "True" Real Wages
100,000
10,000
1,000
100
10
Real Wage (1800=100)
Real wage with high bias
Real wage with low bias
Measured real wage
1800
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000