ALSO BY DAVID WARSH

*The Idea of Economic Complexity*
(1984)

*Economic Principals:*
*Masters and Mavericks of Modern Economics*
(1993)

# KNOWLEDGE
## *and the*
# WEALTH *of* NATIONS

## *A Story of Economic Discovery*

DAVID WARSH

Journalist, not Econ.
Can you tell?

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# INTRODUCTION

One of the oldest chestnuts in the inventory of our common sense is this: Give a man a fish, and you feed him for a day. Teach a man how to fish, and you feed him for a lifetime. To which it now must be added, invent a better method of fishing, or of farming fish, selling fish, changing fish (through genetic engineering), or preventing overfishing in the sea, and you feed a great many people, because these methods can be copied virtually without cost and spread around the world. Of course, depending on the circumstances, your invention can make *you* rich as well. New ideas, more than savings or investment or even education, are the keys to prosperity, both to private fortunes, large and small, and to the wealth of nations—to economic growth, in other words, with its incalculable benefits for all. In the background are the intricate rules of the game that we summarize as the rule of law—and politics.

Yet it was not until October 1990 when a thirty-six-year-old University of Chicago economist named Paul Romer published a mathematical model of economic growth in a mainstream journal that the economics of knowledge at last came into focus, after more than two centuries of informal and uneasy presence in the background. The title of the paper was at once deceptively simple and intimidating: "Endogenous Technological Change."

The thirty-two-page article in the *Journal of Political Economy* observed all the ordinary conventions of scientific writing: passive voice, mathematical analysis, modest claims. There were careful citations of earlier work in the same tradition, especially the paper which it sought to supplant and on which it sought to build, "A Contribution to the Theory of Economic Growth," published in 1956 by Robert Solow.

The first paragraph contained a sentence that was initially more puzzling than not: "The distinguishing feature of . . . technology as an input is that it is neither a conventional good nor a public good; it is a nonrival, partially excludable good. . . ."

And thereupon hangs a tale. For that particular sentence, written more than fifteen years ago and still not widely understood, initiated a far-reaching conceptual rearrangement in economics. It did so by augmenting the familiar distinction between "public" goods, supplied by governments, and "private" goods, supplied by market participants, with a second opposition, between "rival" and "nonrival" goods—between goods whose corporeality makes possible their absolute possession and limited sharing (an ice-cream cone, a house, a job, a Treasury bond) and goods whose essence can be written down and stored in a computer as a string of bits and shared equally by many persons at the same time practically without limit (a holy book, a language, the calculus, the principles of design of a bicycle). Inevitably, most goods must consist of at least a little of each. In between these extremes lie myriad interesting possibilities.

A designer dress. The operating system software in a personal computer. A jazz concert. A Beatles recording. The design of a new computer chip. The coded signal from a communications satellite. A map of the human genome. The molecular structure of a new drug—and the secrets of its efficient manufacture. A genetically altered seed—and the series of manipulations that produced it. A Picasso painting, both the canvas itself with its brushstrokes and layers of paint, and its myriad reproductions. A "Baby on Board" sign in an auto window. The text of the book you are reading now. The equation on page 24. All these are nonrival goods because they can be copied or shared and used by many people at the same time. Most are partially *excludable* as well, meaning that access to them can in some degree be controlled, at least in principle. Rival goods are *objects* and nonrival goods are *ideas*—"atoms" and "bits," in a catchy phrase borrowed from computing, where ideas are expressed in strings of binary bits; or "convexities" and "nonconvexities," in the more austere language of mathematics.



By itself the concept of nonrivalry wasn't altogether new to economics. For more than a century public finance specialists had used a series of often confusing terms to explain the source of "market failure"—to describe the underlying commonality of, say, national defense or streetlights, a new bridge or the warning provided by a lighthouse. Nonrivalry took its place among them in the 1960s. It was by marrying nonrivalry to the concept of excludability, and applying the distinction where it had not been employed before, that Romer cast a new light on the ubiquitous role of ideas in the economics of everyday life—meaning trade secrets, formulas, trademarks, algorithms, mechanisms, patents, scientific laws, designs, maps, recipes, procedures, business methods, copyrights, bootleg copies; collectively, that is, the economics of *knowledge*. He illuminated an inescapable tension between creating incentives for the production of *new* ideas and maintaining incentives for the efficient distribution and use of *existing* knowledge—the social choice that creates what we call intellectual property.

Managing the tension between these ends—furthering the growth of knowledge while ensuring that its benefits are widely shared—is a responsibility of government every bit as important as monetary and fiscal policy. If the intricate system of incentives to create new ideas is underdeveloped, society suffers from the general lack of progress (most of all, the poor). So, too, if those incentives are too lavish or too closely held.

Grasp that, and you understand the punch line of the story that this book has to tell. Chances are that intuitively you understood it well enough already

But with the publication of "Endogenous Technological Change," Romer won a race of sorts, a race within the community of university-based research economists to make sense of the process of globalization at the end of the twentieth century, and to say something practical and new about how to encourage economic development in places where it had failed to occur. That there had been a race at all was apparent only to a relative handful of persons, those offering competing explanations of events. That there might exist a "right answer" to the riddle of economic growth, or even that a riddle existed at all, was denied by many people and probably doubted by most.

Yet within a few years the issues attending the post–World War II growth in the wealth of nations had been clarified and, if not resolved, at least reframed in the formal language of technical economics. The basic choices had become clearer than before. The contribution of the growth of knowledge had been broached in a way that permitted its analysis. A new emphasis had been placed on the role of institutions. And a secure role finally was assigned to that long-neglected figure (at least in economics classrooms), the enterpreneur.

"Romer '90" (to use the article's citation shorthand) doesn't fit our conception of a classic, to be placed on the shelf alongside the works of other great worldly philosophers. But it *is*—for reasons that are relatively easy to explain.

Consider the basic building blocks of economic theory—the familiar "factors of production." They are described in the first chapter of almost any elementary economics text. For three centuries these most fundamental analytic categories of economics were land, labor, and capital. Land was shorthand for the productive capacities of the earth itself, its pastures and forests and rivers and oceans and mines. Labor, for the diverse efforts, talents, and simple motive power of working men and women. Capital, for the equipment that they employed and the structures in which they work and live, not just the goods themselves, but financial assets of all sorts representing command over these goods and the services of labor. These categories had been worked out during the seventeenth century, when the expanding global economy gave birth to modern capitalism. They referred to familiar, everyday things and seemed to leave nothing out. They enabled economists to argue about who should produce what goods and for whom, about work relationships, about the



determinants of the size of the human population, about which responsibilities properly belonged to government and which were best left to markets.

From the beginning, some circumstances in the human condition were simply taken for granted. The extent of knowledge was one. Human nature itself, expressed as tastes and preferences, was another. These were "givens," not necessarily thought to be unchanging, but considered to be determined by noneconomic forces—a simplifying custom in technical economics that went back at least to the nineteenth century and John Stuart Mill. These background conditions were, in modern parlance, treated as being *exogenous* to the economic system. They lay outside the model, treated as a "black box" whose detailed internal workings were to be willfully ignored. Exogenous to her concerns is what the waitress means when she says, "It's not my table."

Certain loose ends arose as a result of this way of dividing up the world, especially a well-known family of troublesome effects that were filed under the heading of "increasing returns" to scale. Decreasing returns to additional investment were a familiar topic in economics. After all, even the richest vein of coal plays out. The first barrel of fertilizer does wonders for a plot of land; the tenth only burns the crops. Decreasing or diminishing returns simply mean that you pick the low-hanging fruit first, and that you collect less fruit for the same amount of effort over time. It means that your costs slowly rise.

Increasing returns are just the opposite. They set in when the same amount of work or sacrifice produces an *increasing* quantity of goods or, to turn the definition on its head, when your average costs fall and keep falling with the number of articles produced. Pins are the example usually given, after a famous passage by Adam Smith about the gains from specialization. But Smith's story of falling costs seemed to be only about the benefits of the subdivision of tasks. Obviously there were limits to that, too.

Throughout the nineteenth century, increasing returns were considered to have to do mainly with the output of machines—the printing press, the mechanical loom, the steam engine. Gradually it was recognized that increasing returns were present any time there was little or no additional cost to adding a customer to a network—railroads, electricity, telephones, for example. Increasing returns (falling costs) in these and other industries were so destructive of the ordinary forces of competition that such businesses soon were declared to be not just monopolies but "natural monopolies," markets whose fundamental properties led inexorably to a single producer of goods with no close substitutes, and whose conduct in the absence of competitive forces necessarily would have to be overseen by government.

Economists who came after Adam Smith never were very comfortable with the phenomenon of increasing returns, of steadily falling costs. It ran counter to their most basic intuition—that scarcity was the fundamental problem, that the human race was forever running out of something, whether land, or food, or coal, or clean air. Falling costs violated this understanding, and they were much less consistent than rising costs with the mathematical tools that they employed to describe and analyze the effects of competition. Monopolies were understood to be exceptions to the rule. Situations in which producers were free to set their prices, rather than have them set by competitive forces, were special cases of "market failure," to be mentioned in footnotes, left out of the argument altogether, while economists focused on competition.

So the problem of increasing returns was put aside for some later date. Economists finessed it, introducing concepts that seemed to make the contradictions disappear—the convenient assumption, for example, that overall returns to scale might generally be neither increasing nor decreasing but *constant*, that effort and output forever would increase only in direct proportion to one another. In establishing this assumption as a mostly unconscious mental habit, growing formalization played a central role.

With the addition of each new wave of technique, from literary economics to syllogism in the eighteenth century, from syllogism to calculus in the nineteenth, from calculus to set theory and topology in the twentieth, the status of increasing returns became more problematic and obscure, especially after the triumph in the 1950s of formal models of the economy as a whole.



In the late 1970s and early 1980s, the situation began to change. The developments in growth theory with which this book is concerned unfolded mainly in Cambridge, Massachusetts, and Chicago, very far indeed from the controversies over "supply-side economics" that garnered headlines in New York City and Washington, D.C. in those days. A handful of graduate students at the University of Chicago, the Massachusetts Institute of Technology, Harvard University, and Princeton University discovered for themselves that the blind spot in the vocabulary and analytic framework of economics, once small, had with the passage of time (and increased abstraction) become enormous. They set out to make formal models of the phenomena that led to increasing returns. And in fairly short order they succeeded.

For a time these matters were no more earthshaking than conversations among the young economists and their teachers, their spouses, friends, and competitors. Excitement slowly spread throughout the discipline. New ideas about subjects such as novelty, variety, and market power were mapped into the tapestry of economic thought—first in the subfield of industrial organization, then in trade, then in growth, then back into industrial organization. New models were applied to policies for population, education, science, entrepreneurship, trade, antitrust, and cities, not to mention the familiar macroeconomic concerns of monetary and fiscal policy. These studies meshed with the new emphasis on political economy. They turned rapidly to the political and economic institutions that accommodate change—arrangements that were themselves a kind of knowledge. For a few years in the early 1990s, almost everybody in economics had something to say about the new ideas regarding increasing returns.

These developments, which would otherwise remain quite obscure, have the advantage of having been a deeply human drama as well, in which present-day heroes in certain ways personify the generations of modern economics—Robert Solow born in 1924, Robert Lucas born in 1937, and Paul Romer born in 1955. The story of how knowledge was left out of economics for so long—and why, in some quarters, it is *still* met with a reluctant reception—makes a pretty good yarn by itself.

For the significance of "Endogenous Technological Change" becomes clear as soon as soon as the paper's key equations are translated into everyday language. Romer's 1990 paper divided up the economic world along lines different from earlier ones. Overnight for those who were involved in actually making the intellectual revolution, more slowly for all the rest of us, the traditional "factors of production" were redefined. The fundamental categories of economic analysis ceased to be, as they had been for two hundred years, land, labor, and capital. This most elementary classification was supplanted by people, ideas, and things.

People, ideas, and things. This phrase isn't in the textbooks yet. It isn't widespread in the literature. But once the economics of knowledge was recognized as differing in crucial respects (nonrival, partially excludable goods!) from the traditional economics of people (human beings with all their know-how, skills, and strengths) and things (traditional forms of capital, from natural resources to stocks and bonds), the matter was settled. The field had changed. The familiar principle of scarcity had been augmented by the important principle of abundance.

Technical change and the growth of knowledge had become *endogenous*—within the vocabulary and province of economics to explain. A certain amount of commotion was the result. To see it, however, you have to know where to look.

CHAPTER TWENTY-FOUR

Skipped 23 chapters so you wouldn't yell at me. This one is the best.

# A Short History of the Cost of Lighting

VERY FEW ARGUMENTS in economics are ever settled. The question of which model to prefer is not easily resolved. In physics whatever doubts existed about the significance of $E = mc^2$ were settled once and for all among scientists and laymen alike by the detonation of a nuclear fission bomb. But there are few such explosive confirmations in economics. That is not to say that there are none.

The controversy over the economics of knowledge was interrupted in December 1993 by news of a study that, by itself, would all but resolve the question of which model of economic growth to prefer, fundamentally. Regression analysis is all very well. But a good experiment is can make the case for a new idea with overwhelming rhetorical force.

The conventional wisdom is that economics can't have experiments. Here, however, was a case drawn from human history, not even a "thought experiment" but a real one, with the ultimate in hard data. No purchasing-power parity adjustment was necessary. No cross-country comparisons were required.

Clearly technological change has been the major source of economic growth. On that much both the Solow and the Romer models could agree. But was the growth of knowledge a fundamentally economic process? Or were its wellsprings still so mysterious or intractable that they should remain out of bounds to economists? Exogenous? Or endogenous? Black box? Or not? The nub of the question concerned the implications for policy. Was growth a matter for economic policy for sovereign nations? Or was there nothing much to be done about it?

The shape of the data was as singular as a mushroom cloud.

pronounced Nord-house

THE EXPERIMENTER was William Nordhaus, the same Nordhaus who as an MIT graduate student in 1967 had tried to build R&D into the Solow growth model, using monopolistic competition. That section was dropped from his dissertation, and from the book that it became, *Invention, Growth, and Welfare: A Theoretical Treatment of Technological Change*. It was eventually published as a short paper in the 1969 proceedings of the *AER*. Whatever disappointment he felt as a young man, he had never showed it. He returned to Yale University to teach (he had been captain of the ski team as an undergraduate there), and applied himself to a variety of topics connected with the environment, mineral depletion, and, of course, the energy crisis.

Over the next thirty-five years Nordhaus blossomed into an unusual combination of inventive thinker and useful citizen. Work that he began in the early 1970s on extending the national income accounts to include the environment steadily bore fruit. He became a leading expert on global warming and on nonmarket accounting in general. From 1977 to 1979 he was a member of President Jimmy Carter's Council of Economic Advisers, then provost of Yale University and, for a time, vice president for finance and administration. In 1985 he joined Paul Samuelson as coauthor of his famous text, whose eighteenth edition was published in the fall of 2004.

The conventional wisdom is that the best experiments are connected in the mind of the experimenter with the proof of some bold hypothesis. William Harvey's vivid experiment on circulation of the blood, for example, was designed to demonstrate that the body works in a certain fashion. Was any such intent on Nordhaus's mind when he conceived the experiment? No, he says—at least not consciously. When he started, in the 1970s, he was only trying to get a handle on the price of oil.



The year was 1974. Nordhaus was a newly tenured professor at Yale, affiliated with the Cowles Foundation. Like nearly every other economist in that year in which oil prices quadrupled, thanks to OPEC, he was thinking about the energy problem. Because of his dissertation, he well understood that technical change was one of the predictable responses to the higher price of oil.

True, purchasers would cut back on the oil they purchased and seek substitute sources, such as natural gas. True, too, prospectors would seek and find new reserves. Supply and demand would seek an equilibrium. But inventors, meanwhile, would go to work to find more efficient ways to make the most out of whatever oil was available—inventors of all sorts, to be found inside corporations and outside of them, not only at lab benches but in purchasing departments as well. Of the factors that would influence the future price and availability of oil, Nordhaus guessed, technical change probably was the most potent. How to illuminate the question?

What Nordhaus wanted was a measure of the cost not of crude petroleum but of the uses to which the products refined from it were put to create things wanted for their own sake—heat, light, travel, work—and not only substances refined from oil, but the various fuels that had been put to those same uses before oil was discovered, and the substitutes for oil that had emerged subsequently as well: electricity and gas and solar and nuclear power. He wanted to measure the *output* of whatever fuel was employed, in terms of the work it performed, rather than the various *inputs*, meaning the price of the fuel and whatever additional equipment was required to convert it to work—the furnace, the lamp, the car. Theorists call this a *true* cost-of-living index, one that measures the cost of goods and services that are wanted for their own sakes instead of relying on a rule of thumb (a production function) to calculate the yield from the prices and quantities of the ingredients.

But then, output was notoriously hard to measure, especially where changing technology is involved. For example, how to compare the transportation furnished by a car with that of a train or a horse? How to compare the reach of a copyist employed to communicate your views with that of a printing press or a copy machine? Or a monotonous diet of beer and bread with one that included sushi and Moon Pies? The energy represented by a barrel of oil was especially difficult to pin down. It could be put to so many different uses in the modern age. For this reason economists had hit on the idea of service characteristics, meaning the underlying utility that the customer seeks from the good that he purchases.

To simplify matters, therefore, Nordhaus zeroed in on a consumer good whose nature hadn't changed very much in hundreds of thousands of years—the cost of lighting a room at night. Nighttime illumination is one of humankind's oldest consumer goods. It was an uncommon luxury for thousand of years, gradually giving way to an entitlement, but never changing in its most essential characteristics, regardless of whether it is thrown up by a fire in a dark cave, an oil lamp in a Pompeiian villa, a candle in an eighteenth-century drawing room, or a warm pink bulb in a late twentieth-century kitchen. The great virtue of the cost of lighting was that it would be easy to measure. The inputs to produce it would vary greatly, of course. So would the efficiency with which they were converted into illumination. But the nature of output would remain the same. Light was light.

So Nordhaus became a student of the history of lighting. He perused old histories of lighting and nineteenth-century laboratory notebooks. He combed through the work of anthropologists, all the way back to the discoverers of the Beijing cave that contained the earliest-known ashes of a hearth fire. He described the history of lighting technology in the following table.

### Milestones in the History of Lighting

| | |
|---|---|
| 1,420,000 B.C. | Fire used by Australopithicus |
| 500,000 B.C. | Fire used by Beijing 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 |
| 1794 | William Murdock uses coal gas illumination in his 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 Sillman Jr. experiments with "rock oil" |
| 1860 | Demonstration of electric-discharge lamp by Royal Society of London |
| 1860s | Development of kerosene lamps |
| 1876 | William Wallace's 500-candlepower arc lights, displayed at the Centennial Exposition in Philadephia |
| 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 tub |
| 1931 | Development of Sodium-vapor lamp |
| 1980s | Marketing of compact fluorescent bulb |

Don't skip this. Read it.

SOURCE: Timothy F. Bresnahan and Robert J. Gordon, *The Economics of New Goods* (Chicago: University of Chicago Press, 1997)

LED not included. This is HUGE.



With his rough history of the technology of illumination complete, the next step would be to estimate the efficiency of each light-producing apparatus. Now Nordhaus had to become more precise. What exactly did he mean by illumination? For his purposes, it was the simple flow of light that mattered—its flux, measured in lumen-hours per thousand Btus. He noted the many aspects of lighting that are important to us today because they can easily be controlled—color, dependability, convenience, and safety. These he simply left out of his calculations altogether, for the variation was simply too great to measure. True, improvements in all of these factors were part of what we meant when we spoke of a higher standard of living. But such considerations detracted from the point that he was most interested in investigating, which was the extent of the improvement in the sheer efficiency of its provision over the years, both of finding fuel and turning it into light.

The experiment became a hobby. Sometimes he found data on the differing efficiency with which various technologies produced illumination that had been collected carefully by others in the course of work. One researcher in 1855 had examined the illuminating possibilities of "rock oil," just about the time it was discovered in large quantities in Pennsylvania. Another in 1938 carefully compared data on candles, town gas, kerosene, and electricity (observing, in the process, that "the discovery of petroleum in Pennsylvania gave kerosene to the world, and life to the few remaining whales").

First oil drill?
1859, Titusville, PA

At other times Nordhaus had to make the measurements himself. One day he burned twenty-one pounds of wood in his home fireplace and calculated that it produced an average of 2.1 footcandles of illumination for about three and a half hours, or about 17 lumens per pound. Another time he bought a little terra-cotta lamp dating from Roman times. He rigged it with a wick from a modern candle and fired it up with sesame oil brought from the little Himalayan principality of Hunza. A quarter cup burned for seventeen hours and produced 28 lumens, a major improvement over logs. He combined his own results with nineteenth-century engineering data, as carefully as he could. The result was an index of the price of lighting expressed in cents per lumen-hour.

Even then, however, Nordhaus was not finished. The nominal price alone could give a distorted picture of improvements in living standards. A case in point: a modern hundred-watt bulb, burning three hours a night, would produce 1.5 lumen-hours of illumination per year. At the beginning of the nineteenth century, a similar amount of light would have required burning 17,000 candles. To buy them an average worker would have had to work a thousand hours, or nearly half a year. Naturally, nobody thought that much light was needed. It would be necessary, therefore, to calculate a labor price of light. Good data on average wages was available since 1800. But for three critical junctures before that, Nordhaus made his own estimates—the length of time it might have taken an artisan to make a

Wow!



soapstone lamp and earn the money for some sesame oil, to catch a duck for its fat, to gather wood for a fire.

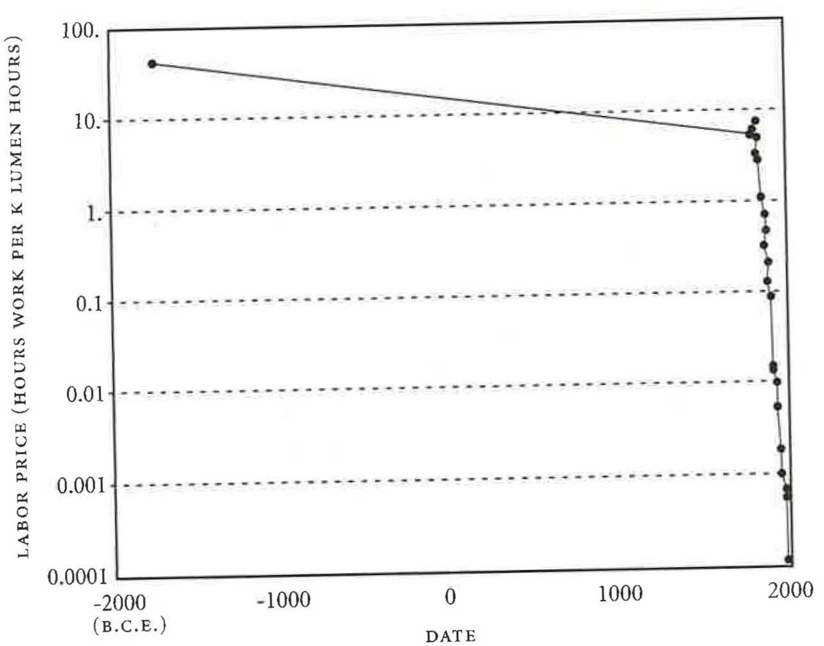
Half a million years ago, Beijing man would have worked sixteen hours a week to gather wood to illuminate his cave, he estimated. A Neolithic man, burning animal fat, would have spent only a little less time chasing down and rendering the duck. A Babylonian man, on the other hand, would have worked just ten hours a week for an equivalent amount of lamp oil, and both the quality of light and the ease with which it could be controlled were much improved. Some four thousand years later, at the beginning of the nineteenth century, candle technology had improved matters further still—but only by a factor of ten. In the end Nordhaus had a history of the true price of a lumen-hour of the cost of lighting, expressed in terms of a carpenter's wage, dating back to the dawn of human use of tools.

Then, some fifteen years after the oil crisis in which he first conceived it, Nordhaus realized that his project might have some bearing on a larger issue. The oil crisis had abated in the 1980s. But the controversies among economists over the sources of growth had heated up. It hadn't escaped him that his cost-of-lighting index bore directly on the Solow-Lucas-Romer debate. on economic growth

So Nordhaus neatened up his data, cut it back to the mere 4,000 years for which he had money wages and prices—the 2,000 years before the Christian era began and 2,000 years after. He took it first to the NBER in December 1993, then to a meeting of the Conference on Research in Income and Wealth in Williamsburg, Virginia, the next April. Somewhat disarmingly, he titled it "Do Real Income and Real Wage Measures Capture Reality? The History of Lighting Suggests Not."

THERE ARE FEW more remarkable pictures in all of economics than Nordhaus's chart "Labor Price of Light: 1750 B.C. to present." It shows the rough cost of illuminating a room at night over a period of four thousand years. For almost forty centuries there is barely perceptible movement. Then, suddenly, starting around 1800, the cost of light falls off a cliff and begins declining at a rate approximating a right angle. You don't see many right angles in economics.

LABOR PRICE OF LIGHT: 1750 B.C. TO PRESENT




SOURCE: Bresnahan and Gordon, *The Economics of New Goods*

In this chart the history of the human race falls neatly into two parts. For most of its history humankind worked fairly hard for what little light it was able to obtain. People simply tended to go to bed when it got dark. For something like half a million years—from the time of the first fires in caves until candles illuminated the whole of the palace at Versailles—there is no evidence of any very great change in the labor price of light. It declined, to be sure, but the gradual improvement in lighting technology over the millennia was too slow for most generations to be aware of it.

By the beginning of the eighteenth century, the taste for lighting had been broadly enough acquired that the authorities had begun to tax windows (a good proxy for wealth) and candles. Between 1711 and 1750 the real price of candles in England rose by something like a third, causing cutbacks all around—a somewhat different kind of "dark age," according to Roger Fouquet and Peter J. G. Pearson, who



studied the history of English lighting. Adam Smith, among others, inveighed against the tax on candles as being unfair to the poor; John Stuart Mill observed a "deformity of buildings" caused by the windows tax. **Remember Bastiat? Look at p. 180 in Heilbroner.**

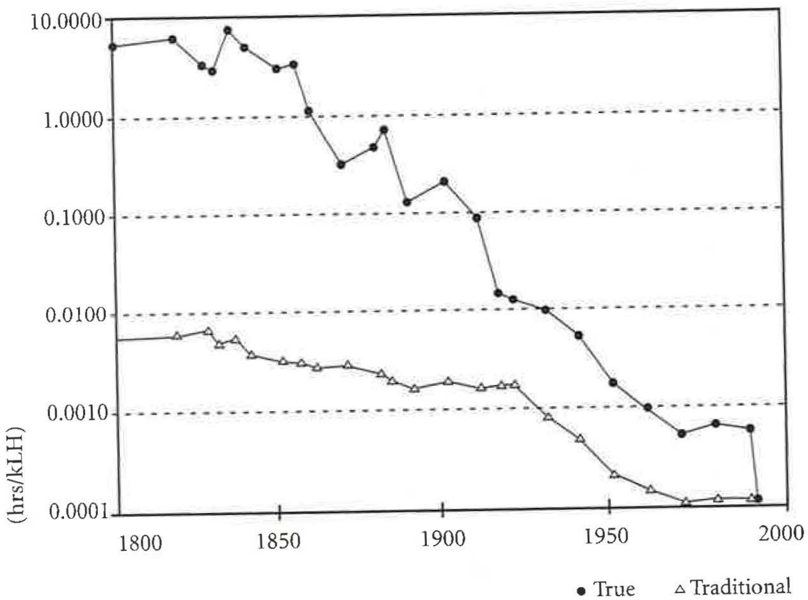
Then abruptly, about 1800, the cost of illuminating a room at night began to drop, year after year. Shortages of fuel came and went, but none could deflect the trend. Gaslight cost a tenth as much as candlelight; kerosene a tenth as much as gas. Electricity, starting in the 1880s, was the real wonder. Within a decade or so it ceased to pose a danger to its users. And by the twentieth century, nearly constant improvements were taken for granted.

**Schumpeter!** To put it another way, ordinary people became rich. The real wage exploded, at least the real wage measured in terms of the cost of light. Illumination went from being a major heading in the consumer basket to being so small a fraction of consumption that, by the 1940s, it was expected that soon it might be free.

That was the essence of the experience of economic growth. The concept itself emerged only slowly in economic discourse from the nineteenth-century notion of "the national dividend." For a long time it was more or less synonymous with "the standard of living." Only after Robert Solow's growth model appeared did economists become much more careful about its definition. And now Nordhaus was warning that the official estimates of growth, conceptually at least, were way off, because of the manner in which new goods were linked into the index. Estimates of real income were only as good as the price indices were accurate. And it seemed that prices indices, by their very nature, simply ignored the most important technological revolutions.

When Nordhaus compared the light component of the consumer price index since 1800 with his own index, he found that the stories diverged radically. Money prices had risen three- to fivefold in 200 years, or only half as fast as the overall CPI. But in his own, "true" price index, money prices had steadily *fallen* year after year, until they were merely a tenth of 1 percent in 2000 what they had been when Thomas Jefferson was in the White House. And when he compared the changes in the purchasing power of a laborer's wage over

THE TRUE AND THE TRADITIONAL STORIES
OF THE LABOR PRICE OF LIGHT




SOURCE: Bresnahan and Gordon, *The Economics of New Goods* (University of Chicago Press.) © 1997 by the National Bureau of Economic Research

those two centuries, he produced the picture above. On this one particular heading, the traditional story was off by *three orders of magnitude*, or a factor of a thousandfold!

It was not just light whose provision had greatly changed. Automobiles had replaced horses, television had replaced cinema, air travel had replaced trains, and pharmaceuticals had replaced snake oil. The only product that, superficially, had remained the same was food. When he toted up the effect of all the "tectonic shifts" (a distinction very much in the Schumpeterian tradition) that had occurred—in household appliances, medical care, utilities, telecommunication, transportation, and electronics—as opposed to the run-of-the-mill improvements, which price indices were designed to capture, and changes in "seismically active" sectors (tenements give way to tract homes and high-rise apartments), Nordhaus concluded that conventional measures of real output and real wages dramatically understate the extent to which standards of living have improved. "The lowly toilet is classified as furniture but delivers a service that would delight a medieval prince," he wrote.



(A battle of such anecdotes, he warned, was likely to turn out to be a war of attrition, "because the number of products involved far outnumbers the number of interested and competent economists and statisticians." His suggestion: take a stratified sample of commodities from the CPI and put a dozen teams of economists to work on it for half a dozen years, estimating the "true" price of services delivered by those items, in the spirit of his experiment with the cost of light. There had been careful studies of televisions, pharmaceuticals, and computers, he said, but none for bananas, haircuts, or church sermons. He found it hard to think of a more exciting and worthwhile topic in applied economics.)

The real power of the Nordhaus experiment is to subvert the normal telling of the story. Was a 10,000-fold increase in the standard of living (as measured by the cost of light) sufficient to avert a proletarian revolution? *Why* did the improvements in the technology of illumination begin exactly when they did? What kept them going once they had begun? How much longer could they continue? (Not long after Nordhaus published his paper, the Department of Energy announced that scientists working in one of its labs had hit on a technique that promised a another tenfold improvement in the efficiency of fluorescent lighting.) What was it that happened around 1800 that made the years thereafter so very different from the years before? "I don't see how you can look at that chart," said Nordhaus, "without thinking of the industrial revolution."

"INDUSTRIAL REVOLUTION" is a term so common today that it is hard to imagine a time when it wasn't part of our everyday language. The term was employed by the French as early as the 1820s, and then Marx introduced it in his hazy way to economics. But not until Arnold Toynbee gave a famous lecture in 1888 did the term enter common parlance. Remember, barely fifty years before, Ricardo and Malthus had adamantly dismissed the possibility of an industrial revolution.

By the 1890s it was clear they had been wrong. "The bitter argument between the economists and human beings has ended in the conversion of the economists," wrote Toynbee. He was a trifle premature. Instead, two broad traditions had developed during the nineteenth century. Non-economists—"human beings," as Toynbee described them, saw the change as not just technological but also social, intellectual, religious, cultural, and political. These students now produced whole departments of knowledge, histories of all sorts, theories of all kinds.

C'mon, that's funny.

The more general theoretical approach was dominated by Karl Marx. But Alexis de Tocqueville and Edmund Burke established a parallax view of politics. Max Weber turned Marx's idea on its head, forcefully suggesting that it was religious conviction in the form of a Protestant ethic that had produced capitalism, not the other way around, and so helped establish sociology as a subject in its own right. Emile Durkheim took up the division of labor from a different angle, and built bridges to the loosely structured discipline of anthropology. Less durable attempts to parse the great changes of the last few hundred years ran in every conceivable direction.

The main line of descent however, from Adam Smith through Max Weber, down to Alfred Chandler and Thomas Kuhn, with their histories of business and science in the present day, can be described as a preoccupation with the causes and the consequences of specialization—that is, with the underlying significance of the Pin Factory.

The economists, on the other hand, have given us growth theory. What do growth theorists have to say about the history of the true cost of light?

AMONG THOSE LEAST SURPRISED by his student Nordhaus's remarkable exercise was Robert Solow. After all, he had come up with the same answer, at first cut. Accumulation of capital is not the dominant force. Could modern abundance have been achieved by adding millions more candles? It was unlikely. More coal miners and farmers? Probably not. Remember Solow's initial calculation of the Residual of seven-eighths of increased output that could not be explained by the additions to the stocks of capital and labor. If the same methodology were applied to Nordhaus's data for the cost of light, the Residual might very well be 99 percent. Almost all of the action was in technological change.



This is super hard to understand.
I will try to explain it in class.

On the other hand, Solow observed, there was nothing in the light experiment to tell you what fraction of national income you should commit to R&D. Nor was there anything to tell you what national income would have been without it. For Solow the new models were suggestive, but they were not yet fully formed.

For Lucas, who had been so keen on identifying policies that might improve the lot of the poor, the demographic transition was the key. Insofar as the industrial revolution was defined as a matter of sustained income growth, it was not exclusively, or even primarily, a technological event. "A small group of leisured aristocrats can produce Greek philosophy or Portuguese navigation," he wrote, "but this is not the way that the industrial revolution came about." Instead, a large fraction of the population changed the horizons of the lives they imagined for themselves—defying their parents, leaving their villages, taking work in impersonal cities, losing touch with their children themselves, in order to enjoy a standard of living that had suddenly begun to rise for large numbers of people. Economic development required "a million mutinies" against the traditions of the past, Lucas wrote, adopting a phrase from the novelist V. S. Naipaul, whose classic *A House for Mr. Biswas* described the passage of one family in three generations from the sugarcane fields of rural Trinidad to Oxford University.

Without wishing to dispute the place of knowledge in the growth equation, Lucas wrote, he wanted to make a complementary point. "Growth in the stock of useful knowledge does not generate sustained improvement in living standards unless it raises the return to investing in human capital in most families." The important thing was to get a fertility term into the model, Lucas wrote. Blueprints by themselves were not enough.

And Romer? If technical change matters so much, he asked, can we afford to continue to leave its secret rhythms unexplained? No wonder that the Lost Patrol thought it had tumbled on "secrets of the universe" when in 1965 it began examining the systems of incentives to knowledge creation and diffusion. To treat all this story as being outside the capacity of economics to influence or explain—as exogenous to economic models—is indeed, as Schumpeter had once described it, like playing *Hamlet* without the prince. This will be clear later.

On the other hand, Romer's model underscored the importance of incentives to invention that were created by institutions. Consider the other developments that began to take hold in the late eighteenth century—the Declaration of Independence of Britain's North American colonies; in France, the Declaration of the Rights of Man. Changes in the law of property and patents affected the pace of technological change; there were parallel developments in taxation, banking, and finance, in science and education. Romer's model led directly to consideration of the institutions favorable to commerce—precisely the consideration that had been championed for years by Douglass North, Richard Nelson and Sidney Winter, Nathan Rosenberg and Paul David. The old-timers grumbled that they had known it all along. They lamented seeing the broad outlines of the work they had done restated in mathematical terms, especially since the new mathematical approach seemed to wash out precisely the details that were important to them.

Romer replied with his own version of the parable of mapping Africa, the metaphor of an hourglass. For much of its history, he said, economics has evolved in decentralized fashion, with its applied fields developing language and conceptual tools appropriate to their separate concerns. These were like so many dialects of a demotic tongue—labor economics, industrial organization, banking and finance, international trade, public finance, development economics, and so on. But with the coming of mathematics, field after field had gone through a process that could be thought of as resembling an hourglass resting on its side, with the vertical dimension representing the breadth and immediacy of its concerns, and the horizontal dimension representing the passage of time. As the younger generation turns to mathematics for its tools, a progressive narrowing takes place. For a while what its students have to say about the world is severely constricted by unfamiliarity with their newly acquired abstractions. But as they develop facility with their new vocabulary and new tools, these specialists' concerns gradually widen, until they are once again talking about a full range of issues—but now with a new and more precise understanding than before.*

What about the analysts who warned that humankind would soon be running out of the fossil fuels that had made possible the era of cheap and abundant light? It was one thing to recognize that prognosticators since Malthus and Ricardo had been forecasting imminent shortages for two centuries. It was another to note that human resourcefulness had intervened at every juncture to devise still cheaper and less environmentally disruptive alternatives. (Save the whales!) But just because alarmists were wrong in the past didn't mean they would always be wrong. Human ingenuity is very great, but, as Nordhaus himself has cautioned, "Sometimes the wolf is real."

No economist in the late 1990s thought more carefully about the three competing theories of growth than did Charles Jones, the Berkeley researcher who had raised the first questions about the *Star Trek* implications of Romer's model. At one point Jones obtained a National Science Foundation grant to develop teaching materials, and in 1998 he published *An Introduction to Economic Growth*. After carefully explicating each model, he concluded that each economist was preoccupied with a slightly different question. Why are we so rich and they so poor? Solow answered that it was because rich countries invested heavily in equipment and education and used these resources productively, and poor countries did not. Lucas asked how the rapid transformations known as economic "miracles," as in Japan or Germany or Korea, were to be understood. With a careful study of their transition dynamics, he declared. And Romer posed the question, What is the engine of economic growth? His model clearly demonstrated that the engine is invention, and that its drivers are entrepreneurs who, for one reason or another, create the stream of new ideas that, taken together, we call technological progress.

* David Kreps described Romer's hourglass in detail in his "Economics: The Current Version," in the winter 1997 issue of *Daedalus*.

To the most fundamental question of all—What does economics itself have to tell us about our the prospects for *our* lives?—the traditional answer, that economics is about scarcity and diminishing returns, surely can no longer seem adequate. The newest improvement in illumination is the solid-state white light–emitting diode (WLED), a fundamentally more efficient (and thus environmentally friendly) source of light than the cheapest fluorescent lighting now in use. WLEDs may transform Western nations' dependence on imported oil. But the new technology is of special interest to the 1.6 billion or so persons in the poorest regions of the world who still lack access to electricity today, for not only do WLEDs offer illumination comparable to the kerosene lanterns now most widely used, at a tenth to a hundredth of the cost; they also do not require an expensive electric power grid to do their work. Their AA batteries can be recharged by solar panels no bigger than a paperback book. They represent an advance as dramatic as did cell phones.

The W has been dropped. It's just the LED now.

So what is economics all about? Land, labor, and capital, with technology considered as a force apart? Or people, ideas, and things, with the production and distribution of knowledge a matter of central concern? Scarcity? Or the countervailing forces of scarcity *and* abundance? For most people the story of the true cost of lighting is persuasive. It is the growth of knowledge that is the engine of economic growth. As the poet Blake put it, "Truth can never be told so as to be understood and not believed."

Damn, this journalist can write!

CHAPTER TWENTY-FIVE

# *The Ultimate Pin Factory*

ANOTHER EXAMPLE OF THE POWER of bits-and-atoms economics to make sense of the modern world was becoming apparent in the mid-1990s. This one was covered extensively in the newspapers. The rise of Microsoft demonstrated the possibilities open to a modern equivalent of the Pin Factory.

Thanks to its success in establishing its Windows operating system as "the universal" for personal computers, Microsoft enjoyed powerful increasing returns to scale, both internal and external. It was like the story of the QWERTY keyboard, except that in this instance Microsoft owned the design, and the market was truly global.

What, then, of the Invisible Hand? Might the forces of specialization win out over the countervailing forces of competition? Could a single firm take over a world market? Could it control the development of technology, crushing competitors when they arose? What about the bifocals of Adam Smith?

In the 1990s these were pressing questions of public policy, for the personal computer was, in fact, only one of two great information-processing technologies that appeared in the 1970s. A second industry made its appearance in those years, approaching many of the same tasks from a different direction—as differently as did, say, personal automobiles from railroads. The second system was, of course,



Are you curious? Ask me in class.