Education for Innovation:
Entrepreneurial Breakthroughs vs. Corporate Incremental Improvements

William J. Baumol[1]

> "Procter & Gamble has a world class, global research and development organization, with over 7,500 scientists working in 22 research centers in 12 countries around the world. This includes 1,250 Ph.D. scientists. For perspective, this is larger than the combined science faculties at Harvard, Stanford and MIT…. P&G holds more than 24,000 active patents worldwide, and on average, receives about 3,800 more patents per year. This makes P&G among the world's largest holders of U.S. and global patents, putting it on a par with Intel, Lucent and Microsoft."
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> Procter & Gamble, www.pg.com, accessed February, 2004.

> "Edison, Thomas Alva. Born in Milan, Ohio, he had very little schooling."
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> Encyclopedia Britannica, "BritannicaReadyReference," accessed January, 2004 (Edison's formal schooling ended by age 12).

> "In established businesses, innovation is mostly shaped through small, incremental steps of additional features to augment basic functionalities. With short product lifecycles, time to recoup R&D investments is limited…. Success is relatively predictable through the execution of well-defined innovation processes and in-depth knowledge of their markets in the respective business units."
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> A. Huijser, Ph.D., executive vice president and chief technology officer, Royal Phillips Electronics, The Hague, September 2003.

First, some preliminary observations on which the hypotheses at the heart of this paper are founded: As should not be surprising, only a very small proportion of the enterprising founders of business firms actually engage in the innovative activity that is a key element in the extraordinary growth performance of the industrialized free-market economies. In fact, it has been suggested that something on the order of only five percent of firm-creating entrepreneurs engage in significant innovation. Rather, most private-sector expenditure on research and development is attributable to very large corporations, and this share is growing. These corporations are prime employers of scientists and engineers, personnel characteristically highly educated and technically erudite. But, despite this concentration of knowledge, talent, and expenditure in these major enterprises, an examination of the list of revolutionary technological breakthroughs since the onset of the Industrial Revolution suggests that they were contributed in overwhelming proportion by independent inventors and small, newly founded enterprises, not by major firms.[2] Finally, and intriguingly, a review of the biographies of the most celebrated of these innovators shows, in a surprising share of these cases, a most remarkable absence of rigorous technical training and, in many cases, little education at all. The obvious names of yore, Watt, Whitney, Fulton, Morse, Edison and the Wright brothers, illustrate the point.[3]

The preceding observations would seem to lend support to two surmises: that the concentration of R&D in corporate hands is a gross misallocation of social resources, and even that education contributes little and may even be a hindrance to technical progress. Research recently undertaken by several colleagues and myself already indicates that the curious observations just listed are generally consistent with the facts, but that the dubious conclusions that they would appear to imply are incorrect and misleading. Rigorous education does play a critical role in support of technical progress, and R&D expenditure by the giant corporations, *together* with the efforts of the independent entrepreneur-innovators provide a crucial contribution to the process. However, the corporate contribution and that of the innovative entrepreneur are characteristically very different from one another and characteristically play complementary roles. Moreover, the contribution of the two together is superadditive, that is, the combined result is greater than the sum of their individual contributions.

I. Education as a Help, and a Hindrance, to Innovation

Historical evidence indicates that the design of the educational process has significant consequences for two highly pertinent, but very different, capabilities of the individuals engaged in innovative activities. On one side, education provides technical competence and mastery of currently available analytic tools to future entrepreneurs and others who will participate in activities related to innovation and growth. On the other side, education can stimulate creativity and imagination and facilitate their utilization. But it is at least a tenable hypothesis that educational methods that are effective in providing one of these benefits may actually tend to be an obstacle to attainment of the other. For example, the student who has mastered a large body of the received mathematical literature, including theorems, proofs and methods of calculation, may be led to think in conventional ways that can be an obstacle to unorthodox approaches that favor creativity. And our preliminary evidence suggests that there is a comparable difference between the ways of thinking of the personnel of large industrial laboratories who focus on successive, incremental technical advances in product and process design, and the innovative entrepreneur (the inventive individuals who are responsible for true technological breakthroughs). This suggests two companion premises: one related to education, and the other to the complementary activities of invention and incremental innovation. The first premise is that education designed for technical competence and mastery of the available body of analysis and education designed to stimulate originality and heterodox thinking tend to be substitutes more than complements. The second and more complex premise is that technical progress requires both breakthrough ideas and a protracted follow-up process of cumulative incremental improvement of those breakthroughs, with the combined incremental contribution of this second phase often exceeding that of the first. Further, the industrial laboratories of the giant corporations are ill-suited to the provision of the seminal breakthroughs but well-designed for the subsequent development tasks, which are indispensable for achievement of the technological breakthroughs' full promise. The study of these ideas promises to provide a deeper understanding of both the nature of education and that of innovative and inventive activity. In addition, it can perhaps suggest ways in which it may be desirable to modify the educational system in general and the preparation of future entrepreneurs in particular.

II. Background Evidence on Inventive Entrepreneurs vs. Incremental Innovators

There are at least three strands of evidence about the differences between inventive entrepreneurs and incremental innovators. The first is related to the types of contributions to economic growth that are characteristic of these two types of innovative enterprise; the second deals with the differences in the educational levels of inventive entrepreneurs and incremental innovators; and the third focuses on the nature of the educational process itself.

Type of Enterprise, Innovation and Growth. The evidence shows that there is a rather sharp differentiation between the contributions to the economy's technological innovation that are provided by entrepreneurs and those that are offered by the large internal R&D laboratories of established businesses. Large business firms, which account for nearly three-quarters of U.S. expenditure on R&D, have tended to follow relatively routine goals, slanted toward incremental improvements rather than revolutionary ideas. Greater user-friendliness, increased reliability, marginal additions to application, expansions of capacity, flexibility in design—these and many other types of improvement have come out of the industrial R&D facilities, with impressive consistency, year after year, and often pre-announced and pre-advertised.

In contrast, the independent innovator and the independent entrepreneur have tended to account for most of the true, fundamentally novel innovations. In the list of the important innovative breakthroughs of the 20th century, a substantial number, if not the majority, turn out to be derived from these sources rather than from the laboratories of giant business enterprises. For example, the U.S. Small Business Administration (1995) provides a list of important 20th century innovations for which small firms were responsible, and its menu of inventions spans an astonishing range (see Table 1, below). Other studies come to similar conclusions. It is a plausible observation, then, that perhaps *most* of the revolutionary new ideas of the past two centuries have been, and are likely to continue to be, provided more often by these independent innovators who, essentially, operate small business enterprises. This is not to say, however, that the routine innovative activities have not accomplished a great deal. Though their outputs have usually been less dramatic and less spectacular, if one takes their incremental contributions together and sums their achievements, it becomes clear that their accomplishments of the large corporations have been very substantial. A very clear example is the airplane. The comfort, speed and reliability of modern passenger aircraft and complex military flying machines clearly, by contrast, make the Wright brothers' revolutionary device into a historical curiosity. Automatic piloting, communication, location and computing equipment were surely undreamed of in the years following the first flights. And most of the sophistication, speed and reliability of today's aviation equipment is probably attributable to the combined incremental additions made by routine research activities in corporate facilities. Other careful observers have extended such examples and have concluded that incremental and routinized innovation activities have been responsible for a very respectable share of the contribution of innovation to economic growth in the 20th century.

Educational Attainment of Personnel. All of this is pertinent to study of innovation and growth because our communications with a number of major firms with substantial R&D activities indicate that these enterprises generally employ at least some, and often a profusion of, persons with advanced technical training and higher academic degrees. In contrast, a preliminary sample of successful entrepreneurs and independent inventors indicates that they frequently have had only a basic education and that, though at least some of them have consulted closely with more extensively trained advisors, the core ideas were contributed by the entrepreneurs and inventors themselves.

Education for Mastery of Received Knowledge versus Education for Innovative Ideas. I will end this recapitulation of the preliminary evidence with an observation on a very different subject though, as will be seen below, for purposes of study of the issues under discussion it is closely related to the preceding observations. This is the contrast between U.S. and foreign educational performance at different levels of education. As has been widely publicized, international comparison tests on subjects such as mathematics, physics and other technical and scientific disciplines apparently show consistently that the performance of American students at the elementary school and high-school levels is markedly inferior to that of some European and Asian countries. Yet, the U.S. is universally considered the superior venue for Ph.D. training, so that the best students from the other countries in question vie to come to this country for their graduate work. Moreover, it appears to be the American graduate students who frequently produce the more original and more substantial dissertations. This difference in performance at the two levels of education is a paradox, but like many paradoxes, it may have a straightforward explanation. It may be that the educational approaches that are most effective in providing mastery of the already extant body of intellectual materials actually tend to handicap a student's ability to "think outside the box" and thus discourage unorthodox ideas and breakthrough approaches and results.

I am led, then, back to my first two premises. The exploration of these premises may, in Benjamin Franklin's words, constitute useful knowledge for the design of educational procedures, for promotion of entrepreneurship, for facilitation of the innovation process and for extension of equality of opportunity in a market economy. Specifically, my colleagues and I are undertaking the study and testing of the following five hypotheses:

Hypothesis 1. Training for mastery of currently available scientific and technical methods and materials is of enormous value for innovation and growth. But educational practices that encourage heterodox thinking and exercise of originality and imagination is evidently also of very great importance for society.

Hypothesis 2. The educational approaches best suited for the first of the preceding purposes may be quite different from those that contribute to the second. Indeed, the two approaches may be somewhat inconsistent, with promotion of the one objective tending to impede attainment of the other.

Hypothesis 3. The R&D division of the large firm tends primarily to require personnel who have undergone training for mastery of extant information and analytic methods, while the work of the independent entrepreneur and inventor may prove to be more effectively facilitated by avoidance of that sort of preparation to the extent that it impedes imagination and originality.

Hypothesis 4. Incremental improvement of complex products may require mastery of far more demanding technical information and techniques than was needed for the original ideas that resulted in the invention of those products. The technology needed to improve the design of a Boeing-777 passenger airplane is obviously enormously more complex than that underlying the Wright brothers' first vehicle.

Hypothesis 5. Thus, while the two educational approaches are quite different and to some degree inconsistent, neither can be considered irrelevant or inferior. Each is essential for the process of innovation and growth, and it is important to investigate what educational approach is most appropriate for each task that underlies invention, development and economic expansion.

Let us, then, turn to the preliminary evidence and see what it implies about the validity of the hypotheses.

Entrepreneurship and its Role in the Growth Process

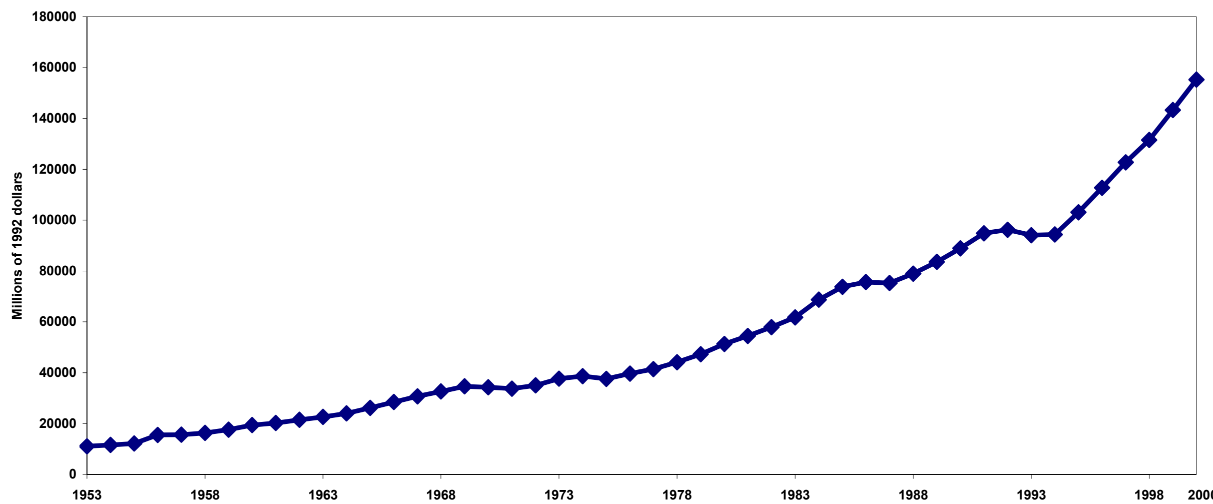
Entrepreneurship has long been valued as a key contributor to the growth of an economy.[4] Indeed, it is widely believed that economies that are abundantly supplied with entrepreneurs will tend to grow far more rapidly than those in which entrepreneurial talent is scarce. Yet Joseph Schumpeter himself, indisputably the 20th century's prime contributor to the economic analysis of entrepreneurship and innovation, was led to conclude that the day of the entrepreneur was waning, that the expanding role of routinized innovation by big business was threatening to make the entrepreneur obsolete. I will argue here that part of the pertinent mechanism has been correctly discerned both by those who continue to have faith in the individual entrepreneur's critical role in economic growth but also by any who follow Schumpeter in concluding that routinized innovation by giant enterprises is assuming a primary role. But each side here is telling only part of the story and, as a result, overlooks much of its essence. The entrepreneur continues to play a critical part in the growth process, and there is no reason to expect that role to disappear. But in the modern economy the entrepreneur, working alone in the marketplace, cannot carry out the task most effectively. Fortunately, the market mechanism has provided the partners that the entrepreneur needs for the purpose.

Market Pressures for an Enhanced Large-Firm Role in Technical Progress

Free competition—that is, competition not handicapped by severe government regulations or tightly enforced customary rules, like those of the medieval guilds that prevented gloves-off combat among rival firms—has arguably played a critical role in the growth of the capitalist economies. Of particular significance in the arena of innovation is rivalry among oligopolistic firms—those large firms in markets dominated by a small number of sellers. And crucial here is the fact that in today's economy many rival oligopolistic firms use *innovation* as their main battle weapon, with which they protect themselves from competitors and with which they seek to beat those competitors out. The result is precisely analogous to an arms race—to the case of two countries, each of which fears that the other will attack it militarily and therefore feels it necessary always at least to match the other country's military spending. Similarly, either of two competing firms will feel it to be foolhardy to let its competitor outspend it on the development and acquisition of *its* battle weapons. Each firm is driven to conclude that its very existence depends, at the least, on matching its rivals' efforts and spending on the innovation process. In an economy in which this is so, a constant stream of innovations can be expected to appear, because the giant warring firms to whom the story pertains do not dare relax their innovation activities.

Increasingly, at least in the United States, the funding for innovation has been supplied by large oligopolistic enterprises, hardly the sort of firms that one associates with the entrepreneur. Today some 70 percent of R&D expenditure in the U.S. is carried out by private business, and the annual level of real investment by the private sector is growing with a trajectory that seems near geometric (Figure 1). Most of this growing outlay is provided by the larger firms. According to data gathered by the National Science Foundation (National Science Board, 2000, Chapter 2, p. 24), in 2000, 46 percent of total U.S. industrial R&D funds were spent by 167 companies with 25,000 or more employees; 60 percent of these funds were spent by 366 companies with at least 10,000 employees, and 80 percent was spent by 1,990 firms of 1,000 or more employees. At the other end of the spectrum, about 15 percent of total U.S. industrial R&D funds were spent by 32,000 companies with fewer than 500 employees each.

Figure 1
Real U.S. Private R&D Expenditures, 1953-2000



Source: National Science Board, 2002, and *Economic Report of the President, 2002*. Expenditures are adjusted for inflation using GDP implicit price deflators.

In these enterprises, innovative activities are carefully designed to prevent unwelcome surprises and to keep risks to a minimum. As a result, there is little of the free-wheeling, imaginative, and risk-taking approach that characterizes the entrepreneur. Instead, the large firm's top management often keeps a tight rein on the activities of the company's laboratories, with budgets determined by the upper strata of control within the firm, who also may determine how many persons and what sort of specialists at what levels will be employed on R&D endeavors. It is not even unusual for management to determine what new products and processes the laboratories should next seek to discover. Sometimes, large firms try to unleash their employees engaged in innovative activity by organizing a subsidiary operation that is more inviting to the free exercise of entrepreneurship, but often without much success.

The natural incentive system for a bureaucratically governed enterprise is to run research and development in accord with bureaucratic rules and procedures. All of this leads to the conjecture, voiced by Schumpeter, that the work responsibilities the economy assigns to the entrepreneur are narrowing and are destined to shrink even further. One can easily surmise what prompted Schumpeter to foresee a limited future for the entrepreneur where industry and its innovation processes are widely characterized in the manner just described. Yet, I will argue next that this is fundamentally a mischaracterization. Rather than being condemned to obsolescence, a vital role continues to be played by independent entrepreneurs.

Revolutionary Breakthroughs: A Small-Firm Specialty

It is convenient here, if patently inaccurate, to divide up inventions with the aid of two polar categories: revolutionary breakthroughs and cumulative incremental improvements. Of course, many new products and processes fall into neither extreme category, but are somewhere in-between. Still, it will become clear that the distinction is useful. Moreover, there are many examples that clearly fit into one of these categories or the other quite easily. For instance, the electric light, alternating electric current, the internal combustion engine, and a host of other advances must surely be deemed revolutionary, while successive models of washing machines and refrigerators—with each new model a bit longer-lasting, a bit less susceptible to breakdown, and a bit easier to use—arguably constitute a sequence of incremental improvements.

The relevance of the distinction should be evident, given what has been said about the working and organization of R&D in the large business organization. The inherent conservatism of the process naturally leads to the expectation that these firms will tend to avoid the risks of the unknown that the revolutionary breakthrough entails. The latter, rather, is left most often to the small or newly founded enterprise, guided by its enterprising entrepreneur. Though that is to be expected, the degree of asymmetry in the apportionment of this specialized activity between large and small firms in reality is striking. Table 1 is a list, made up by the U.S. Small Business Administration, of small-firm innovations in the last century. Its menu of inventions literally spans the range from A to Z, from the airplane to the zipper.

Table 1. Some Important Innovations by U.S. Small Firms in the Twentieth Century

Air Conditioning	Heart Valve	Portable Computer
Air Passenger Service	Heat Sensor	Prestressed Concrete
Airplane	Helicopter	Prefabricated Housing
Articulated Tractor Chassis	High Resolution CAT Scanner	Pressure Sensitive Tape
Cellophane Artificial Skin	High Resolution Digital X-Ray	Programmable Computer
Assembly Line	High Resolution X-Ray Microscope	Quick-Frozen Food
Audio Tape Recorder	Human Growth Hormone	Reading Machine
Bakelite	Hydraulic Brake	Rotary Oil Drilling Bit
Biomagnetic Imaging	Integrated Circuit	Safety Razor
Biosynthetic Insulin	Kidney Stone Laser	Six-Axis Robot Arm
Catalytic Petroleum Cracking	Large Computer	Soft Contact Lens
Computerized Blood Pressure Controller	Link Trainer	Solid Fuel Rocket Engine
Continuous Casting	Microprocessor	Stereoscopic Map Scanner
Cotton Picker	Nuclear Magnetic Resonance Scanner	Strain Gauge
Defibrillator	Optical Scanner	Strobe Lights
DNA Fingerprinting	Oral Contraceptives	Supercomputer
Double-Knit Fabric	Outboard Engine	Two-Armed Mobile Robot
Electronic Spreadsheet	Overnight National Delivery	Vacuum Tube
Freewing Aircraft	Pacemaker	Variable Output Transformer
FM Radio	Personal Computer	Vascular Lesion Laser
Front-End Loader	Photo Typesetting	Xerography
Geodesic Dome	Polaroid Camera	X-Ray Telescope
Gyrocompass		Zipper

Source: U.S. Small Business Administration, 1995, p. 114.

This remarkable list includes a strikingly substantial share of the technical breakthroughs of the twentieth century. Besides the airplane, it lists FM radio, the helicopter, the personal computer, and the pacemaker, among a host of others, many of enormous significance for our economy.

Two very recent studies, also sponsored by the U.S. Small Business Administration (CHI Research, 2002, 2004) provide more-systematic and powerful evidence to similar effect.[5] These reports examine technical change through patenting and define "small firms" as "businesses with fewer than 500 employees." Perhaps most notably, the first of these studies finds that "…a small firm patent is more likely than a large firm patent to be among the top 1 percent of most frequently cited patents." Among other conclusions, in the words of its authors, this study reports that, "Small firms represent one-third of the most prolific patenting companies that have 15 or more U.S. patents…. Small firms are more effective in producing high-value innovations—the citation index for small firm patents averaged 1.53 compared to 1.19 for large firms…. A small firm patent is at least twice as likely to be found among the top 1 percent of highest-impact patents as a patent from a large firm" (CHI Research, 2002, p. 2).

Moreover, the more recent study found that, "The technological influence of small firms is increasing. The percentage of highly innovative U.S. firms (those with more than 15 U.S. patents in the last five years) that are defined as small firms increased from 33 percent in the 2000 database to 40 percent in the 2002 database." In addition, "Small companies represent 65 percent of the new companies in the list of most highly innovative companies in 2002" (CHI Research, 2004, p. ii).

As we will see next, however, large firms have made equally important contributions to technological progress. Though the small enterprises have specialized in the breakthroughs, they are not alone in making critical contributions to innovation and growth.

Revolutionary Consequences of Aggregated *Incremental* Improvements

The type of innovation in which the giant enterprises tend to specialize is primarily devoted to product improvement, increased reliability and enhanced user-friendliness of products and the finding of new uses for those products. The approach tends to be conservative, seeking results whose applicability is clear and whose markets are relatively low in risk. As already noted, the bureaucratic control typical of innovative activity in the large firm serves to ensure that the resulting changes will be modest, predictable and incremental. These firms are not predisposed to welcome the romantic flights of the imagination, the entrepreneurial leaps of faith and plunges into the unknown that often lead only to disaster, but which alone are likely to open up new worlds.

However, having recognized the critical role of the smaller enterprises, one should not go to the other extreme and undervalue the incremental contribution of the routine activity that at least sometimes arguably adds even more to growth than do the more revolutionary prototype innovations. Though each such small improvement may be relatively unspectacular, added together they can become very significant indeed.

Table 1 provided a set of extreme examples of the contributions of the small, entrepreneurial firms. But one can easily obtain equally startling examples of the magnitude of the innovative contributions of the large companies, whose incremental contributions can add up and compound to results of enormous magnitude. One such illustration is the progress in computer chip manufacture by the Intel Corporation, which is the leading manufacturer of these devices and has brought to market successive generations of chips and transistors, on which the performance of computers is so heavily dependent. According to a recent report,[6] over the period 1971-2003, the "clock speed" of Intel's microprocessor chips—that is, the number of instructions each chip can carry out per second—has increased by some *3 million percent*, reaching about 3 billion computations per second today. During the period 1968-2003, the number of transistors embedded in a single chip has expanded more than *10 million percent,* and the number of transistors that can be purchased for a dollar has grown by *five billion percent.* These are evidently no minor contributions. Added up, they surely contribute far more computing capacity than was provided by the original revolutionary breakthrough of the invention of the electronic computer. Of course, that initial invention was an indispensable necessity for all of the later improvements. But it is only the combined work of the two together that made possible the powerful and inexpensive apparatus that serves us so effectively today. Yet we must not ignore a *caveat* here. The 2004 CHI Research study cited above reports that in their large sample the 5.3 percent of all patent citations by large firms that entailed patents owned by small firms was substantially smaller that the small firm's ownership share (6.1) percent of patents owned. "This suggests that large firms build upon the patents of small firms at a rate 14 percent lower than expected given the number of patents owned by small firms" (p. 11).[7]

III. Some Suggestive Inter-Country Comparisons

Having set the background, I can return now to the central issue of this paper and its hypotheses: the role of educational orientation in affecting the amount and type of innovation, here distinguishing once more between "breakthrough" and "incremental" innovations. Since there is no easy way of dividing innovations between these two categories, one cannot expect to find any systematic body of data that permits any formal test of the hypotheses. However, the United Nations publishes a report that does offer information on patenting, patent license revenues, and R&D spending and personnel in 175 countries (2003, Table 11, "Technology: Diffusion and Creation, pp. 274-6). These data permit some suggestive observations, though they can hardly be deemed to approximate rigor.

Recall that one of the conjectures at least implicit in my earlier discussion is that the U.S. educational system is less effectively designed than that of most other industrialized countries to inculcate full mastery of currently available bodies of scientific and technological knowledge, but that this country's educational process is better adapted to stimulation of heterodox and imaginative thinking. The implication is that the U.S. system is better suited to the creation of breakthrough innovation but less well adapted to incremental innovation. Let us see what the data suggest about these conjectures.

The following four figures (which were created directly from the United Nations [2003] data) in each case include the nine countries that are the highest performers in the whatever measure is at issue in each graph. The graphs also include the Russian Federation, for a reason that will be brought out presently, though that country is generally far from the top performer in terms of each variable studied.[8] Figure 2 shows the number of patents granted to residents in 1999, per million people. At first glance, it appears that Japan and Korea are very far ahead of everyone else (with Japan's patents per capita approximately 3.5 times as numerous as those of the U.S., the third ranking country). However, that is most likely related to Japan's and Korea's so-called "first to file" patent systems, which promote rapid filing of a large number of patent applications that can be prepared quickly, are narrow in scope and often represent mere incremental advances Leaving these two countries aside for this reason, it is clear that the U.S. is the world leader in terms of patents per capita.

Figure 3 shows receipts of royalties and license fees, in U.S. dollars per person in 2001. First, we observe that, in this case, Japan ranks third from the bottom, indicating either a marked unwillingness to license or, instead, that its large number of patents have

Figure 2: Patents per Million Residents, 1999

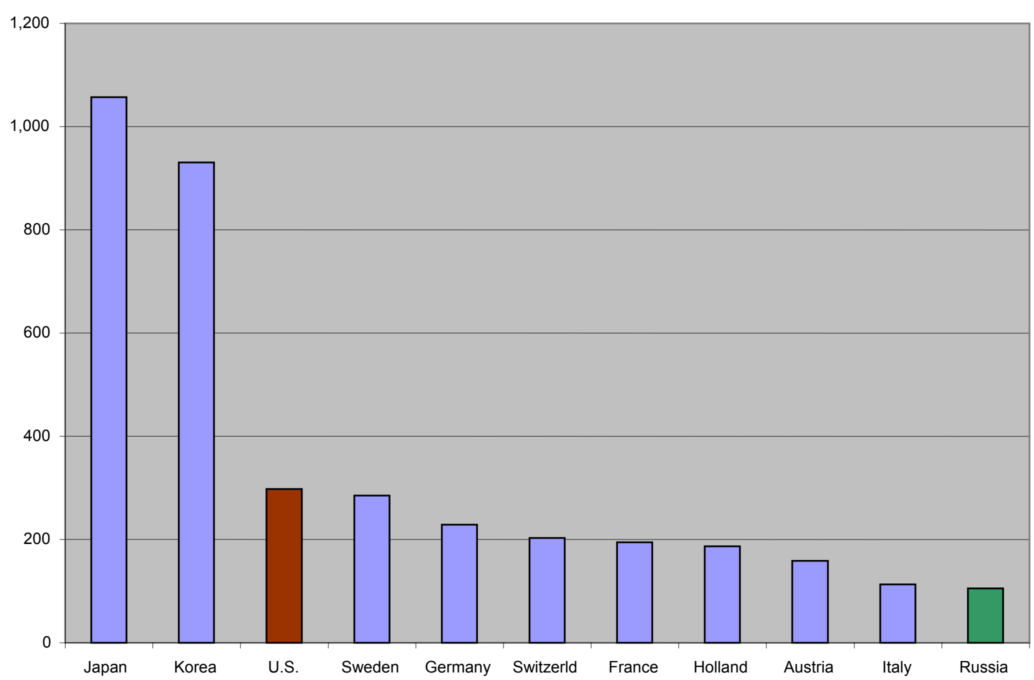
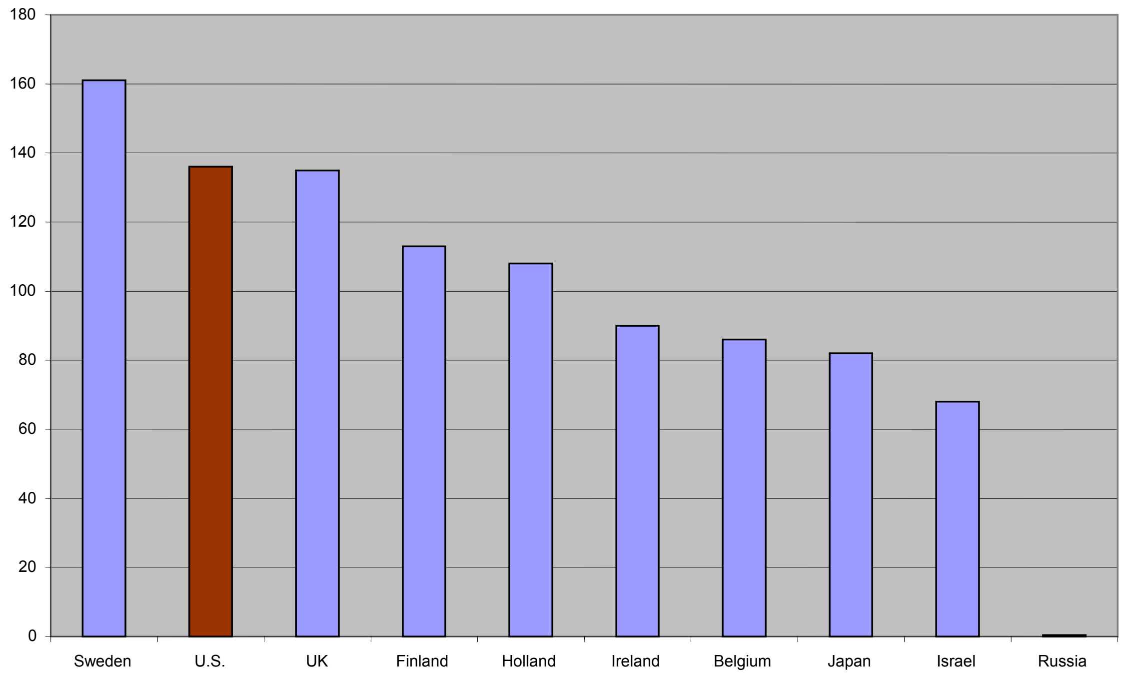


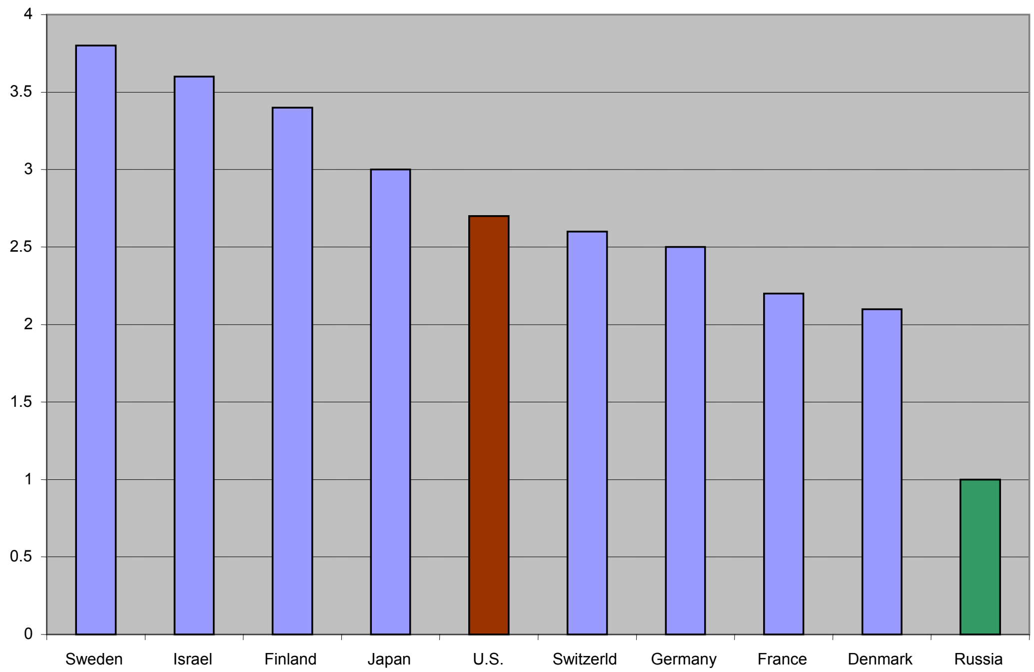
Figure 3. License Royalties, $ per Person, 2001



relatively little market value, a possibility consistent with the explanation that was just offered for its extraordinary number of patents. We see that the U.S. is not the leader in terms of license royalties per capita, but is second only to Sweden. In contrast, as shown in Figure 5, the U.S. is very much in the middle in terms of its R&D spending as percent of GDP (1996-2000) (Figure 4), as well as in number of scientists and engineers in R&D, per million people.

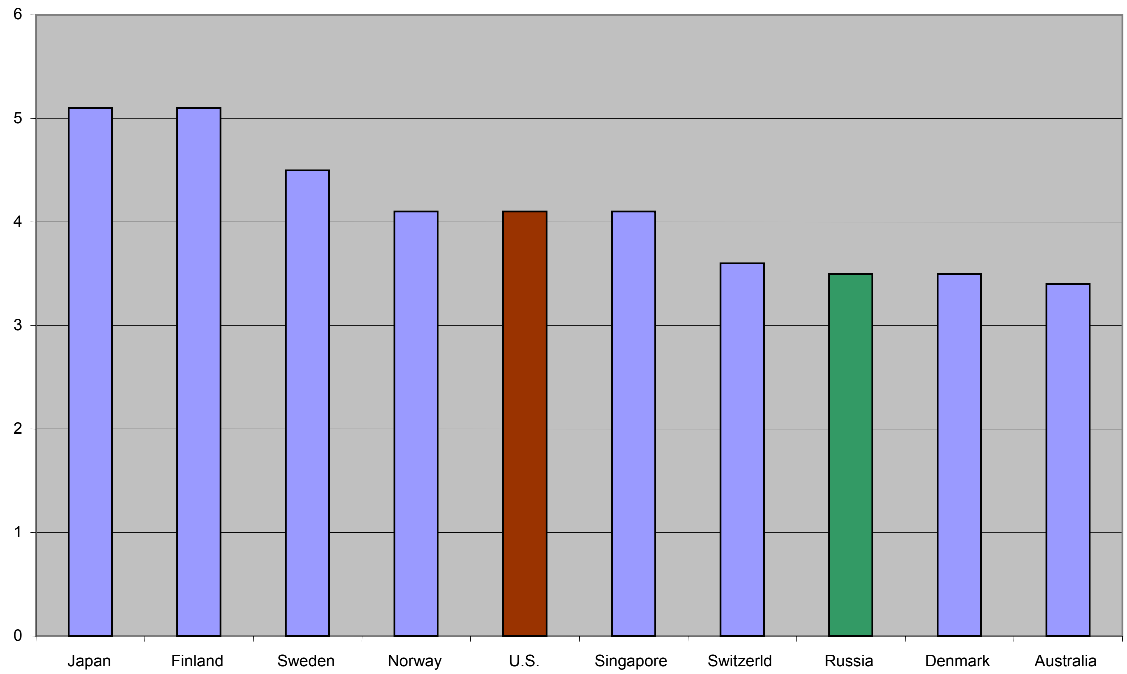
While nothing can be inferred categorically from this set of observations, they do at least appear to be consistent with the conjecture that superior performance in the number and economic significance of the inventions that are produced in the U.S. place it in or near the lead, despite the relatively mediocre levels of its expenditure on R&D and the size of the body of persons with advanced formal education who are employed in this arena. This surely is not inconsistent with our conjectures on U.S. education, though one cannot claim any more.

Figure 4. R&D as % of GDP, 1996-2000



A word should be added about the performance of the Russian Federation, which is close to the other end of the spectrum, at least in the number of scientists and engineers devoted to R&D, as contrasted with its near-zero licensing royalties. It is suggestive here that technical training in the sciences and engineering in Russia has for many years been quite rigorous, satisfying exceedingly high standards. But the Russian data are even more to the point for an issue I have discussed elsewhere (see Baumol, 2002, p. 67). There I argued that the Soviet Union's poor performance in terms of innovation (including the putting of inventions to actual use), despite its fine body of scientists and engineers, was ascribable in good part to the absence of the incentives for rapid and effective utilization provided in the free market economies. The data described above seem to confirm that the Russian economy still has far to go before it achieves the full free-market stimulus to innovation and growth.

Figure 5. R&D Scientists, Engineers per Million Population.1996-2000



IV. Trends in the Required Education of the Entrepreneur

I have argued earlier that, by the nature of his task, the entrepreneur-innovator has required less advanced education than the industrial scientist and engineer who focus on cumulative incremental improvement. More than that, I have suggested that such *limited* education has been helpful to the former, and indeed almost essential, as a way of liberation from the rigidities and standardized ways of thinking that current practice in higher education is apt to impose. Yet it is arguable that the advantages of limited education may be subject to diminishing returns. As time passes, the cumulative character of technological information makes it increasingly complex and this imposes an ever more severe handicap upon relatively unaided intuition. Even ill-educated entrepreneurs, with Steve Wozniak and Bill Gates apparently prime examples, cannot usually get along without at least some limited knowledge of physics, chemistry, computer technology, or some other body of analysis and information. This complicates to some degree our hypothesis about the ideal education of the innovative entrepreneur. That hypothesis must apparently be modified to assert that while over-rigorous education is an impediment to exercise of the imagination (which is an entrepreneur's prime professional instrument), nevertheless the minimum educational attainment characteristically needed for the task is growing. No carpenter such as John Harrison, who solved the longitude problem, no mere bicycle repairmen such as the Wright brothers, can any longer hope to contribute, for example, today's mind-boggling medical breakthroughs. An illustration is (the already extant and workable) equipment that makes it possible for surgery to be carried out by computer-guided robots, with immediate and automatic restocking (without reordering or human intervention) of surgical equipment and medication (this is partly already in use), and remote surgery in which the operating surgeon (who controls the computer) may be thousands of miles from the patient during the procedure, as has already been done successfully (American Philosophical Society, 2003).

V. On the University's Role in Innovator Education

I have so far omitted two other key players in the innovation process, the universities and the pertinent government agencies, which, of course, have also made major contributions to technological progress. I do not mean to undervalue their role—one need only mention once again the development of the electronic computer, or the creation of the Internet, to illustrate their important contributions. But these institutions have also tended to carry out a rather specialized and different function from those discussed above. It is to these not-for-profit players that we must look primarily for the results provided by *basic* research as distinguished from *applied* research.

The reasons for this division of labor with private industry are well understood, so that only a few words (but taking a viewpoint that is not quite standard), need be said on the subject here. I have argued earlier that the market mechanism is a powerful enforcer of corporate innovative effort, making mandatory its growing participation in applied innovative research. But the same market mechanism also inhibits investment in basic research, that mainstay of long-run innovative output. From the point of view of the unthinking market mechanism, investment in basic research is largely a "wasteful" expenditure, because the outlay offers no dependable promise of addition to the profits of the firm.[9] By its very nature, it is nearly impossible to predict whether basic research will yield any financial benefit at all and, if so, who will ultimately be the beneficiary. Certainly, it need not be the enterprise that was so improvident as to have carried it out. That is why governments and universities have had to step in, if truly basic research of any magnitude was to be carried out in the market economies.

The importance for technological progress of this contribution of academia and the public sector need hardly be argued. The focus here, however, is not upon innovation itself, but on the education of the innovator. Obviously, the institutions of higher education are at the heart of this process. And university *research activity* is directly pertinent to this subject. For as the universities themselves frequently point out, one of the major purposes of research in the academy is the training of the researchers of the future. The participation of graduate students in the investigations of senior faculty members, as well as the research the students carry out themselves under faculty supervision, is clearly an effective way, perhaps even the most effective way, to equip the next generation to carry on the tasks of discovery and innovation.

Though their work at institutions of higher learning leans toward basic research, many of these students will, of course, go on to jobs in the industrial laboratories of private enterprise, swelling the number of employees with advanced academic degrees. Moreover, such research activity of the postgraduate students can help to prepare them for participation in either camp. It can offer them both of the two types of education that have been stressed here: mastery of the currently available body of analysis that arguably is of primary importance in the industrial laboratories, and more free-wheeling exercise of the imagination in the unorthodox directions from which the technical breakthroughs are more likely to emerge. But there is also a danger here. As in any activity, many university teachers understandably succumb to the temptation to direct students to follow all-too-closely in their own footsteps, thereby leading to mastery of the already available research paths but weakening their ability to proceed in unexplored directions. There is no obvious way to eliminate this arguably widespread problem, but it may at least be possible to contain it to some degree if the evidence supports the educational hypotheses that have been offered here and the results are appropriately disseminated.

VI. On Appropriate Educational Programs for Innovative Entrepreneurship

I have already argued that at least some limited amount of technical training, presumably at the university level, is growing increasingly indispensable even for the most independent of innovating entrepreneurs. Though there presumably remains a marked difference between this sort of education and that needed for cumulatively-incremental product development, the implication is that it is increasingly appropriate for the universities to provide a place for these prospective entrepreneurs, but to design for them a program that avoids the inculcation of standardized and unimaginative ways of thinking. That, in essence, is the difficult task—but the critical assignment—that faces those who would provide a better program for educational preparation of the *innovating* entrepreneur of the future. It is not something that need significantly concern the training of prospective entrepreneurs as defined in a broader sense, in other words, the process of equipping those who hope to create new firms that are likely to be of some standard type, with products and procedures that are largely conventional and replicative. But it is an issue that pertains to the education of the entrepreneur with innovative propensities.

Of course, there are also more humdrum educational activities that can be helpful both to the nascent innovating entrepreneur and the prospective entrepreneur in the more general sense. As we know, it has generally proven convenient, if not essential, even for innovating entrepreneurs to establish new business firms as their vehicle for economic exploitation of their ideas. But the inexperienced founder of any new company is apt to be handicapped, sometimes fatally, by lack of types of rather elementary knowledge that are particularly critical for successful and innovative firms. This includes things like guidance on the different sources of funding, their relative advantages and perils. It can also encompass steps that can be adopted to reduce the dangers raised by the financing process, pitfalls stemming from the tax system, safety requirements to protect the labor force, and environmental regulations. Inventors need guidance through the morass of the patent laws and the complications with which they threaten inventive activities, as well as the difficulties that can be introduced by institutions that deal with patents, such as patent pools and standard setting organizations. The founders of new enterprises need help in dealing with regulations, from the tax laws to the fire laws, in avoiding difficulties entailed in construction of their facilities, in the requirements of record keeping, and so on. It follows that nothing said in this paper should be taken as an effort to induce prospective entrepreneurs to avoid education. Rather, the purpose here is to suggest what differences in the contents of the entrepreneur's education are most promising.

VII. Conclusion

This paper offers two relatively novel observations that may contribute to our understanding of the growth process. The first asserts that our economy derives its innovations from two sources: from the routine activities of giant firms and from independent inventors and their entrepreneur partners. The second observation is that the education that is best adapted to the requirements of the one of these activities is very different from that most suitable for the other.

These two types of inventive effort are not as inherently substitute activities as they may appear to be. Rather, there has been a predictable tendency toward specialization, with the entrepreneurs providing the more heterodox, breakthrough innovations, and the R&D establishments of the larger firms creating the enhancements to those breakthroughs that contribute considerably to their usefulness. These “Goliath” innovators have not eliminated the role of the entrepreneurial “Davids.” Instead, the two have tended to specialize and, together, they have enhanced the process beyond what either type of innovator might have been able to achieve by itself. Thus, there is a critical complementarity between the roles of the two types of innovating enterprise, and growth is arguably enhanced by this division of their labor.

Routine innovation processes--those guided by standard-business decision principles—are of great and probably of growing importance. But the entrepreneurial independent innovator in his small business enterprise continues to play a critical role. Revolutionary breakthroughs continue to be provided to a considerable degree by small enterprises that can avoid the conservative propensities of the giant firm. Without their revolutionary entrepreneurial contributions there would be much less for the large firms to develop further.

It is fortunate for the U.S. economy that its institutions and arrangements are such as to facilitate and stimulate profuse formation of small firms and to encourage their more-radical innovative contributions. And the American educational system seems to be less rigid and demanding than those in the other industrialized countries, thereby enabling it to serve more effectively the needs of innovative entrepreneurship. If further investigation indicates that these two observations are valid, they can perhaps offer some useful guidance for design of better-adapted educational procedures, particularly those that are intended as preparation for entrepreneurship.

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Endnotes

[1] Professor of economics, New York University, and professor emeritus and senior research economist, Princeton University. This paper is an early report on a research project at New York University and made possible by the generous support of the Ewing Marion Kauffman Foundation. I am also grateful to my colleagues Melissa A. Schilling, Edward N. Wolff and Sue Anne Batey Blackman for their contributions to the research and to this article. Many of the ideas in this paper are based on Baumol (2002).

[2] There are, of course, significant exceptions, notably the invention of the transistor at Bell Laboratories. But in that particular case, the parent firm was in a special situation that was arguably highly relevant. Most notably, at that time AT&T was a regulated monopoly protected from competitors who might otherwise have benefited from the spillovers generated by the innovative breakthrough, and regulation virtually guaranteed AT&T recoupment of the R&D outlays that other, less-protected firms might have considered a wild gamble on a harebrained project.

[3] Samuel Morse did attend Yale but, like Fulton, was trained as an artist. More recently, the jet airplane engine was invented by Frank Whittle, who came up with the idea while he was a pilot in the Royal Air Force, years before he attended Cambridge University.

[4] Here, I will emphasize Joseph Schumpeter's conception of the entrepreneur as a partner of the inventor—as a businessperson who recognizes the value of an invention,

determines how to adapt it to the preferences of prospective users, and brings the invention to market and promotes its utilization.

[5] Quoting the release describing the study, "A total of 1,071 firms with 15 or more patents issued between 1996 and 2000 were examined. A total of 193,976 patents were analyzed. CHI [the firm that carried out the study] created a data-base of these firms and their patents. This list excluded foreign-owned firms, universities, government laboratories, and nonprofit institutions" (p. 2). The 2004 study expanded the sample to 1,270 firms and dealt with the period 1995-99, and a total of 1777,899 patents.

[6] John Markoff, "Technology; Is There Life After Silicon Valley's Fast Lane?," *New York Times,* Business/Financial Desk, Section C, April 9, 2003, p. 1.

[7] However, "There are a number of individual industries in which large firms cite a higher than expected number of small firm patents, suggesting that they are building extensively on small firms' technology. These industries include high-tech areas such as biotechnology, medical electronics, semiconductors and telecommunications" (CHI Research, 2004, p. iii).

[8] I have omitted Luxemburg and Iceland from the graphs, as special cases that limit their interest for the discussion here.

[9] For a fuller discussion of the market's propensity to interpret a variety of socially beneficial investments as wasteful, see Baumol and Blackman (1991).