Believe it Or Not! The 1930s Was a Technologically Progressive Decade

January 2007

Abstract:

We present new indicators of U.S. technological change for the period 1909-49 based on information in the Library of Congress' catalogue. We use these indictors to estimate the connections between technological change and economic activity, and to investigate the relationship between fluctuations in innovative activity and the Great Depression. Although we find statistically significant links between technological change, output and productivity, our results suggest that the slowdown in technological progress in the early 1930s does not appear to have contributed significantly to the Great Depression. The remarkable acceleration in innovations after 1934, however, did play a role in the recovery.

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In light of the central role played by technical change in most models of growth, fluctuations, and productivity advances, it is surprising that economists have, on the whole, failed to come up with compelling ways to measure it. The usual suspects – patents, expenditures on and/or numbers engaged in research and development, and enumeration of innovations – are all, for various reasons, flawed, especially for the years prior to WW II. Similar to a Pirandello play, we have the characters but lack a good way to identify the author.

This brings us to the issue of measuring and evaluating the impact technological change in the 1930s. In two recent articles, Alexander Field (2003, 2006) argues, on the basis of advances in TFP and narrative histories of technological change, that the decade of the 1930s (1929-41) was the most technologically progressive of the twentieth century for the United States. On the face of it, this is a startling claim since it was also the decade during which the country experienced the most severe economic downturn in its history. Although Field's (2003) primary focus is on long term trends in innovation, his observations about the 1930s are related to an equally interesting set of issues – namely what role did fluctuations in technological change play in the onset of and recovery from the Great Depression? In recent work by Cole and Ohanian (1999) and Francis and Ramey (2004) suggest that negative technology shocks, broadly defined, contributed to the fall in economic activity following 1929, while others have argued that new technologies aided in the economic recovery after 1934. Among the latter, both Mensch (1979) and Kleinknecht (1987), following Schumpeter (1950), maintain, on the basis of direct evidence of innovations, that recovery from the depression was directly linked to the dramatic jump in technical change. The view that innovative activity accelerated after 1933 receives further support from Mowery and Rosenberg's (2000) data on industrial research and development personnel during the depression decade and from Weintraub's (1939) detailed review of labor and capital saving technological innovations in the 1930s. [1] Although patent data

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[1] If one is willing to take membership in scientific societies as an indirect measure of inventive activity, it is worth noting that after a brief downturn in the early 1930s, membership in the U.S. jumped sharply in the second half of the decade.

do not, on the whole, support their view, the problem, it seems, resides in the data, not in the argument. (See, for example, Schmookler's (1961) discussion on this subject)

These observations raise an interesting question. If there is widespread evidence of rapid technical change and productivity growth during the 1930s, and evidence that technological innovation played a significant role in economic fluctuations during this decade, why has this failed to become part of the conventional wisdom? The answer, we contend, resides in the nature of the evidence. That is, the shortcomings associated with the traditional indicators of technical change make it difficult (if not impossible) to investigate three key hypotheses in this literature: first, that the 1930s were technologically progressive, second, that negative technology shocks played a significant role in creating the economic downturn and, third, that the dramatic upswing in innovative activity contributed to America's recovery from the Great Depression. Were we to have better measures of technological change, we would have the data required to evaluate them. Our objective in this paper is to present new (and, we believe) vastly improved indicators of technological change based on publications for the period 1909-49 and to use them for exactly this purpose. To make a long story short, we find the following. First, there is a significant link between technological change, GNP per capita and TFP in this period. Second, our sectoral breakdown indicates that not all advances were created equal - some innovations had a much greater impact on growth and productivity than others. Third, the decade of the 1930s was technologically progressive with the large upswing in inventive activity occurring after 1933. Fourth, technical change does appear to have helped the U.S. economy recover from the depression. Finally, our results fail to support the view of some that negative technology shocks (at least as captured by our indicators) were a main cause of the economic downturn in the early 1930s in the US.[2] Before we describe our new measure of technological change in detail and outline our approach, it is useful to review briefly the shortcomings associated with previous attempts to quantify it.

[2] Note that this result is consistent with Ohanian's (2001) view that the large productivity decrease in the early 1930s was due less to technological regress than to a combination of labor hording, increasing returns, and changes in capacity utilization, inputs quality, and output composition.

It is generally agreed that patent statistics provide an imperfect measure of innovative activity. Patent applications, the usual metric, offer no guarantee that a commercially viable innovation will be forthcoming[3] and, even if it were to occur, knowledge of the filing date provides no information on the release date of the product or process. Use of these statistics maybe problematic since the lag between an innovation, as measured by a patent, and its impact on output and productivity is often long and uncertain. Moreover, as Schmookler (1961) notes, the patent statistics have an additional handicap for the late 1930s because the propensity to patent by corporations was adversely affected by the increase in political and judicial antipathy towards corporate patents.[4]

The other widely accepted measure of innovation is R&D expenditures and/or numbers employed in private, non-farm research facilities. The problem for our purposes is that, for the period prior to WW II, figures on R&D employment are limited to a few benchmark dates while R&D expenditures during the inter-war period pertain to a very small sector of the economy. While perhaps useful as broad indicators of trends in inventive effort[5], they are practically useless for detailed statistical analysis. Moreover, R&D data capture inputs into the inventive process not the output of commercially viable innovations. It is the latter not the former that matters to those interested in the impact of technical change on economic activity.

The enumeration of important innovations - the method used by Mensch (1979) and others to measure innovative activity - remains the best direct estimate of technical change but suffers from two serious drawbacks. Both the significance of the product/process and the timing of its introduction are highly subjective. The predicament is clear: if we want to evaluate the link between technical change and economic activity, especially in the pre-WW II period, we need numbers that provide consistent, complete, objective, and direct estimates of commercially viable innovations.

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[3] Schmookler (1961, p. 55) observes, on the basis of patent applications for the period 1901 to 1945, that roughly half of patented inventions never result in commercial innovations.

[4] Although Griliches (1990) is skeptical of this explanation, the fact remains that patent applications are out of step with other evidence of an increase in innovative activity in the 1930s.

[5] See, e.g., Mowery (1981); Mowery and Rosenberg (2000); Kleinknecht (1987, p. 111).

Our new indicators of technological change, we believe, satisfy these requirements. They are based on previously unexploited information from the Library of Congress (LOC) on the number of new technology titles (manuals, handbooks, and the like) in various fields published in the U.S. during the period 1909-1949.[6] Since the Library of Congress is the largest library in the United States and acts as the country's copyright depository, these data provide an accurate representation of the flow of new technology books available to the trade and to the public.[7] Moreover, publication statistics on new technology books in the early part of the twentieth century are likely to offer first rate indicators of technological change for the simple reason that there were so few alternatives to books as a way to "spread the news".[8]

Our new measure is superior in a number of respects to the traditional indicators of technical change. First, it is amenable to statistical analysis because the LOC data can be used to create a consistent time series on an annual basis for the entire period 1909-49, both for technology in general and for various sub-groups of technologies that would have been used in the private, non-farm economy. Second, unlike patents and R&D statistics, publications of new technology books are timed to coincide with the commercialization of new products or processes. That is, the books appear at the precise moment that the innovations are most likely to exert their influence on output and productivity. Third, these indicators suffer from none of

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[6] We are only aware of two other attempts to use publications to measure technical change. Alexopoulos (2006a, 2006b) employs data based on LOC holdings to create measures similar to the ones presented in this study for the period 1955-1997 while Sullivan (1984) uses the number of British books on agricultural techniques published between 1523 and 1900 to measure technological change in English farming.

[7] According to the Copyright act of 1870, all copyright applicants were required to send two copies of their work to the LOC.

[8] It is probably safe to say that new books on technology provide an even more complete picture of technological change during our period than they do for the years covered by Alexopoulos (2006a). This is encouraging because Alexopoulos was able to show that these data offer an excellent measure of advances in commercially viable innovations.

the arbitrariness associated with enumeration exercises – timing and numbers are strictly determined by their appearance in the catalogue records of the LOC.

We can now outline our approach. In the next section, we first describe in more detail our new indicators and the intuition that underlies them and then show that they are, for the most part, consistent with the case studies reported by Mensch (1981), Field (2003) and others. Following this, we use Vector Autoregressions (VARs) to establish a causal link between technological advances as measured by new publications and changes in TFP and GNP per capita during the period. Although we find that the impact of technical change on economic activity was substantial, our results also indicate that some innovations mattered more than others. Thus, advances in electrical and mechanical machinery, manufacturing, and automobiles seem to have had a powerful, positive influence on both GNP per capita and measured TFP, new chemical technologies pushed up the latter but had little impact on the former, while innovations in telecommunications, although numerous, appear to have had little effect on either variable.

In section four, we use the coefficients and shocks generated by our regression to answer two questions. First, what would have happened to output and productivity had the rate of technological innovation been less vigorous in the 1930s than it was? And, second, what role did pure technology shocks play in the Great Depression? The results are striking. While technological progress does appear to have slowed in the early 1930s, the decline does not seem to have been responsible for a significant part of the decrease in output between 1930 and 1933. Other factors were, obviously, at work.[9] On the other hand, the acceleration of technical change after 1934 does appear to have played a significant role in the recovery to the end of the decade. More generally, on the assumption that technological progress remained at rates achieved in the 1920s, our calculations suggest that it would have taken an additional 14 years for GNP per capita to have matched the actual level reached in the 1939 because of slower growth in TFP. In section 5, we conclude and offer suggestions for further research.

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[9] These may include, among other things, aggregate demand shocks (see, for example, Romer (1990) and Olney (1999)), monetary shocks (Friedman and Schwartz (1963)) and the kind of real shocks investigated by Cole and Ohanian (1999).

II. Book Publications as an Indicator of Innovative Activity

Although much of the basic science underlying an innovation is likely to be known, at least by others in the field, knowledge of the commercial product or process developed out of the science is, almost by definition, unknown until it hits the market. Thus, successful launch necessitates dissemination of information and this is where books enter. In this section, we describe our indicators, give the intuition behind them, and then compare them with the traditional measures of technical change.

II.A. Description:

We have constructed our new indicators of technological change from the MARC (***MA***chine ***R***eadable ***C***ataloging format) records of the LOC database. These files are used by the library to run its online book search program, and are available to other libraries to help them catalogue new books. The LOC is by far the largest library in the U.S with over 130 million items on approximately 530 miles of bookshelves.[10] The MARC records of the LOC, in short, provide a virtually complete list of all new titles copyrighted within the United States across a vast range of subjects.

Each MARC record contains, among other things, information on the type of book (for example, a new title or a new edition of an existing one), the country of publication, the language of publication, the LOC's Classification Code, and a list of major subjects treated in the book. We use the first three categories plus the classification code to create our indicators: new titles in different fields of technology (subgroups of T) published in English in the US between 1909 and 1949.[11] We exclude all books that include history as a descriptor for the obvious reason that they are unlikely to have much to do with the new innovations. Thus, a book that chronicles the early

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[10] The Library of Congress' collections include more than 29 million books and other printed materials, and over 58 million manuscripts.

[11] See Appendix A for a listing of the major groupings and sub-groupings in T. To focus on new technologies used in the market economy, we exclude books on handicrafts (under subgroup TT) and all books in the subgroup TX (Home Economics) with the exception of books on the hospitality industry.

years of Alexander Graham Bell's invention will not be counted since it tells us nothing about the current state of technology in the communications industry. The list of titles includes manuals and books that deal with all technology related topics including their nature and function, how they work, and how to use and/or repair them. Some are published or sponsored by the innovator/company that developed the new technology, others by third parties who hope to profit from book sales. In all cases, the motive for publishing is the same: to obtain financial gain from spreading the word.[12]

In Figure 1, we report the results of our efforts. The graphs represent the number of new titles by year drawn from the following fields (chosen with one exception to correspond with those identified by Mensch (1979) and Field (2003) as technologically dynamic in the 1930s): total technology, chemicals, automobiles, electrical machinery and electronics, mechanical machinery/manufacturing, telecommunications, and (the exception) children's books. Although we discuss the results in detail in the next section, even a cursory glance reveals first that technical change was alive and well during the depression decade and, second, that the pattern traced by new children's titles differs from that in technology. There is, it would seem, something special about our technology series.

II.B. Intuitive Appeal:

A good indicator of technical change needs to capture innovations at the moment of their commercialization. We would expect publications, for sound economic reasons, to do precisely that. Innovating companies want to promote their innovations; independent writers want to sell books. For both, timing is critical – too early and the publication is useless, too late and it is, at best, dated. Our new measure, therefore, overcomes one of the principal defects associated with

[12] For example, in the early part of the century, there were a number of changes in automobile tires. The period witnessed the introduction of the first inflatable tires as well as a variety of changes in the materials used to make them. The LOC's collection contains the following sorts of titles: repair manuals for products brought out by companies such as Goodyear and Firestone, books released by general publishers with tire maintenance tips, and publications by the United States Bureau of Standards reporting government standards and endurance tests for different types of tires and advice on use and care.

indicators based on patent applications and R&D expenditures – long and indeterminate lags between conception and commercialization.

Publications have an additional attractive feature as measures of technical change - they weight the various new technologies differently, an important factor in determining the impact of the different innovations on economic activity. The argument runs as follows. Since more titles are likely to appear on a major (or general purpose) technology than on a minor (or sector specific) one, our indicator more closely resembles citation-weighted patent indicators than it does indicators based on the simple number of annual patent applications.[13] However, in our case, the weight given to each technology annually is determined by the number of new titles released on it each year. This means that our indicators are high for one of two reasons: (1) lots of small innovations are brought to market during the course of the year, each accompanied by a couple of new publications, or (2) a major innovation debuts that affects many sectors and fosters numerous new titles. In both cases, we would expect to observe a positive correlation between the number of new publications and output and productivity. And, this, of course, is exactly the causal relationship that we are trying to capture.

There are, finally, innovative changes in management, organization, and other non-technical aspects of the production process that traditional measures of technical change tend to overlook. They are often not amenable to the patent process, they have nothing to do with the research lab, and they are not embodied in some new piece of equipment or the equivalent. They can, however, show up in publications for the simple reason that someone stands to profit from writing about them.[14] Moreover, their impact is frequently considerable. For example, Weintraub (1939) argues that, in many cases, it was these types of innovations that powered many productivity advances in the latter part of the 1930s.

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[13] See Jaffe and Trajtenberg (2002) for some examples of papers that use patent citations as the measure of technical change.

[14] Good contemporary examples include Total Quality Management (TQM) and just-in-time production and inventory management, both of which spawned a large number of new technology titles.

Books, of course, are not the only way to disseminate information about new technologies. Even in the pre-WW II period, trade journals, professional and/or scientific conferences, and direct marketing, among others, served as sources of information on new technologies. In the final analysis, of course, the proof of the pudding is in the eating but it is reasonable to believe that these other methods of communications acted as complements to our book based measures of technical change. In any case, to the extent that our indicators omit some innovations, the bias runs against (and not in favor of) our finding a relationship between publications and increases in economic activity and should, therefore, be viewed as establishing a lower bound on the true impact of technological change over this time period.

II.C. Old and New Indicators Compared

While perhaps intuitively appealing, we must still demonstrate that our new measures provide an accurate, quantitative account of innovative activity. In a previous article, Alexopoulos (2006a) established a strong positive link between new publications of technology books – in general and by sub-categories – and innovations for the post-WW II period. The question is whether a similar connection can be shown to exist for the pre-WW II period? Although we are prevented by data problems from repeating the statistical analysis carried out by Alexopoulos (2006a), we can show that our new indicators are, at the very least, consistent with the findings of Mensch (1979) on major innovations and Mowery and Rosenberg (2000) on R&D expenditures and personnel.

Mensch (1979, p. 127-8) presents a table in which he lists major inventions and innovations by date and by nature of the product or process. The table contains a synthesis of case studies of inventions and inventors reported in Jewkes, Sawers, and Stillerman (1969). The numbers, he maintains, confirm his view that the 1930s, particularly from 1933 on, was a time of intense innovative activity. (See also Field 2006) Although the years chosen by Mensch (1979) for his innovations are often less cut-and-dried than he would like us to believe (see Jewkes, et al (1969) for the details), they do offer widely accepted benchmarks with which we can evaluate our indicators.[15] In Table 1, we compare the innovation dates reported by Mensch (1979) and the commercialization dates from Jewkes, et al (1969), with the dates that the same innovations made their first appearance in the LOC database.[16] There is, on the whole, a reasonable coincidence of timing between the series. Although we are reluctant to draw too much comfort from these results, they do suggest that publications are in general agreement with a standard measure of innovations during this time period.

In Figure 2, we compare our publication series with the estimates of scientists employed in R&D laboratories, spending on R&D in industry and Mensch's (1979) series on important innovations. Although the R&D figures measure inputs into the inventive process not the output of commercially viable innovations[17] and Mensch's (1979) series is subjective, the results reveal a rough correspondence in trend between the measures. On the basis of these, it seems safe to conclude that new technology titles drawn from the MARC records of the LOC do offer reliable indicators of innovative activity in the U.S. in the first half of the twentieth century.[18] And, of course, they have advantages that the other measures lack. The next step is to determine the

[15] Although the dating of major innovations can help to single out periods of intense innovative activity, as we mentioned before, both timing and significance are highly subjective. A good example of this is the radio. An apparently straightforward innovation, the radio was, in fact, the outcome of a series of independent innovations, each one of which gave rise to something that resembled the modern radio. It was, without question, a major innovation but it is unclear which of the many steps should be used for dating purposes.

[16] In light of the inherent subjectivity of Mensch's (1979) exercise, in a few instances we modified his dating on the basis of a reconsideration of the case studies in Jewkes et al (1969) and with corroboration from other sources. Moreover, when the commercialization dates were not available from Jewkes, et al (1969) our dates are based on information from http://inventors.about.com

[17] Although R&D outlays may be a good measure of the intensity of inventive activity, it is important to note, as Mowery and Rosenberg (2000) and others do, that many innovations are not lab based and much lab research does not result in commercially viable innovations.

[18] Since none of these measures match the pattern traced by patent applications reported by the U.S. Patent and Trademark Office, especially in the 1930s, we would argue, following Schmookler (1961) and Griliches (1993), that the problem lies with the latter not the former.

extent to which productivity improvements and growth in per capita GNP during this period were driven by innovative activity during this period.

III. Technological Change, Productivity, and GNP

III.A. The Data

In our analysis we use annual data for the time period 1909-1949 drawn for the most part from four sources: the LOC MARC records for our technical change indicators, and Kendrick (1961), the Economic Almanac (various years) and Goldsmith (1956) for input and output statistics. Aside from the MARC records, these are the standard sources for data on inputs and output during the period. To be more precise, our real GNP series expressed for the private non-farm economy in 1939 and 1947 dollars are drawn from the Economic Almanac while real GNP for the private non-farm economy in 1929 dollars comes from Kendrick (1961).[19] Following Solow (1957), we obtain our labor input measure from the Economic Almanac and our estimate of the capital stock from Goldsmith (1956). Finally, in order to compute our TFP series, we employ Solow's (1957) figure for the share of property in income which he, in turn, bases on data in the Economic Almanac and Burkhead (1953).[20]

For our analysis, we examine three different real GNP series and recalculate TFP using the GNP and capital stock numbers expressed in 1929, 1939 and 1947 dollars (referred to as TFP(1929), TFP(1939) and TFP(1947) below). We do this because there are reasons to believe that our results are sensitive to the choice of base year used to create the price deflators. Our reasoning runs as follows. A large number of producer and consumer goods which were important by the end of our period were either trivial or non-existent at the beginning. Moreover, as Kendrick (1961) observes, there is likely to have been a large degree of measurement error in the 1929 price deflators because the Bureau of Labor Statistics (BLS) only began to compile

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[19] The Economic Almanac cites Kendrick as the source of their 1939 base year estimates.

[20] Goldsmith's (1956) capital stock estimates are only available in 1929 dollars. Since the base year matters, when we calculate our TFP series, we convert these numbers to 1939 and 1947 prices using the GNP deflators.

price information on a number of items including durable equipment in the late 1930s at which time a virtual sea change occurred in the type and scope of price data collected.[21] In brief, then, because of the dramatic changes that occurred between the beginning and the end of the decade in the availability and measurement of prices and in the weights assigned to goods and services in the different price indexes, making inferences based solely on real series created using 1929 price deflators may be both problematic and misleading.[22] The results reported in the next section confirm the shortcomings of these deflators.

III.B. GNP and technology

We begin by examining the links between technological change (as measured by our indicators) and non-farm private GNP per capita.[23] Specifically, we estimate the following bi-variate VAR:

$$Y_t = \alpha+\gamma t+\rho Y_{t-1} +\varepsilon_t \qquad (1)$$

In equation (1), α is a constant, ε_t is a vector of time t errors, $Y_t = [\ln(GNP_t/POP_t), \ln(X_t)]'$, where GNP_t is real GNP in year t measured in one of 1929, 1939 or 1947 dollars, POP_t is the population at time t, and X_t is one of our technology indicators.[24] As in Shea (1998) and Alexopoulos (2006a), we identify technology shocks by assuming that they only affect GNP per capita with a one year time lag (that is, the technology shock has no contemporaneous impact on

[21] Kendrick (1961), who uses numbers expressed in constant 1929 dollars, acknowledges the possibility that the choice of the base year could affect his productivity estimates but he does not experiment with alternatives in his famous book.

[22] Kuznets (p. 505-10, 1961) makes exactly this point, for a different period, when he describes the impact that the choice of base year can have on the growth rate of output expressed in constant prices.

[23] We focus on the private, non-farm sector since this has been the standard in the literature. (See, for example, Field (2006))

[24] Since unit root tests are inconclusive we opt to use levels instead of first differences and include a time trend. It should also be noted that, in the following, we report the results for the case of a single lag for all variables, with the exception of chemical technologies, included in the VAR. Additional lags failed to affect the performance of the models.

output).[25] In Figures 3 and 4 and Tables 2-4, we report the response of GNP per capita to various technology aggregates including: all technology, automobiles, chemicals, mechanical/manufacturing, electrical machinery and electronics, and telecommunications.[26]

Figures 3 and 4 display the impulse responses of GNP per capita to a technology shock for each of the indicators along with 1.65 Monte Carlo standard error bands. They show that GNP per capita rises in response to a positive technology shock with the peak response occurring after 2-4 years.[27] They also indicate (as we would expect) that some shocks have a more powerful effect on GNP per capita than others. Thus, technological change in manufacturing, automobiles, and electronics/electrical machinery appears to have had a significant impact on GNP per capita while shocks associated with chemical technologies do not.

These results are confirmed by point estimates, Granger causality tests and the variance decompositions reported in Tables 2-4. As is revealed by the point estimates in Table 2, technical change in chemicals and telecommunications have little success in explaining movements in GNP per capita while innovations in manufacturing, electrical, and automobiles technologies have a strong and significant impact on output; in fact, the last three are often significant at the five percent level. In addition, the Granger causality tests in Table 3 show that technology tends to Granger cause GNP per capita - not the other way round – with the exception, once again, of chemicals.

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[25] See Francis and Ramey (2004) for an analysis that uses the long-run restrictions approach in a VAR to identify technology shocks in the pre-WWII period.

[26] To determine if the ordering of variables that we assumed in our VARs had a significant impact on our results, we reran them with the technology indicator entering before ln(GNP/POP) and found little evidence to suggest that it mattered. These results are not reported in the paper but are available upon request.

[27] Alexopoulos (2006b) demonstrates that for the post WWII period the importance of technology shocks is not diminished by the inclusion of other shocks such as those associated with monetary and fiscal policy or oil prices.

It is important to note that standard errors associated with the point estimates indicate that the statistical significance of our results are, as we anticipated, sensitive to the choice of the base year. Technical change measured in either 1939 or 1947 dollars has a much greater impact on economic activity than it does when GNP is based on 1929 dollars. This, as explained earlier, is in keeping with our expectations. Many of the new products or processes in sectors such as manufacturing and electrical machinery were introduced in the latter years of our sample period and would thus have received little or no weight in the 1929 price deflators. They would, on the other hand, have been picked up by the 1939 and 1947 price deflators. There was, in addition, the problem of inclusion since the BLS collected very limited price information before the mid-1930s – especially in areas such as durable equipment. It is interesting to note that our results echo those reported by researchers who initially failed to find in the output and productivity statistics much evidence of the impact of computers - leading to Solow's famous quip that computers are everywhere except in the data. Only with the introduction of new price indicators did the IT revolution finally appear in the numbers.

The variance decompositions reported in Table 4 provide further information on the role technological change plays in determining the variance of GNP per capita. Although the results are somewhat sensitive to choice of base year, the variance decomposition exercise suggests that about 14 percent of the short-run variation is attributable to electronics and electrical technology, 8-13 percent to automobiles, and between 2 and 12 percent to manufacturing technologies. Moreover, these effects increase significantly over the medium to long term, an indication that the shocks in all likelihood had long-lasting consequences for output.

Our results raise an obvious question – are they a case of correlation without causation? That is, does the increase in new technology titles merely represent a serendipitous upswing in all publications in tandem with increases in GNP per capita or do they instead capture a causal link between technological change and output growth? To answer this question, we ran the same regressions using the number of new children's books in place of the number of new technology books. The coefficient on this series in the GNP per capita equation is reported at the bottom of Table 2. On the basis of the standard errors and the Granger-causality tests we reject the hypothesis that new children's books predict GNP per capita. This result is further confirmed by the impulse responses shown in Figure 5. Shocks to children's books fail to have a significant impact on output. Overall, then, it is safe to conclude that while new technology titles do seem to affect economic activity, children's book do not. Although not foolproof, the finding is, at the very least, reassuring.

III.C. TFP and technological change

Our next task is to examine the impact of technical change on TFP.[28] Before we do this, it is necessary to say a few words about the TFP statistics. There are two widely employed ways to compute TFP for the early part of the twentieth century, that of Kendrick (1961), based on a linear production function, and that of Solow (1957) based on the more general function Q=F(K,L).[29] The latter is superior for our purposes. As Domar (1962), among others, points out, over long horizons the Solow (1957) method is likely to prove the more reliable of the two. Moreover, the Tornqvist/Solow approach, the one we adopt here, is now the method of choice among scholars. We also present two sets of findings for TFP. The first is based on TFP series adjusted for capital utilization using Solow's (1957) assumption that utilization rates vary with the unemployment rate, while the second employs numbers calculated with no such correction. In both cases, we again estimate bi-variate VARs, this time to uncover the relationship between productivity and technological change:

$$Y_t = \alpha+\gamma t+\rho Y_{t-1}+\varepsilon_t \qquad (2)$$

where $Y_t = [\ln(TFP_t), \ln(X_t)]'$. We again assume that technology shocks only affect TFP with a one year lag. The estimated coefficients for the TFP regressions are reported in Table 5 with the Granger-causality tests and the variance decompositions for the regressions reported in Tables 6 and 7 respectively.

[28] We also ran regressions using output per man-hour as the relevant productivity measure. While there are some differences in magnitudes, the results are broadly similar to those for TFP and therefore are not reported here. They are, of course, available upon request.

[29] For example, Cole and Ohanian (1999) and Ohanian (2001) report Kendrick's (1961) productivity numbers, while Field (2003) reports both Solow's (1957) and Kendrick's (1961) measures.

We begin with the point estimates reported in Tables 5. They indicate, much as they did for private non-farm GNP per capita, that increases in technological change raise productivity.[30] The impact, again, varies across technologies and is sensitive to the choice of the deflator whereas correction for capital utilization has virtually no impact on the results.

In Table 6, we report the Granger causality tests for the TFP measures. As can be seen, the responses of TFP (1939 or 1947) to technical change in all subgroups, save telecommunications, are statistically significant at the five or ten percent levels. [31] On the other hand, changes in automobile technologies appear to be the only ones that have a significant impact on TFP(1929). [32] The difference, once again, is caused by inclusion in the price deflators. Automobile manufacturing was already a major part of the U.S. economy in the late 1920s while many of the other sectors rise to prominence only in the 1930s.[33]

Table 7 contains the variance decompositions for the TFP VARs. The numbers indicate that the percent of variation in TFP explained by new technology grows over time. It is much greater in year nine than in year three and the effect is substantial for all sub-sectors, again with the exception of telecommunications, when using 1939 or 1947 dollars to compute TFP. The major player is manufacturing which accounts for roughly 34 percent of the variation in TFP by year three and over 40 percent by year nine. Automotive, electrical, and chemical technologies while less powerful are still non-trivial – by year three, between 7.5 and 14 percent of the variation in total TFP is explained by these three indicators.

[30] Coefficients that are negative are insignificantly different from zero at conventional levels of significance.

[31] The failure of telecommunications to predict changes in TFP may due to the relatively short times series or the fact that many innovations in this area, like television and radio, may not have a strong affect on TFP.

[32] Although we do not report the results using Kendrick's (1961) TFP measure, they are essentially the same as those using the Solow TFP measures computed with data using 1929 as the base year.

[33] See Field (2006), Bresnahan and Raff (1991), and Weintraub (1939).

The impulse responses for TFP, reported in Figures 6-8, tell a similar story. In particular, as is illustrated in Figure 6, a positive technology shock significantly increases TFP (1939 or 1947) for approximately 7 years with the peak response occurring 1-2 years after the shock. Further, a similar pattern appears in Figures 7 and 8 where we report the responses of TFP (unadjusted and adjusted for capital utilization), along with 1.65 Monte Carlo Error bands, to technology shocks in chemical, automotive, electrical, telecommunications and manufacturing. Here again we find that, with the exception of telecommunications shocks, TFP (1939 or 1947) significantly increases for 5-8 years following a technology shock. In contrast, only automotive and telecommunications technology shocks significantly increase TFP (1929).

IV. Did technological change overcome the Great Depression?

We now turn our attention to the 1930s – the decade Field (2003, 2006) argues was the most technologically progressive of the twentieth century. Consistent with Field's (2003, 2006) argument, our indicators, graphed in Figure 1, do show that the 1930s was a more technologically progressive period than either 1909-29 or 1941-49. We find, moreover, that technological innovations in manufacturing, electrical machinery and electronics, chemicals, and automobiles all made statistically significant contributions to the expansion of output and productivity in the thirties. [34]

Although Field does not examine annual differences in innovation during the 1930s, other researchers have noted that the pace of technical change in the U.S. from 1929 to 1933 greatly differed from that seen in the recovery period 1934-41. For example, Francis and Ramey (2004) and Cole and Ohanian (1999) argue that negative technology shocks in the early 1930s may have caused much as 40 percent of the economic downturn while others, including Mensch (1979) and Kleinknecht (1981), contend that the later part of the decade saw the introduction of

[34] Field (2006) shows that wholesale and retail trades, transportation, public utilities, and manufacturing accounted for roughly 95 percent of productivity gains in the 1930s. He provides some anecdotal evidence that these gains were driven by technological change. Our data at this point are not fine grained enough to allow us to evaluate the specifics of this argument.

important new technologies that played a key role in the country's economic recovery. Our measures reveal a remarkably similar pattern of fluctuations in technological change over the decade. Specifically, they indicate that there was a decrease in the rate of technological change in the early 1930s followed by a significant upswing in innovative activity during the later half of the 1930s. Moreover, our regressions results suggest that the economy was hit by a series of negative technology shocks between 1929 and 1935, and a series of highly positive ***ones*** from 1936-1941. Despite these results, a fundamental question remains unanswered: how important quantitatively was this technological change to the performance of the economy during this period? With our new indicators and the estimates presented in the previous section, this question can now be answered. We do this through the use of counterfactual analysis in which we examine what the economy would have looked like had technology not progressed as it did during this decade.

To begin this exercise, we attempt to answer the following question: what would have happened to TFP and GNP per capita in the period 1929-41 had there been less innovative activity? In a nutshell, we find that without innovations, TFP improvements would have been much more modest and GNP per capita in 1941 would have been substantially below the level actually achieved. This is illustrated by the Panel A in Figure 10. Here we display the paths that GNP per capita in 1939 dollars and TFP(1939) would have taken had technological progress in the economy continued in the 1930s at: (1) the average rate that was achieved in the 1920s, and (2) the 1929 rate that was greater than the decadal average.[35] Quantitatively, we assume that from 1930 onwards, GNP per capita and TFP are determined by the following relationships:

$$\ln(GNP_t /Pop_t)=\underset{(0.6298)}{-0.0435}+\underset{(0.0017)}{0.0006}*t+\underset{(0.0747)}{0.8651}*\ln(GNP_{t-1} /Pop_{t-1})+ \underset{(0.0794)}{0.1439}*\ln(Tech_{1920s}) \quad (3)$$

$$\ln(GNP_t /Pop_t)=\underset{(0.6298)}{-0.0435}+\underset{(0.0017)}{0.0006}*t+\underset{(0.0747)}{0.8651}*\ln(GNP_{t-1} /Pop_{t-1})+ \underset{(0.0794)}{0.1439}*\ln(Tech_{1929}) \quad (4)$$

and

[35] In the years prior to 1929, according to our indicator, only 1922 and 1916 saw higher levels of technical change than that achieved in 1929.

$$\ln(TFP_t) = \underset{(0.2224)}{-0.4690} + \underset{(0.0011)}{0.0009}*t + \underset{(0.0849)}{0.8337}*\ln(TFP_{t-1}) + \underset{(0.0365)}{0.0774}*\ln(Tech_{1920s}) \quad (5)$$

$$\ln(TFP_t) = \underset{(0.2224)}{-0.4690} + \underset{(0.0011)}{0.0009}*t + \underset{(0.0849)}{0.8337}*\ln(TFP_{t-1}) + \underset{(0.0365)}{0.0774}*\ln(Tech_{1929}) \quad (6)$$

where GNP_{1929} /Pop_{1929} and TFP_{1929} are the values observed in the data.[36] The figures suggest that had technological innovation held steady over the 1930s, and had there been no shocks hitting the economy, we would not have had the dramatic downturn in economic activity in the early 1930s and by 1941 real GNP per capita would have been 16% - 26% lower (depending on the growth rate assumed) than the actual 1941 value and TFP would have been 8.5% – 13.5% lower.[37]

Panel B of Figure 10 show what paths these variables would have taken if only the 'non-technology' shocks (depicted in Panels 1 and 3 in Figure 9) had hit the economy and technical change had remained at either the average rate of the 1920s or the 1929 rate. [38] Although, as the results in Figure 9 illustrate, both technology and 'non-technology' shocks are negative in the early 1930s, non-technology shocks seem to have played the lead role in the onset of the Great Depression. The paths in the counterfactual economy with constant rates of technical progress and non-technology shocks shown in Panel B mimic well those seen in the actual economy in the early 1930s. The obvious conclusion is that the type of technology shocks identified by our indicators was at most a minor contributor to downturn in the early 1930s. These results are consistent with the findings of Romer (1990), Friedman and Schwartz (1963), Temin (1991), Bernanke (2000), and others, all of whom, for all of their clear-cut differences, attribute the onset of the Great Depression to a variety of non-technology factors, including monetary, fiscal, and

[36] The numbers in parenthesis are the standard errors of the estimates.

[37] Alternatively we can use Solow's (1957) numbers, presented in Field (2003), to compute the difference between the actual and a counterfactual TFP level in 1941. On the assumption that technological change from 1929-1941 occurred at the average rate achieved between 1919-1929, counterfactual level of TFP is approximately 15.7% lower than that actually realized.

[38] Based on our identification strategy, shocks in the 'non-technology' category can include fiscal policy shocks, monetary shocks, and technology shocks that are not picked up by our indicators.

aggregate demand shocks.[39] On the other hand, we do find that technical change made a significant contribution to recovery in the latter part of the decade - without the realized rates of innovation from 1936 onwards, by 1941 the economy would still have had much lower levels of both GNP per capita and TFP.

Panels C and D of Figure 10 confirm the importance of technological change in achieving the 1941 levels of real GNP per capita and TFP. In panel C we report the paths the variables would have taken had: (1) the economy not been hit by shocks from 1929 onwards, and (2) technology evolved according to the equations estimated in section three. In other words, we now allow technical progress to deviate from the 1920s average or 1929 rate and assume that real GNP per capita and TFP after 1929 evolved according to the following estimated equations:

$$\ln(GNP_t/Pop_t) = \underset{(0.6298)}{-0.0435} + \underset{(0.0017)}{0.0006}*t + \underset{(0.0747)}{0.8651}*\ln(GNP_{t-1}/Pop_{t-1}) + \underset{(0.0794)}{0.1439}*\ln(Tech_{t-1}) \qquad (7)$$

$$\text{where } \ln(Tech_t) = \underset{(1.1173)}{3.5388} + \underset{(0.0032)}{0.0073}*t + \underset{(0.1326)}{(-0.0617)}*\ln(GNP_{t-1}/Pop_{t-1}) + \underset{(0.1408)}{0.4877}*\ln(Tech_{t-1}) \qquad (8)$$

and

$$\ln(TFP_t) = \underset{(0.2224)}{-0.4690} + \underset{(0.0011)}{0.0009}*t + \underset{(0.0849)}{0.8337}*\ln(TFP_{t-1}) + \underset{(0.0365)}{0.0774}*\ln(Tech_{t-1}) \qquad (9)$$

$$\text{where } \ln(Tech_t) = \underset{(0.8504)}{3.1613} + \underset{(0.0043)}{0.0091}*t + \underset{(0.3246)}{(-0.2514)}*\ln(TFP_{t-1}) + \underset{(0.1394)}{0.4857}*\ln(Tech_{t-1}) \qquad (10)$$

The results demonstrate the importance of increased innovative activity in the 1930s. Unlike the paths depicted in Panels A and B, the values of GNP per capita and TFP in this counterfactual economy are only about 5 and 1.6 percent below the actual values in 1941. However, as Panel D illustrates, once the impact of the technology shocks depicted in Figure 9 are added to equations (8) and (10) above, the counterfactual economy does achieve the 1941 values although the path

[39] Based on our identification, our non-technology shocks may include more broadly defined technological disturbances such as those that alter work rules and practices or government regulations that affect the efficiency of production. Our results, therefore, should not be viewed as inconsistent with Cole and Ohanian's (1999) finding that a drop in TFP can account for 40% of the decline in output during the period 1929-33. Instead, our findings simply suggest that the type of pure technology shocks identified by our indicators were not a main contributor.

taken by the counterfactual economy differs significantly from that of the actual economy. That is, in our counterfactual economy, the negative technology shocks of the early 1930s would have caused output and TFP growth to stagnate between 1931 and 1936 while the positive technology shocks after that date would have fostered GNP per capita growth of over 17% between 1936 and 1941.

Figure 11 repeats the counterfactuals for the recovery period, 1933-41. Based on the results in Panel A, we find that if technical change had only occurred at the 1920s average rate after 1933, TFP levels would have been ten percent lower in 1939 than they actually were and GNP per capita eighteen percent lower.[40] In fact, had the rate of technological change remained at the average of the 1920s even after 1939, the country would have had to wait until 1952 to reach 1939 levels of GNP per capita and until the late 1950s to match 1939 TFP. The outcome is similar even when the 1929 rate of technological progress is used. In this case, we find that it would have taken until 1945 for the economy to have reached 1939 levels of GNP per capita and TFP. The graphs in Panel B indicate that positive non-technology shocks played an important role in determining the speed of the recovery from 1933 to 1936. They also reveal, however, that had the rate of technological change fallen below that actually achieved in the later half of the 1930s, GNP per capita in 1941 would have lagged the actual level by 16.8 to 25.5 percent, and TFP by 8.6 to12.8 percent.

Panels C and D of Figures 11 again highlight the importance of stepped up technological progress for the economy's recovery. Although these figures suggest that the 'non-technology' shocks did contribute to the speed of the recovery during the period 1933-38, they also confirm that without the major increases in technological change that occurred in the late 1930s, the economy would have taken a much longer time to recoup the losses caused by the Great Depression. As Field (2006) observes, Schumpeter (1950) was on to something - the accelerated pace of technological change after 1933 did wonders for economic recovery.

[40] The rate of technological progress in 1933, as measured by our indicator, is basically the same as the average rate for the 1920s.

In summary, we find that while the technological change identified by our indicators does help explain the recovery path of the US economy from the Great Depression, it provides a much less compelling account of the initial drop in economic activity at the beginning of the 1930s. Although it would be unwise to claim too much for this observation given the inherent problems associated with counterfactuals and the fact that our indicators only pick up a portion of what could broadly be defined as technological change, our results are, nevertheless, suggestive. Since the slowdown in innovative activity as measured by our indicators began, for the most part, after 1930, it would appear unlikely that the onset of the Great Depression can be ascribed to the large, negative technology shocks identified by our indicators.

V. Conclusions

We present in this paper a novel and we believe compelling way to measure technological change based on annual fluctuations in the number of new technology titles (both aggregate and by sub-groups) in the Library of Congress. We argue that our indicators dominate the standard measures of technical change such as patent applications, research and development expenditures, and direct enumeration of major innovations during the years 1909-49 for a number of reasons. They provide a consistent series available on an annual basis, they are based on strictly objective criteria – appearance in the data base of the LOC – and, perhaps most important, new technology publications are likely to track closely the timing of the commercialization of innovations. We use bi-variate VAR regressions to show that causal links did, in fact, exist for our period between innovative activity as captured by our indicators (an important caveat) and GNP per capita and TFP – although, as we point out, some technologies mattered more than others. In particular, manufacturing, automotive, and machine technologies had a much greater impact on output and productivity than those in chemicals and telecommunications.

Field's provocative claim (2003) that the 1930s was the most technologically progressive of the twentieth century gains at least some support from our results – the 1930s, we find, were much more technologically innovative than the periods 1909-1929 and 1941-49. In the final section of the paper we examine the relationship between technology and economy activity in the

1930s. Specifically, we employ a counterfactual analysis to isolate the contribution of technological change to both the start of and recovery from the depression. As we report, the slowdown in technological change measured by our indicators in the early 1930s does not appear to account for much of the drop in output during this period – monetary, fiscal or other factors were clearly at work – but the positive technology shocks and the trend increase in technological change after 1933, as Field (2003, 2006) and others maintain, did play a major role in the economic recovery. Given that pure technology shocks do not appear to be a main cause of the Great Depression, future work on the period should focus on identifying and quantifying those factors that may have had an adverse impact on the efficiency of production.

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Appendix A. Library of Congress Classification Overview

Subclass T Technology (General)

Subclass TA Engineering (General). Civil engineering

Subclass TC Hydraulic engineering. Ocean engineering

Subclass TD Environmental technology. Sanitary engineering

Subclass TE Highway engineering. Roads and pavements

Subclass TF Railroad engineering and operation

Subclass TG Bridge engineering

Subclass TH Building construction

Subclass TJ Mechanical engineering and machinery

Subclass TK Electrical engineering. Electronics. Nuclear engineering

Subclass TL Motor vehicles. Aeronautics. Astronautics

Subclass TN Mining engineering. Metallurgy

Subclass TP Chemical technology

Subclass TR Photography

Subclass TS Manufactures

Subclass TT Handicrafts. Arts and crafts

Subclass TX Home economics

Figure 1. The Indicators

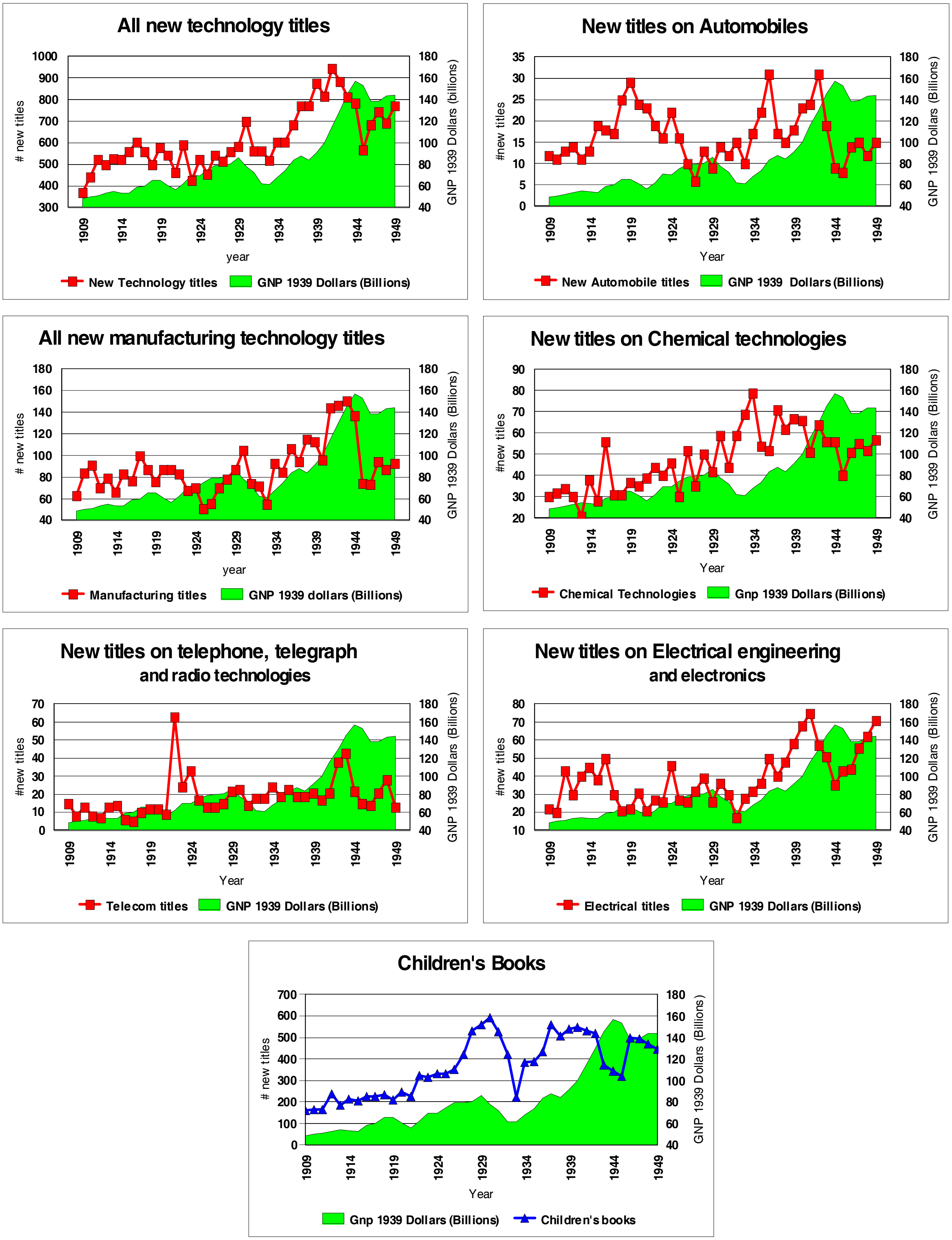


Figure 2. Measures of Technological Change

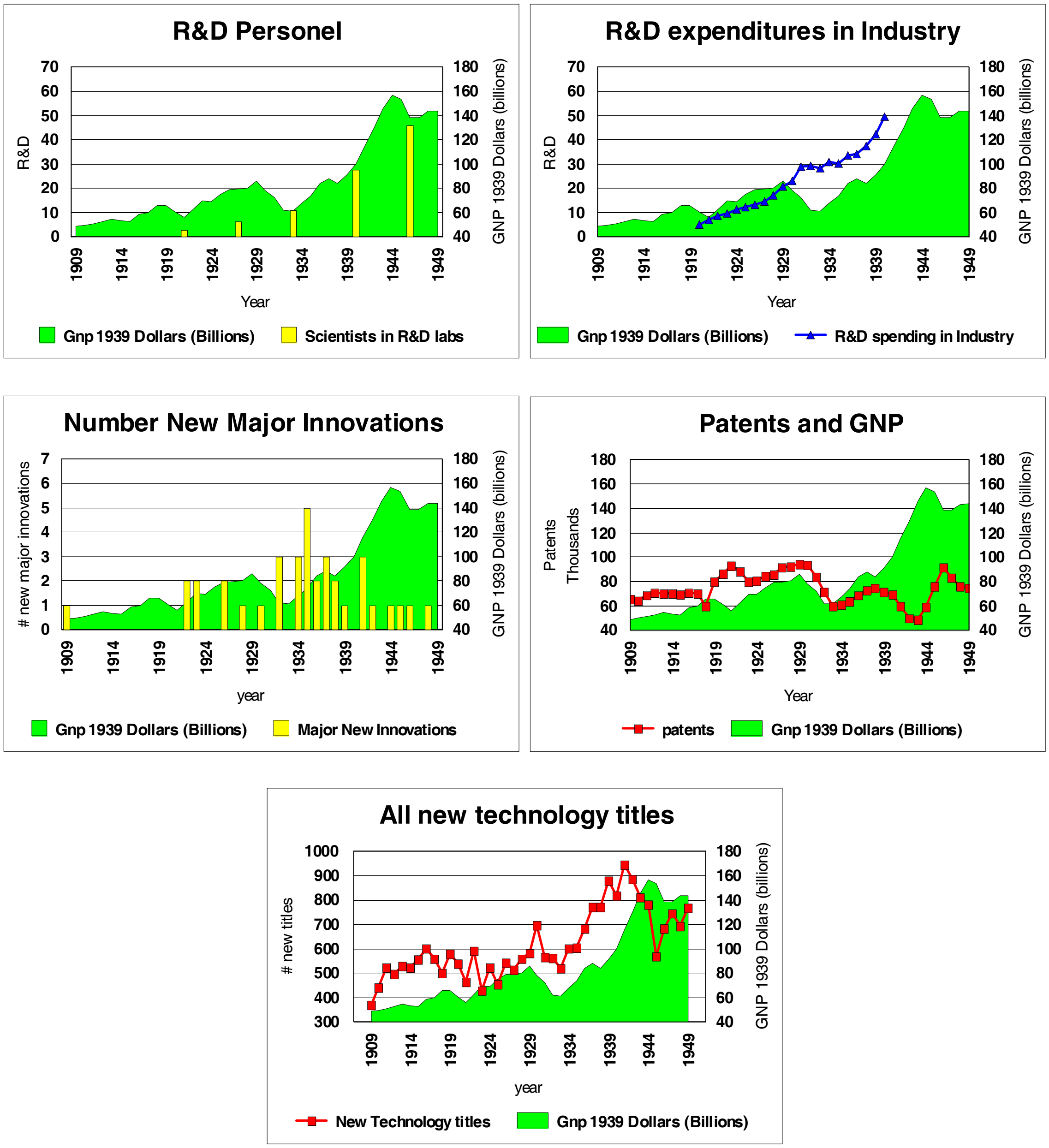


Figure 3. Impulse Response of Real GNP per capita to a Positive Technology Shock

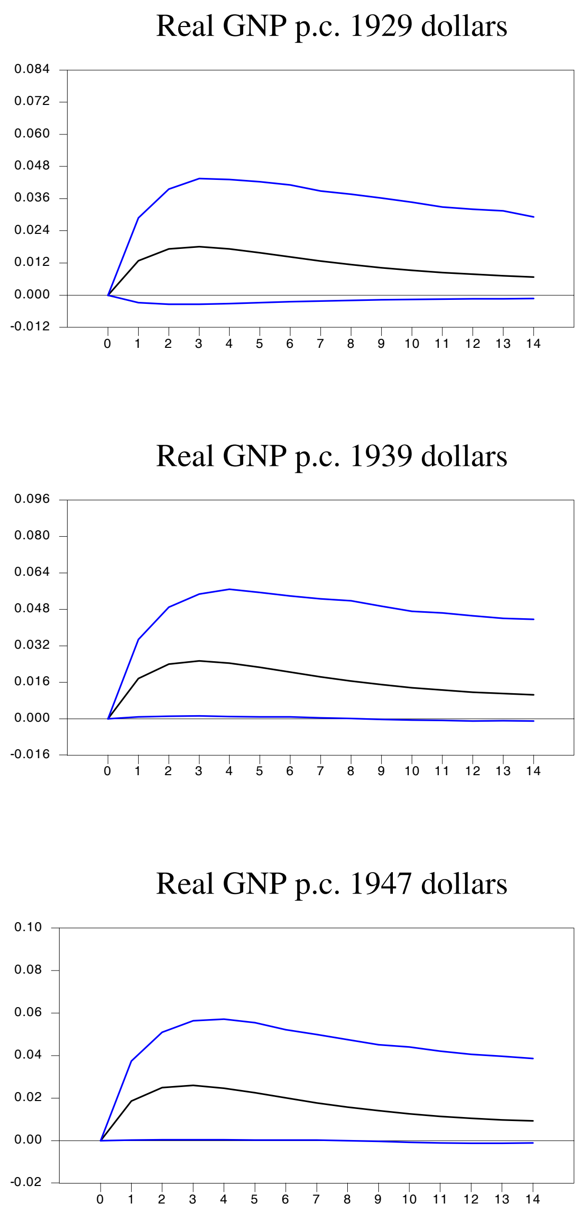
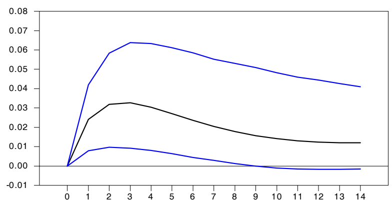


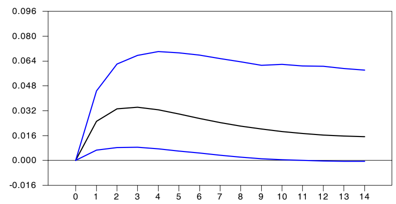
Figure 4. Impulse Responses of Real GNP per capita to Positive Technology Shocks

Electrical Machinery/Electronics

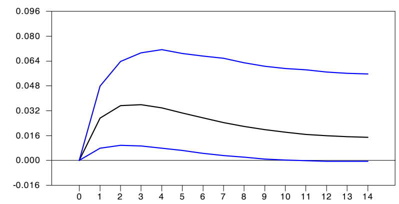
Real GNP p.c. 1929 dollars



Real GNP p.c. 1939 dollars

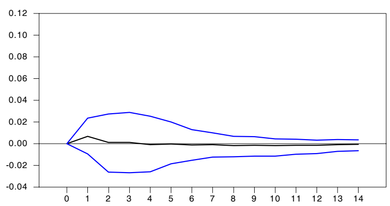


Real GNP p.c. 1947 dollars

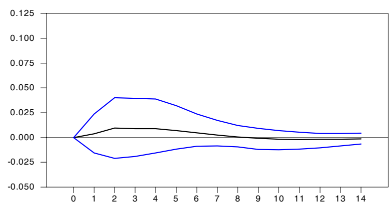


Chemical Technology

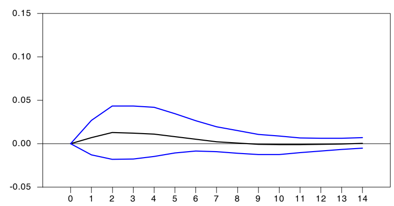
Real GNP p.c. 1929 dollars



Real GNP p.c. 1939 dollars

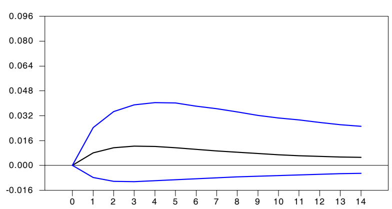


Real GNP p.c. 1947 dollars

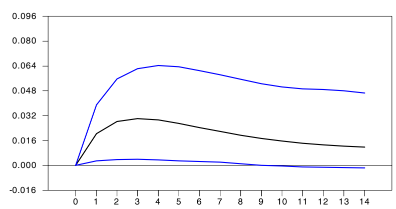


Mechanical machinery and manufacturing tech.

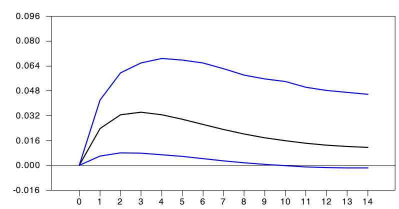
Real GNP p.c. 1929 dollars



Real GNP p.c. 1939 dollars

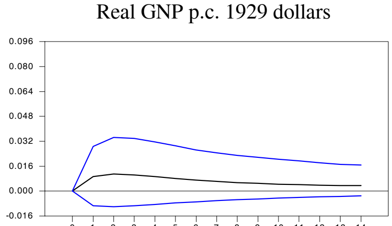


Real GNP p.c. 1947 dollars

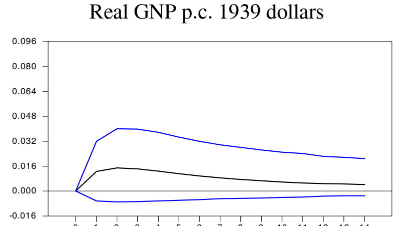


Traditional telecommunications (radio, television, telephone and telegraph)

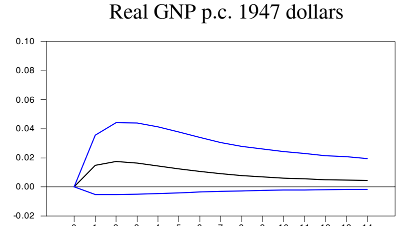
Real GNP p.c. 1929 dollars



Real GNP p.c. 1939 dollars

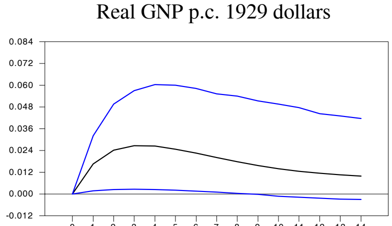


Real GNP p.c. 1947 dollars

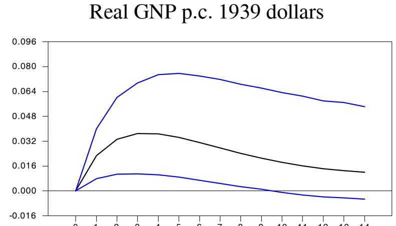


Automobile Technology

Real GNP p.c. 1929 dollars



Real GNP p.c. 1939 dollars



Real GNP p.c. 1947 dollars

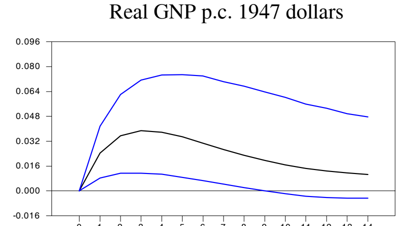
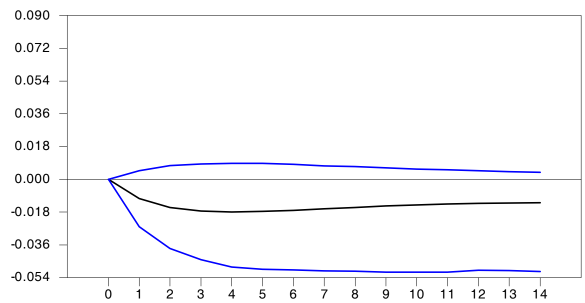
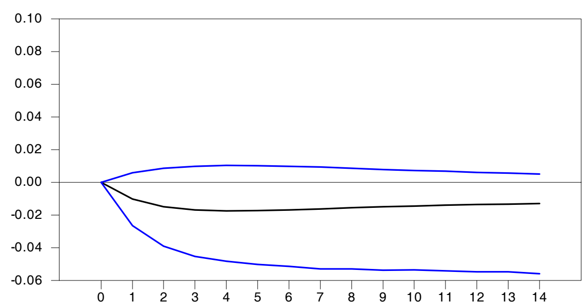


Figure 5. Impulse Response of Real GNP per capita to a Positive Shock to Children's books

Real GNP p.c. 1929 dollars



Real GNP p.c. 1939 dollars



Real GNP p.c. 1947 dollars

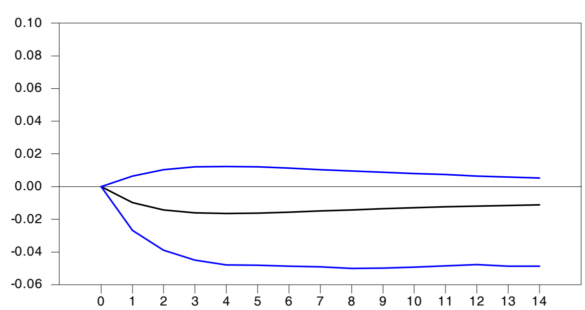
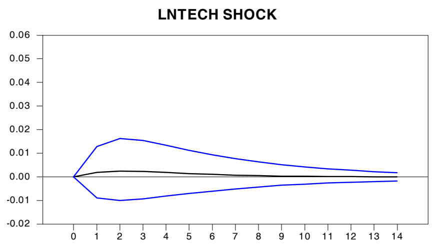
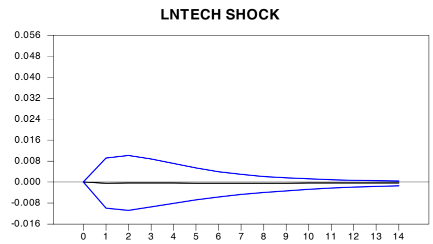


Figure 6. Impulse Response of TFP to a Positive Technology Shock

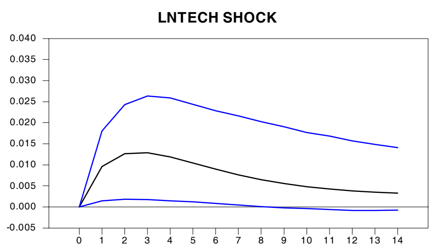
TFP (1929) – unadjusted



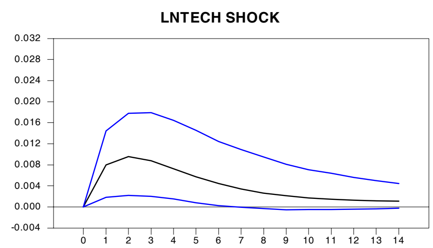
TFP (1929) - adjusted



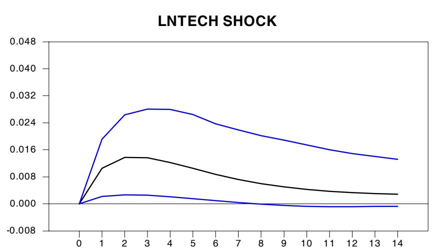
TFP (1939) – unadjusted



TFP (1939) - adjusted



TFP (1947) – unadjusted



TFP (1947) - adjusted

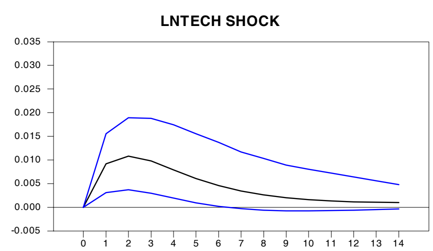
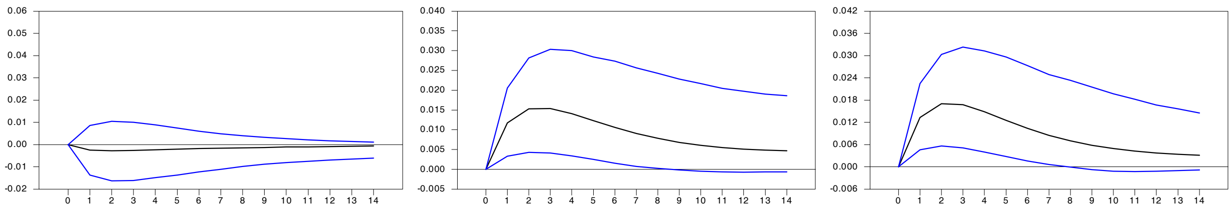


Figure 7. Impulse Responses of TFP to Positive Technology Shocks

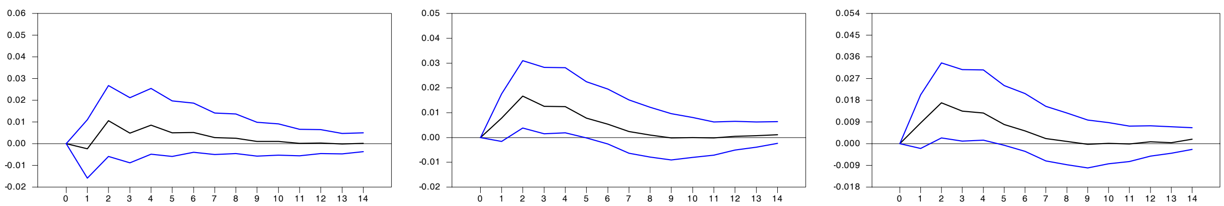
Electrical Machinery/Electronics

TFP (1929) TFP (1939) TFP (1947)



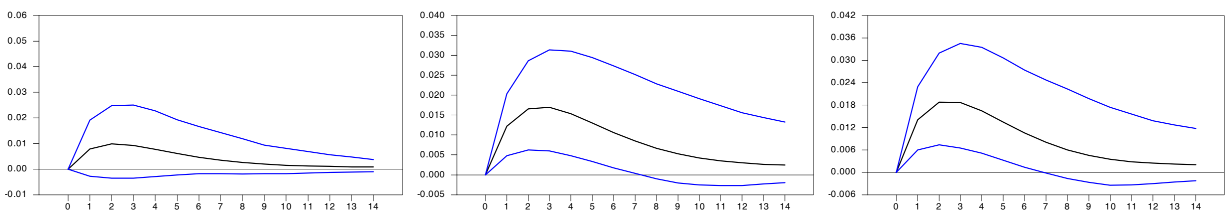
Chemical Technology

TFP (1929) TFP (1939) TFP (1947)



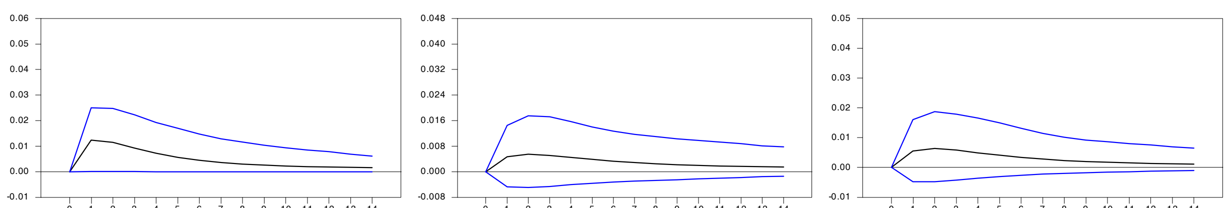
Mechanical machinery and manufacturing tech.

TFP (1929) TFP (1939) TFP (1947)



Traditional telecommunications (radio, television, telephone and telegraph)

TFP (1929) TFP (1939) TFP (1947)



Automotive Technology

TFP (1929) TFP (1939) TFP (1947)

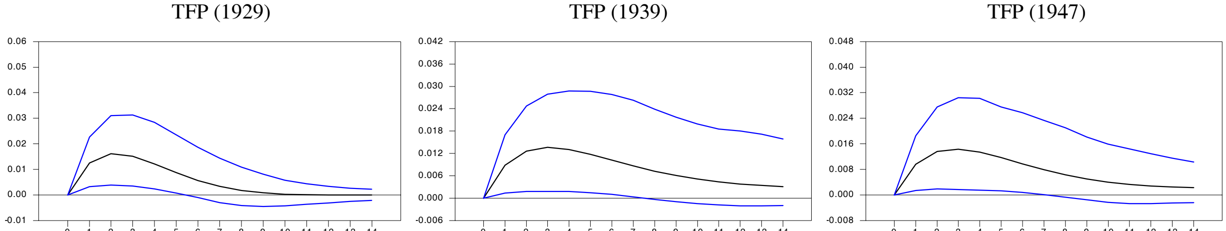


Figure 8. Impulse Responses of TFP to Positive Technology Shocks (adjusted for capital utilization)

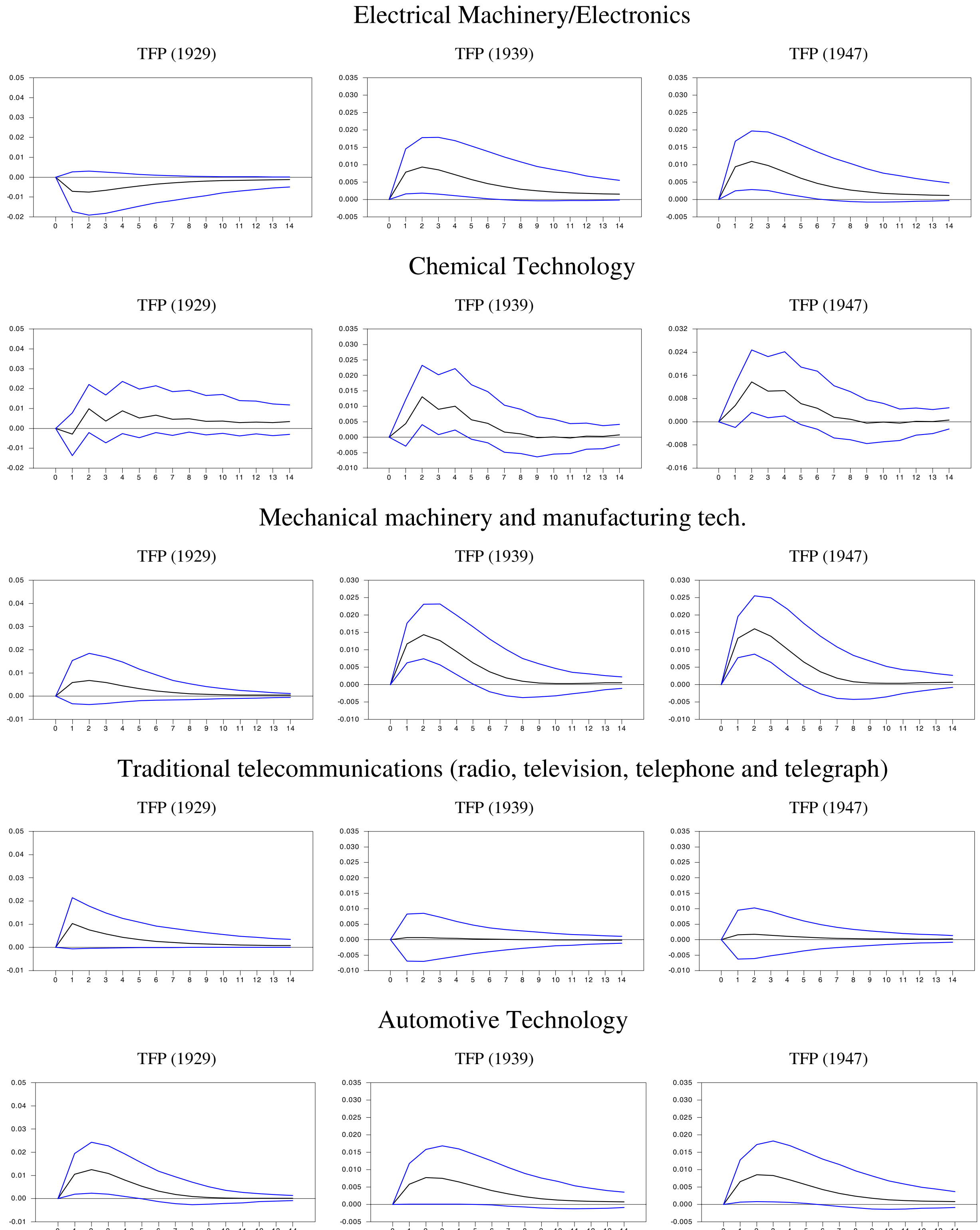
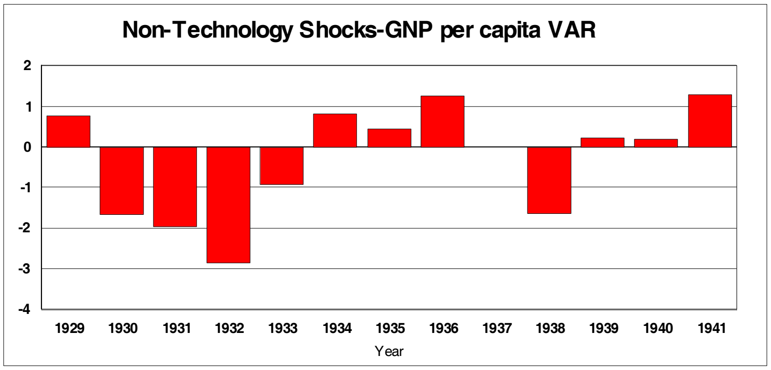
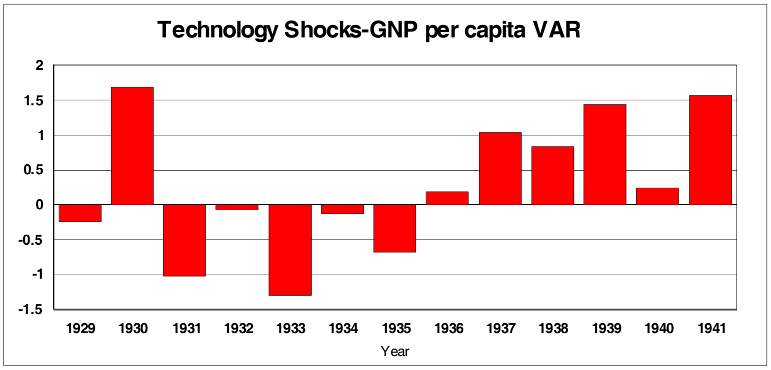
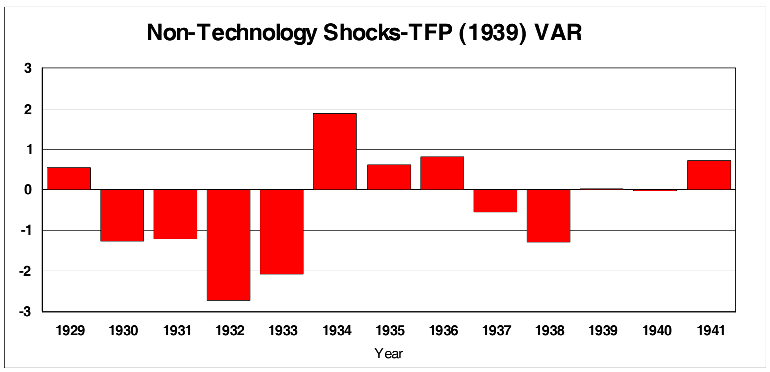


Figure 9. Technology and Non-Technology Shocks







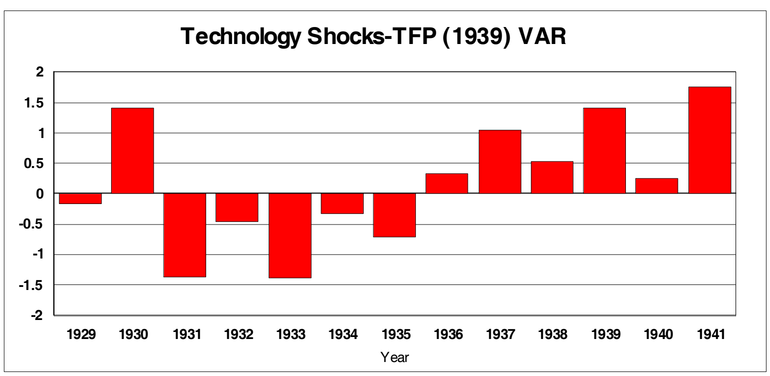
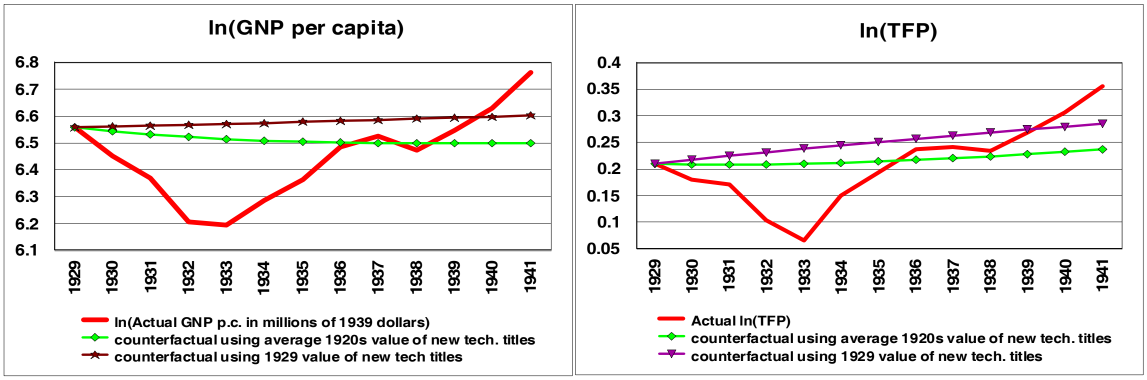
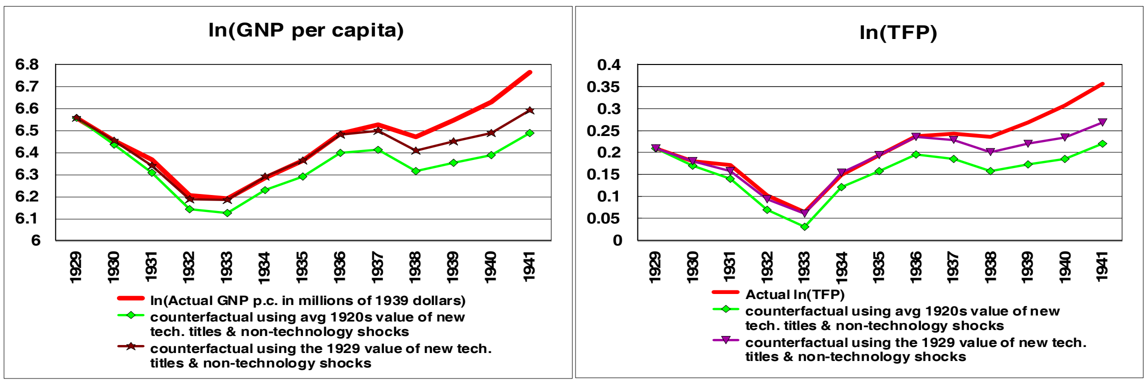


Figure 10. GNP per capita and TFP Counterfactuals: 1929-1941

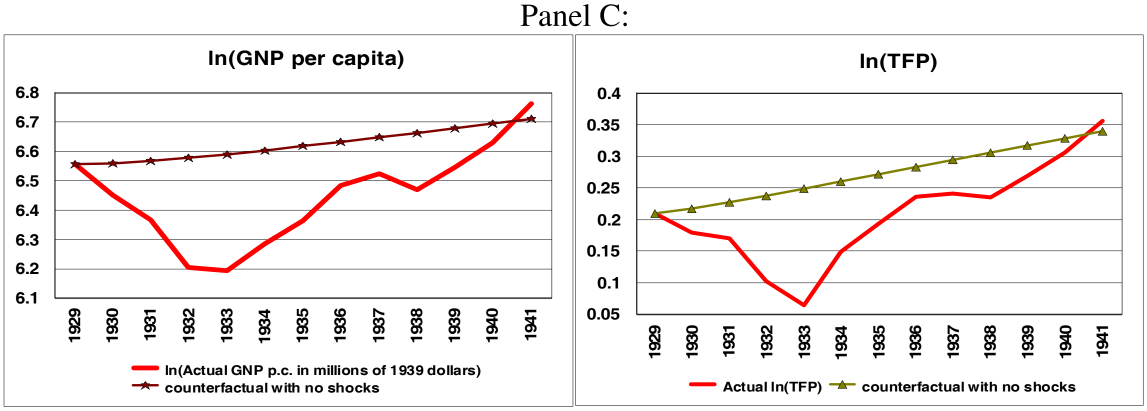
Panel A:



Panel B:



Panel C:



Panel D:

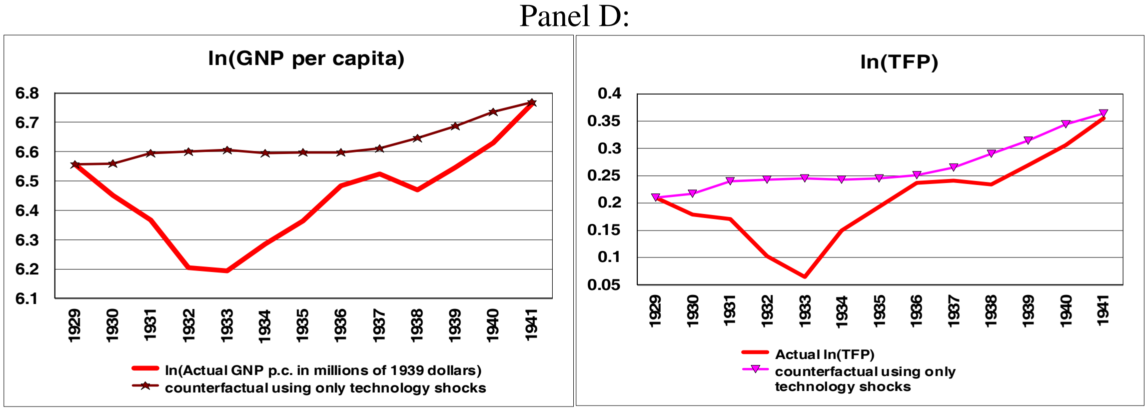
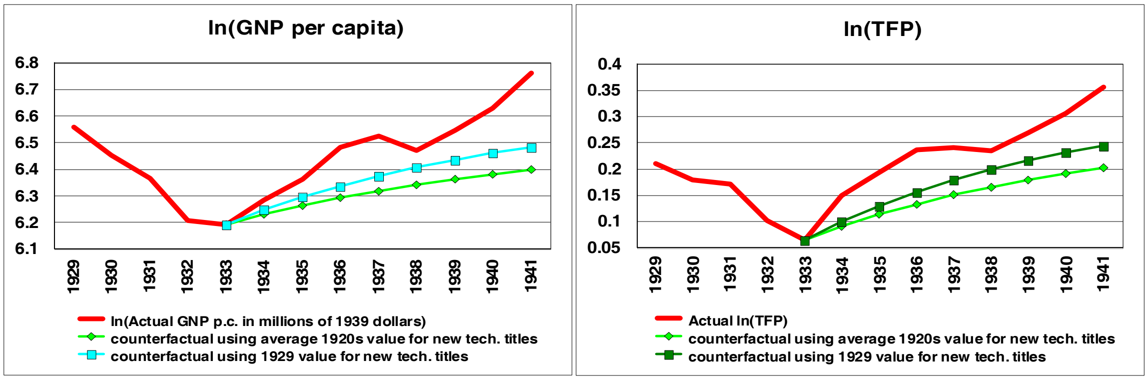
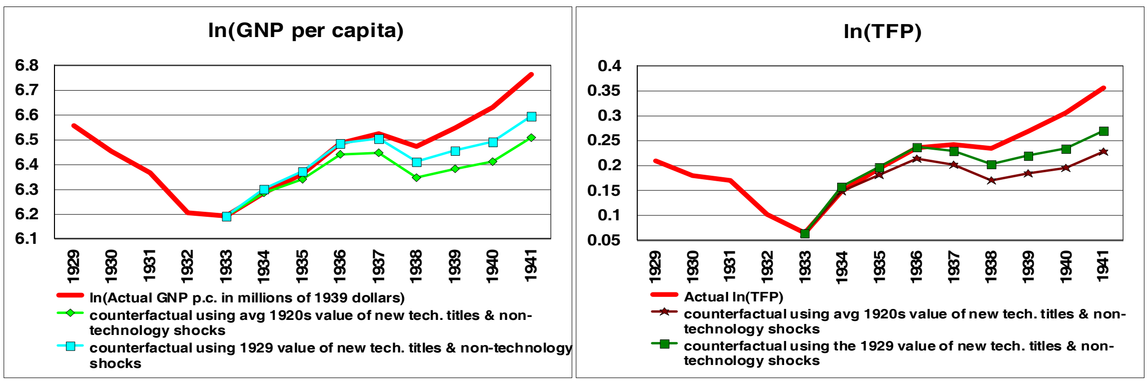


Figure 11. GNP per capita and TFP Counterfactuals: 1933-1941

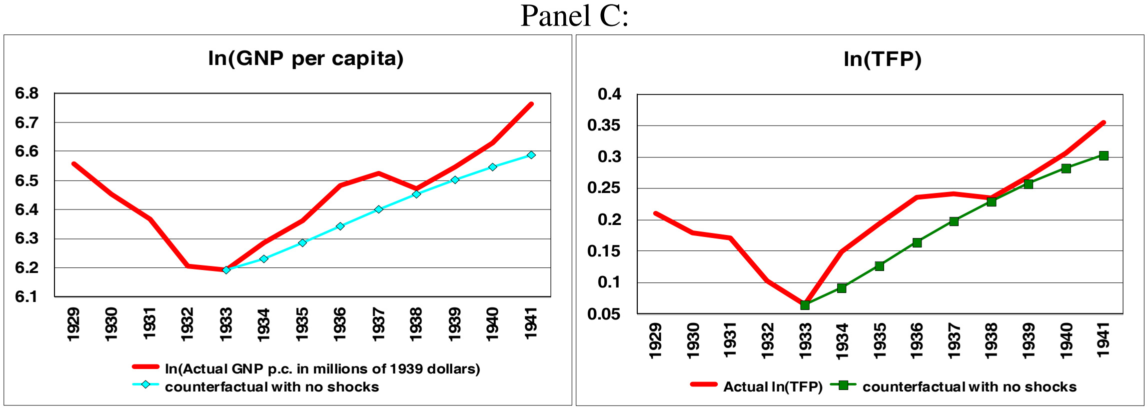
Panel A:



Panel B:



Panel C:



Panel D:

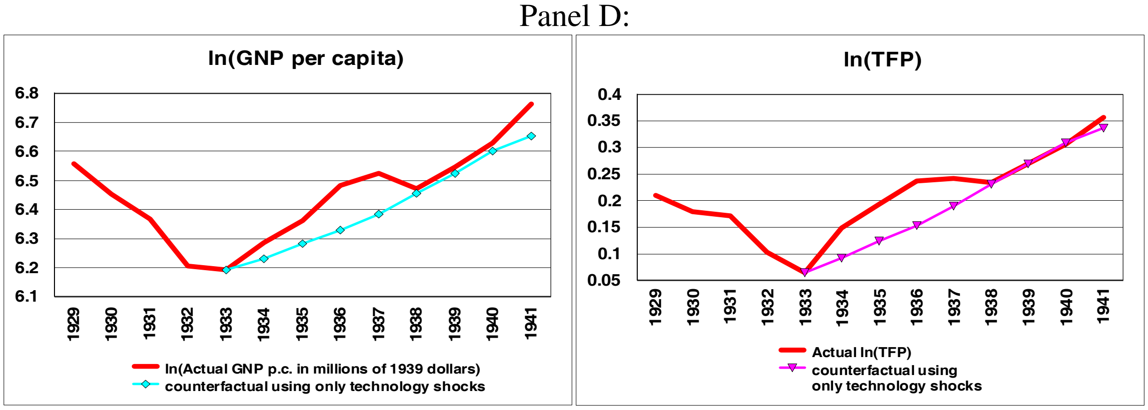


Table 1. Comparison of Dates

Invention	Date of Invention	Date of Innovation	Date of Commercialization	Book Date
Insulin	1889	1922	1922	1922
Neoprene/Duprene	1906	1932	1932	1937
Nylon	1927	1938	Dec. 1939	1939 (1940 in english)
Penicillin	1922	1941	1943	1943
Radio	1887	1922	1922	1910 (1922)
Streptomycin	1921	1944	1945	1945
Kodachrome	1910	1935	1935/1936	1937
Silicones	1904	1946	1946	1946
Terelyne/Polyester	1941	1955	1953	1953/1954
Automatic Transmission	1904	1939	1939	1939

Table 2. Estimates for Real GNP per Capita

Indicator*	GNP p.c. (1929 dollars)		GNP p.c. (1939 dollars)		GNP p.c. (1947 dollars)	
	β	ρ	β	ρ	β	ρ
All Technology	0.1039	0.8538	0.1439	0.8651	0.1505	0.8519
	(0.0745)	(0.0802)	(0.0794)	(0.0747)	(0.0829)	(0.0778)
Manufacturing	0.0410	0.8447	0.1025	0.8395	0.1192	0.8229
	(0.0479)	(0.0836)	(0.0498)	(0.0760)	(0.0511)	(0.0777)
Chemical**	0.0394	1.3390	0.0230	1.3066	0.0414	1.2689
	(0.0573)	(0.1527)	(0.0677)	(0.1524)	(0.0713)	(0.1554)
	-0.0309	-0.5273	0.0401	-0.4354	0.0430	-0.3945
	(0.0581)	(0.1742)	(0.0663)	(0.1832)	(0.0704)	(0.1871)
Electrical	0.0855	0.8243	0.0894	0.8339	0.0959	0.8165
	(0.0327)	(0.0766)	(0.0362)	(0.0742)	(0.0377)	(0.0771)
Telecom	0.0214	0.8678	0.0296	0.8872	0.0353	0.8732
	(0.0249)	(0.0817)	(0.0267)	(0.0766)	(0.0277)	(0.0792)
Automotive	0.0521	0.8713	0.0719	0.9070	0.0779	0.9053
	(0.0270)	(0.0783)	(0.0284)	(0.0723)	(0.0298)	(0.0755)

* For all cases except Chemical the results correspond to the regression $\ln(GNP_t/Pop_t)=\alpha+\gamma t+\beta\ln(Tech_{t-1})+\rho\ln(GNP_{t-1}/Pop_{t-1})+\varepsilon_t$

**In this case the regression is $\ln(GNP_t/Pop_t)=\alpha+\gamma t+\beta_1\ln(Tech_{t-1})+\beta_2\ln(Tech_{t-2})+\rho_1\ln(GNP_{t-1}/Pop_{t-1})+\rho_2\ln(GNP_{t-2}/Pop_{t-2})+\varepsilon_t$ where the first row reports the estimated values of β_1 and ρ_1 and the second row corresponds to the estimates of β_2 and ρ_2.

Table 3. P-values for Granger Causality Tests

Panel A: Does Technology Granger Cause GNP per capita?				
Indicator	Lag Length	GNP p.c. 1929 dollars	GNP p.c. 1939 dollars	GNP p.c. 1947 dollars
All Technology	1	0.1719	0.0781	0.0779
Manufacturing	1	0.3985	0.0470	0.0254
Chemical	2	0.5876	0.8292	0.7767
Electric	1	0.0129	0.0183	0.0154
Telecom	1	0.3957	0.2759	0.2114
Automotive	1	0.0612	0.0161	0.0130
Panel B: Does GNP per capita Granger Cause Technology?				
Indicator	Lag Length	GNP p.c. 1929 dollars	GNP p.c. 1939 dollars	GNP p.c. 1947 dollars
All Technology	1	0.6532	0.6444	0.6770
Manufacturing	1	0.9013	0.8129	0.7859
Chemical	2	0.0013	0.0001	0.0003
Electric	1	0.7326	0.9631	0.9013
Telecom	1	0.2890	0.1509	0.1300
Automotive	1	0.2761	0.1577	0.1058

Table 4. Variance Decompositions

Indicator	Horizon	GNP p.c. 1929 dollars	GNP p.c. 1939 dollars	GNP p.c. 1947 dollars
All Technology	3 years	4.16	6.55	6.76
	6 years	7.75	11.87	12.20
	9 years	8.90	13.56	13.87
Manufacturing	3 years	1.73	9.02	11.67
	6 years	3.54	16.69	21.01
	9 years	4.22	19.12	23.71
Chemical	3 years	0.30	0.59	1.14
	6 years	0.25	1.05	2.01
	9 years	0.25	1.10	2.08
Electrical	3 years	14.53	13.24	14.50
	6 years	24.11	21.95	23.71
	9 years	26.52	24.38	26.16
Telecom	3 years	1.88	2.71	3.43
	6 years	2.81	4.01	5.02
	9 years	3.05	4.35	5.40
Automotive	3 years	7.87	12.41	13.21
	6 years	16.38	24.58	25.65
	9 years	19.37	28.61	29.38

Table 5. Estimates for TFP Regressions

Indicator*	TFP (1929)				TFP (1939)				TFP (1947)			
	Unadjusted		Adjusted		Unadjusted		Adjusted		Unadjusted		Adjusted	
	β	ρ	B	ρ	β	ρ	β	ρ	B	ρ	β	ρ
All Technology	0.0154	0.7088	-0.0037	0.6151	0.0774	0.8337	0.0640	0.7239	0.0855	0.8082	0.0734	0.7059
	(0.0523)	(0.1187)	(0.0461)	(0.1348)	(0.0365)	(0.0849)	(0.0274)	(0.1062)	(0.0391)	(0.0895)	(0.0283)	(0.1065)
Manufacturing	0.0397	0.7026	0.0297	0.6276	0.0625	0.7943	0.0591	0.6555	0.0710	0.7686	0.0669	0.6404
	(0.0315)	(0.1158)	(0.0277)	(0.1313)	(0.0220)	(0.0831)	(0.0157)	(0.0984)	(0.0233)	(0.0865)	(0.0159)	(0.0967)
Chemical**	-0.0124	0.6781	-0.0139	0.5250	0.0493	1.0828	0.0253	0.8416	0.0523	1.0553	0.0324	0.8642
	(0.0385)	(0.1663)	(0.0294)	(0.1591)	(0.0345)	(0.1552)	(0.0240)	(0.1599)	(0.0370)	(0.1589)	(0.0250)	(0.1606)
	0.0613	0.1184	0.0546	0.2201	0.0774	-0.0268	0.0629	0.1485	0.0726	-0.0352	0.0616	0.1078
	(0.0378)	(0.1767)	(0.0297)	(0.1624)	(0.0339)	(0.1984)	(0.0239)	(0.1897)	(0.0366)	(0.2034)	(0.0251)	(0.1941)
Electrical	-0.0087	0.7088	-0.0249	0.6143	0.0415	0.8006	0.0275	0.6958	0.0469	0.7736	0.0327	0.6785
	(0.0240)	(0.1185)	(0.0205)	(0.1304)	(0.0167)	(0.0848)	(0.0129)	(0.1084)	(0.0178)	(0.0889)	(0.0132)	(0.1085)
Telecom	0.0278	0.6732	0.0240	0.5543	0.0108	0.8448	0.0015	0.7280	0.0128	0.8224	0.0037	0.7179
	(0.0167)	(0.1157)	(0.0151)	(0.0240)	(0.0126)	(0.0891)	(0.0097)	(0.1141)	(0.0135)	(0.0939)	(0.0101)	(0.1159)
Automotive	0.0409	0.7057	0.0338	0.5979	0.0281	0.8526	0.0185	0.7268	0.0306	0.8342	0.0208	0.7227
	(0.0181)	(0.1107)	(0.0159)	(0.1257)	(0.0135)	(0.0851)	(0.0104)	(0.1093)	(0.0146)	(0.0899)	(0.0109)	(0.1104)

* For all cases except Chemical the results correspond to the regression $\ln(TFP_t)=\alpha+\gamma t+\beta\ln(Tech_{t-1})+\rho\ln(TFP_{t-1})+\varepsilon_t$

**In this case the regression is $\ln(TFP_t)=\alpha+\gamma t+\beta_1\ln(Tech_{t-1})+\beta_2\ln(Tech_{t-2})+\rho_1\ln(TFP_{t-1})+\rho_2\ln(TFP_{t-2})+\varepsilon_t$ where the first row reports the estimated values of β_1 and ρ_1 and the second row reports the estimates of β_2 and ρ_2.

Table 6. P-values for Granger Causality Tests.

Panel A: Does Technology Granger Cause TFP?

Indicator	Lag Length	TFP (1929) Unadjusted	TFP (1929) Adjusted	TFP (1939) Unadjusted	TFP (1939) Adjusted	TFP (1947) Unadjusted	TFP (1947) Adjusted
All Technology	1	0.771	0.937	0.041	0.025	0.035	0.014
Manufacturing	1	0.216	0.292	0.007	0.001	0.004	0.000
Chemical	2	0.247	0.184	0.083	0.043	0.134	0.057
Electric	1	0.720	0.232	0.018	0.039	0.012	0.018
Telecom	1	0.106	0.122	0.396	0.880	0.348	0.718
Automotive	1	0.030	0.041	0.045	0.085	0.043	0.064

Panel B: Does TFP Granger Cause Technology?

Indicator	Lag Length	TFP (1929) Unadjusted	TFP (1929) Adjusted	TFP (1939) Unadjusted	TFP (1939) Adjusted	TFP (1947) Unadjusted	TFP (1947) Adjusted
All Technology	1	0.214	0.240	0.444	0.529	0.415	0.487
Manufacturing	1	0.245	0.177	0.336	0.167	0.336	0.177
Chemical	2	0.046	0.437	0.000	0.004	0.000	0.005
Electric	1	0.596	0.575	0.744	0.769	0.675	0.663
Telecom	1	0.598	0.098	0.345	0.840	0.273	0.611
Automotive	1	0.061	0.097	0.153	0.197	0.141	0.178

Table 7. Variance Decompositions

Indicator	Horizon	TFP (1929)		TFP (1939)		TFP (1947)	
		Unadjusted	Adjusted	Unadjusted	Adjusted	Unadjusted	Adjusted
All Technology	3 years	0.22	0.02	9.53	13.07	10.24	15.78
	6 years	0.38	0.03	16.87	21.11	17.75	24.57
	9 years	0.40	0.03	18.75	22.17	19.40	25.48
Manufacturing	3 years	4.16	3.18	15.77	28.62	18.70	34.47
	6 years	7.42	5.14	27.17	40.53	31.12	46.55
	9 years	7.87	5.28	29.40	40.70	33.06	46.60
Chemical	3 years	3.11	4.61	10.11	14.26	9.74	15.37
	6 years	4.87	7.61	14.78	23.15	15.05	26.28
	9 years	5.43	9.25	15.08	23.45	15.26	26.40
Electrical	3 years	0.39	4.48	14.01	12.45	15.90	16.19
	6 years	0.69	7.09	23.25	19.81	25.72	24.75
	9 years	0.75	7.43	25.38	20.82	27.60	25.66
Telecom	3 years	7.72	6.66	1.87	0.07	2.25	0.39
	6 years	10.07	7.86	2.79	0.10	3.29	0.54
	9 years	10.35	7.97	3.01	0.10	3.50	0.56
Automotive	3 years	11.31	11.07	8.81	7.52	9.27	8.76
	6 years	19.52	17.34	17.83	14.22	18.49	16.21
	9 years	19.97	17.48	20.44	15.23	20.81	17.17