Was Electricity a General Purpose Technology? Evidence from Historical Patent Citations

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General purpose technologies (GPTs) are credited with generating the increasing returns that drive endogenous growth. For example, Paul David (1991) explains the surge in U.S. productivity during the 1920's as a delayed response to the introduction of the electric dynamo in the 1880's. To the extent that GPTs yield large positive externalities on a wide range of industries some time after they are discovered, individual inventors are likely to underinvest in them, and government intervention may be necessary to reach optimal levels of investment in research and development. This theory assumes that GPTs can be identified.

While the growth implications of GPTs are well documented in theory (Elhanan Helpman, 1998) empirical evidence remains sparse. With the exception of Nathan Rosenberg and Manuel Trajtenberg (2001), who analyze the example of the Corliss steam engine, existing empirical work is based largely on data with a high level of aggregation (Boyan Jovanovic and Peter Rousseau, 2003; N. F. R. Crafts and Terrence Mills, 2004). This leaves a gap in our understanding of the micro-foundations of GPTs. Although Richard Lipsey et al. (1998) define GPTs by four criteria (a wide scope for improvement and elaboration, applicability across a broad range of uses, potential for use in a wide variety of products and processes, and strong complementarities with existing or potential new technologies), these claims have not been verified systematically.

This paper uses historical patent citation data to test whether *electricity*, as the canonical example of a General Purpose Technology, matches the current criteria of GPTs. We use a sample of American patents assigned to publicly traded companies in biennial years of the 1920's to check which of four industry categories (electricity, chemicals, mechanical, and other) most closely matches the key elements of GPTs. We analyze the characteristics of our patents at their grant date and trace knowledge embodied in these patents through citations in patent grants between 1976 and 2002. Our sample consists of 1,867 U.S. patents from the 1920's, and 3,400 forward citations to these patents. Our aim is both to help inform the way that growth theorists model the development of GPTs and to enhance our understanding of technological progress in the last century more generally.

The 1920's are an appropriate decade for our hypothesis test because they were a period of exceptional inventive activity and productivity increases. David (1991) credits electricity with a central role in U.S. productivity growth in the 1920's, 40 years after Thomas Edison's patent of the filament lamp. But the 1920's was not just a decade of electrification. Alexander Field (2003) conjectures that a "larder stock" of 1920's innovations may have accelerated productivity growth during the 1930's, a period he describes as "the most technologically progressive decade of the [20th] century." Electricity made it possible for workflows in the factory to be restructured away from traditional energy sources such as water power. However, other advances, especially those in fuel, automobiles, trucks, and tires, had a significant (possibly even greater) impact on spatial allocation and the structure of economic life. Benzene-powered motor vehicles, with rubber tires and lighter metal casings, depended on chemical rather than electrical inventions.

Our results contradict the hypothesis that electricity was a GPT according to conventional definitions such as those of Timothy Bresnahan and Trajtenberg (1995) or Lipsey et al. (1998). We find that electricity patents were broader in

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scope than other categories of patents at their grant date, and that they were more "original" than their counterparts according to the chronology of citations. However, we also show that electricity patents had lower generality scores, as measured by the distribution of their forward citations, fewer citations per patent (a measure of technological importance), and shorter citation lags (i.e., faster rates of knowledge depreciation). Although the current analysis can only rely on patents from two periods, separated by a large gap in time, our results are strong enough to warrant further investigation. We conclude that technical change, even in the 1920's, was much broader than has previously been considered.

I. The Data

Patents are a valuable source for tracing the dynamics of technological progress. In this study we use a novel set of 1,867 U.S. patents granted in 1920, 1922, 1924, 1926, and 1928 that were cited 3,400 times by patents between 1976 and 2002. Because the quality of invention varies strongly across patent counts (see Zvi Griliches, 1990), we restrict our sample to patents that were assigned to publicly traded firms. Our records on historical patents detail inventions of the large pioneering electricity corporations AT&T, General Electric, and Westinghouse, as well as other major "Chandlerian" corporations of the time such as E. I. Du Pont, Eastman Kodak, and General Motors. Some of the companies for which we have data also possess a more moderate level of assets than the set of firms studied by Alfred Chandler (1990). By market value, our data set of companies closely approximates the population of companies collated by the Chicago Research Center in Securities Prices (Nicholas, 2003). We observe 121 firms to which 17,559 patents were assigned between 1920 and 1928; approximately half of these patents fall in the even years of our sample; 21 percent of these patents were cited in U.S. patents between 1976 and 2002. We use the patterns in these forward citations to study the technological significance of inventions in the 1920's.

An important characteristic of our data is the high proportion of historical citation counts; 21 percent of patents from the 1920's are cited during or after 1976. Although the probability of a patent being cited falls off sharply after ten years from a grant date (Ricardo Caballero and Adam Jaffe, 1993), citations with long lags do exist and provide significant information about the life cycle of technologies. For example, in the National Bureau of Economic Research (NBER) patent data "citations go back very far into the past (some even over a hundred years!), and [therefore] to a significant extent patents seem to draw from old technological predecessors" (Bronwyn Hall et al., 2001 pp. 421–22). The fact that late-20th-century patents cite prior art from the 1920's confirms Suzanne Scotchmer's (1991) argument that technological progress builds on foundations laid by earlier inventors. Historical citations allow us to trace important knowledge flows across these generations.

To measure the general-purpose characteristics of different industries, we first divide our patent data into four industry categories: electrical, chemical, mechanical and other. This categorization is based on Hall et al. (2001), who have established a patent classification that aggregates 417 U.S. Patent and Trademark Office (USPTO) three-digit classes into 36 two-digit technology subclasses. These in turn are combined into six major technology fields: Computers and Communications, Drugs and Medical, Electrical and Electronics, Chemical, Mechanical, and Others. We have very few observations for Drugs and Medical and for Computers and Communications (47 patents altogether) which we omit from this sample to simplify the classification. Differences in forward citations for the remaining four technology fields allow us to examine the relative importance of electricity inventions as a GPT.

II. Definitions of Originality, Longevity, and Generality

We expand measures in Rebecca Henderson et al. (1998) to test which industries best meet the characteristics of a GPT. For patents after 1976, Hall et al. (2001) have shown that Computers and Communications score highest in terms of generality; they interpret this finding as consistent with the notion of general purpose technologies. We use citations to patents in the

TABLE 1—DESCRIPTIVE STATISTICS

Measure	Pooled	Electricity	Chemicals	Mechanical	Other
GENERALITY	0.11	0.08	0.12	0.11	0.13
	(0.21)	(0.20)	(0.21)	(0.21)	(0.23)
ORIGINALITY	0.48	0.57	0.55	0.44	0.41
	(0.45)	(0.46)	(0.44)	(0.45)	(0.44)
Citations	1.82	1.60	2.12	1.77	1.95
	(1.72)	(1.30)	(2.11)	(1.67)	(1.84)
Self-citations	0.04	0.05	0.03	0.03	0.03
	(0.17)	(0.21)	(0.14)	(0.16)	(0.16)
Mean citation lag	63.08	62.10	63.32	63.13	63.85
	(7.51)	(7.74)	(7.63)	(7.33)	(7.42)
Maximum citation lag	64.76	63.41	65.21	64.86	65.70
	(8.23)	(8.44)	(8.61)	(8.00)	(8.01)
Classes	1.78	1.87	1.73	1.76	1.74
	(1.01)	(1.08)	(0.91)	(1.03)	(0.97)
Subclasses	3.17	3.33	3.23	3.11	3.06
	(2.08)	(2.36)	(2.04)	(1.93)	(2.05)
Observations, 1920–1928	1,867	433	277	747	410
Growth rate (percentage) 1920–1928	18.67	30.12	10.90	19.34	20.75

Note: The table presents mean values for measures described in the text. Standard deviations are reported in parentheses. Citation lags are calculated in years. Classes and subclasses are counts of USPTO assignments.

1920's to test how well electricity, as the canonical GPT of the early 20th century, meets criteria of originality, longevity, and generality.

A first look at the data suggests that the 1920's were a period of aggressive growth for inventions in electricity. Between 1920 and 1928, the growth rate of electricity patents, as reported in the last row of Table 1, is much higher than the average rate for chemicals, mechanical, and other patents. This confirms the notion that electricity was a significant source of innovations in the 1920's. However, aggressive growth in patenting does not in itself fulfill the standard definitions of GPTs. To evaluate the general-purpose characteristics of electricity inventions, we examine how knowledge from the patents in the 1920's benefited later generations of inventors.

A. *Originality*

We begin by constructing a measure for the originality of patents. ORIGINALITY exploits the historical aspect of our patent data, which allows us to determine the date of the earliest patent that is cited in an invention between 1976 and 2002. For instance, if a 1976 patent cites a 1920 patent, ORIGINALITY is coded 1 if the 1976 cites start with the 1920 patent and 0 if there are earlier citations. These data allow us to identify the exact arrival dates for influential innovations.

B. *Longevity*

Next, we measure the speed of obsolescence for inventions in different industries. We calculate both the mean and maximum lag (in years) between a 1920's patent grant and the citations that it receives. The mean lag is the difference between the grant date and the citation date averaged over all a patent's citations. The maximum lag is the difference between the grant date and the most recent citation. We also account for the fact that surviving firms may continue to cite their own patents for nontechnical reasons, perhaps status or pride, even after those patents have become obsolete. For example, our variable for self-citations takes the value 1 if General Electric cites a patent in 1976 that was assigned to General Electric in 1920.

C. *Generality*

Bresnahan and Trajtenberg (1995 p. 3) argue that the range of later generations of inventions that benefit from an early patent can be measured as the range of industries that cite the early patent. Using citation data on three-digit USPTO classes, Trajtenberg et al. (1997) compute a Herfindahl-Hirschman index that measures this range, or the extent of a patent's generality. Like theirs, our generality index squares the share of three-digit citing classes over the total number of three-digit class citations (N_i) and subtracts the sum over all citied patents from 1 (i.e., $\text{GENERALITY}_i = 1 - \sum_{j=1}^{N_i} (C_{ij}/C_i)^2$. Thus, a value of 1 implies that the knowledge in a patent from the 1920's benefited inventions in a wide range of patent classes, while a value of 0 means that all benefits were concentrated in a single class.[1] Fol-

[1] This measure may decrease with the coarseness of a classification system and increase with a finer classification system. Joshua Lerner (1994) argues that the World Intellectual Property Organization's classification scheme may better reflect the economic importance of new inventions. For the purpose of this study, however, we prefer the

TABLE 2—MANN-WHITNEY TESTS

Measure	H_0: Elec. = Chem.	H_0: Elec. = Mech.	H_0: Elec. = Other
GENERALITY	−2.77**	−2.07*	−2.87**
ORIGINALITY	0.58	4.53**	5.17**
Citations	−3.96**	−2.56**	−3.47**
Self-citations	0.41	1.51	1.33
Mean citation lag	−2.13*	−2.38*	−3.37**
Maximum citation lag	−2.74**	−2.87**	−3.65**
Classes	1.43	1.84†	1.63†
Subclasses	−0.07	0.52	1.16

† Statistically significant at the 10-percent level.
* Statistically significant at the 5-percent level.
** Statistically significant at the 1-percent level.

TABLE 3—ORDINARY LEAST-SQUARES GENERALITY REGRESSIONS

Variable	Full sample	Full sample	Gen. ≥ 0.5
Electricity dummy	−0.039**	−0.032*	−0.032*
	(0.015)	(0.014)	(0.016)
Chemicals dummy	−0.003	0.002	−0.035*
	(0.017)	(0.017)	(0.016)
Mechanical dummy	−0.018	−0.013	−0.036**
	(0.014)	(0.013)	(0.012)
Originality		0.004	−0.001
		(0.009)	(0.014)
Self-citation		0.037	0.046
		(0.026)	(0.034)
Maximum citation lag		0.007**	0.002**
		(0.001)	(0.001)
Classes		0.037**	0.011*
		(0.005)	(0.005)
Year dummies	yes	yes	yes
F:	1.73†	17.09**	3.23**
R^2:	0.01	0.10	0.15
Observations:	1,867	1,867	270

† Statistically significant at the 10-percent level.
* Statistically significant at the 5-percent level.
** Statistically significant at the 1-percent level.

lowing Joshua Lerner (1994) we also construct a measure of patent scope, at the point of grant date for our 1920's patents, which is calculated as the number of three-digit USPTO classes that a patent was assigned to at the patent-examination stage; additionally, we construct this measure at the level of USPTO subclasses. Therefore, we have a way of correlating contemporary patent scope with patent generality in the future.

III. Findings

Some preliminary insights into the nature of general-purpose characteristics can be gained from the descriptive statistics in Table 1. It is interesting to note that 48 percent of the patents in our data set are truly original patents: they are the starting points for technical knowledge that continues to be relevant to inventions in the late 20th century. This result yields further support for the hypothesis that the 1920's were an important phase for technological progress, especially in the field of electricity, which has the highest proportion of original patents (57 percent).

However, electricity does not perform as expected with respect to other potential characteristics of GPTs. The frequency of citations to electricity patents is lower than in chemical, mechanical, and other industries, despite the fact that the proportion of self-citations is higher. The longevity measures (citation lags) in Table 1 indicate that the value of knowledge from electricity inventions to later generations of inventors depreciated more quickly than the value of knowledge from other industries. We would expect electricity inventions to have the highest generality of all industries. Although these patents were broader in scope at their grant date, as illustrated by the number of USPTO class and subclass assignments, electricity patents have the lowest generality.

We check these results further by subjecting the patent data to some simple statistical tests. Table 2 reports z statistics from nonparametric Mann-Whitney rank-sum tests of the null hypothesis that the median characteristics of electricity patents are identical to chemical, mechanical, and other patents. These tests confirm that electricity patents are disproportionately original compared to mechanical and other patents. At the same time they also show that electricity patents have significantly fewer forward citations, a shorter citation lag, and the lowest generality of any technology field. Least-squares regressions in Table 3 verify this result: chemical, mechanical, and other inventions are significantly more general than electricity

USPTO classification system by function because it is exogenous to the question of technological impact.

inventions. In the final column of Table 3, we restrict the regression to observations with generality of 0.5 or larger, (approximately the top three quintiles of generality scores) to determine whether electricity has a greater impact when the most general inventions are considered. Contrary to the hypothesis that electricity was a GPT, the sign on the electricity dummy is negative.

These patterns in the citation data lead us to question why electricity has been called the most important GPT of the 20th century. One explanation is that, without systematic empirical data, the concept of a GPT has been based on anecdotal evidence involving a few extremely general inventions, such as David's (1991) electric dynamo. As a point of comparison, we identify the ten most general inventions in our data (Table 4). Only two of them, Robert Williamson's windings for an electric dynamo machine and Truman Fuller's invention of an electrical contact, the most general patent in our data set (see Fig. 1), are electricity inventions. Two more inventions, Forshee and Wodson's soldering iron and perhaps Schmidt's portable household washing machine, use electricity as a power source.

The most striking fact about our list of the most general inventions is the relative paucity of electricity patents. Even Fuller's invention of an electric contact is distinguished by the chemical discovery that silver-copper alloys are less sensitive to damage caused by heat and arcing. Three further inventions are chemical based: Gray and Staud's process for making chloroform-soluble cellulose acetate, Donald MacGill's latex closure for milk bottles, and W. B. Harsel's improvement for making finishing strips for tire casings. Gray and Staud's invention, for example, can be used to process film but "may be applied successfully to many different kinds of cellulose, such as high grade clean cotton fibers, cotton fiber tissue paper (...), surgical cotton wool, cotton linters, and even carefully prepared and bleached sulfite wood pulp" (U.S. Patent No. 1,683,347, granted 28 February 1928). The list also includes two inventions whose generality lies in the ingenious simplicity of their design: Farmer's connector for pipes, which is still in use today, and Hadaway's improvement in staple wires. In sum, generality appears to be shared across industries; it rests in the specific characteristics of an invention, rather than in its links to electricity.

TABLE 4—TOP TEN GENERALITY PATENTS

No.	Year	Patent number	Inventor Assignee
1	1928	1,658,713	Truman Fuller, General Electric
2	1928	1,683,347	Harry Gray, Cyril Staud, Eastman Kodak
3	1922	1,418,856	Robert Williamson, Allis-Chalmers Mfg
4	1928	1,660,538	Ralph Whitney, B.F. Goodrich
5	1928	1,664,635	Donald Magill, American Can
6	1920	1,357,319	John Hadaway, United Shoe Machinery
7	1924	1,520,705	Clyde Farmer, Westinghouse Air Brake
8	1924	1,519,246	Frank Forshee, James Woodson, Westinghouse Electric & Mfg
9	1920	1,327,910	William Harsel, Goodyear Tire & Rubber
10	1928	1,673,594	Henry Schmidt, Westinghouse Electric & Mfg

Description of Patent	Citations	Generality
1) Silver-copper alloy electrical make and break contact e.g., for ignition systems	9	0.86
2) Process for making chloroform soluble cellulose acetate	16	0.78
3) Windings for electric dynamo machines	7	0.78
4) Roll for paper-making machines with helix pattern for increased life of use	6	0.78
5) Milk-bottle closing device	8	0.75
6) Staple wire e.g., for attaching shoe buttons	4	0.75
7) Supporting device to connect screw threaded pipes together	4	0.75
8) Electric soldering iron	4	0.75
9) Tire-making machine	2	0.75
10) Portable household washing machine	7	0.73

IV. Conclusions

This paper has used data on 1,867 U.S. patents from the 1920's and 3,400 forward citations to

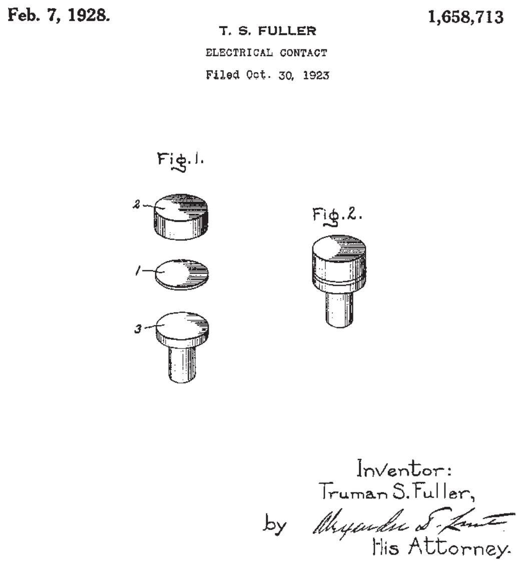

FIGURE 1. TRUMAN FULLER'S INVENTION OF AN ELECTRICAL CONTACT

these patents to examine the general-purpose characteristics of inventions in different industries. Our results contradict the hypothesis that electricity was a GPT, at least when measured against the standard of current definitions. Inventions in other industries, such as chemicals, fulfill the criteria for GPTs at least as well as those in electricity.

Fifty years separate our patents from the 1920's and their citations from 1976. This time lag allows us to examine the long-term influence of inventions, which is especially important in studies of GPTs. It also avoids the problem of truncation, which occurs in studies based on current data (Hall et al., 2001 p. 15), whereby the share of citations that are captured falls toward the last period of data collection. On the other hand, the large gap between patents and their citations in our data set may only allow us to pick up the most persistent effects of invention.

However, even with this caveat, the current results are strong enough to warrant further investigation. We conclude that technological change, even in the 1920's, was much broader than has previously been considered. We believe that it was not electricity alone, but more generally scientific advances of the late 19th century, such as Dmitry Mendeleyev's invention of the periodic table in 1864, that caused the productivity increases in the 1920's. The current analysis is a first step toward illuminating the roots of technological progress beyond the role of electricity. Through further examination of historical patent citations and complementary sources we hope to determine the contributions of other industries as well.

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