The Rate of Technological Improvement before and after the 1830s

Author(s): John H. Lienhard

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The Rate of Technological Improvement before and after the 1830s

JOHN H. LIENHARD

This paper aims to question how the rate of improvement of technology has changed in time. "Improvement" is, of course, a word that will require a lot of restriction before it will be useful. Yet other papers have dealt with concepts of technological improvement and have discussed how rapidly it occurs. What has not been dealt with critically is the way in which such growth rates have changed in the last century or so.

It is the aim of this paper to look quantitatively at a properly circumscribed concept of improvement. We shall find that until the 1830s such rates of technological change were nearly constant, but afterward the rate of improvement increased radically. This acceleration reflects the arrival of new capabilities and attitudes which we should try to understand.

The following restrictions and definitions will be used in the considerations that follow:

1. A technology will only be included in these considerations if it is sufficiently complex that it cannot be brought to completion in a few inventions.
2. *Improvement* must be identified for any technology. Several directions of improvement might be considered. A steam power plant might be improved with respect to total horsepower, power-to-weight ratio, or thermal effiency. We shall restrict consideration to improvements that are *limited* only by man's *ingenuity* and the evolution of supporting technology, and we shall restrict examples to improvements that can be specified quantitatively.
3. The measure of improvement that we choose to consider must be one which clearly reflects a direction in which technologists have been *motivated* to change devices. For example, there is no doubt that technologists have been motivated to improve the speed with which people can be mechanically transported from one place to another. On the other hand, it is doubtful that anyone has been very strongly

DR. LIENHARD is professor of mechanical engineering at the University of Kentucky.

motivated to increase—say—the number of people that can be transported in a single vehicle. Throughout this paper we consciously avoid the development of size for its own sake. Such things as capacity of turbines or height of buildings will be avoided. But the depth of wells or altitude records will be included, because the secondary motivation of finding more oil or learning more about the ionosphere is clearly strong.

4. A particular technology will be considered to have been *replaced* instead of improved when the new development redefines the character of the device. The introduction of electrical timekeeping elements in the mechanical clock constituted such a total replacement of a prior technology.

5. A technology will be considered *complete* when it can no longer be improved indefinitely by further inventions. The steam power plant is presently complete in this respect insofar as thermal efficiency is concerned. Its efficiency has, for a century, been primarily constrained by thermodynamical and materials limitations. It can never again be significantly improved by human ingenuity.

A Rule for Predicting Rates of Technological Improvement

We presume that technologists and/or the society of which they are a part share the same hopes and expectations for any particular device. In a generation, they will neither demand nor absorb a greater percentage improvement than they have come to associate with that device. We shall take a "generation" to be the technologist's years of full inventive productivity. This period typically runs from the mid or late twenties to the mid or late fifties—about thirty years.

How much improvement ought we expect in this characteristic time? Presumably the answer would be some sort of n-folding (i.e., multiplication by a factor of n). A simple doubling ($n = 2$) seems a tempting possibility. However, n probably depends on the expectations of the society in which the particular device emerges.

Designating the *quality* which is to be improved as Q, we obtain from the model above

$$\frac{Q}{Q} = n^{(t-t_o)}/30 = e^{(t-t_o)}\ln n/30 \qquad (1)$$

where Q_0 is the initial quality at time, t_0; and a working "lifetime" is taken to be thirty years. The quantity $30/\ln n$ is called the "time constant," T, for the growth of Q. It is time required to complete one e-folding of Q.

The idea of exponential growth of technology is not new. Various technological forecasters have suggested such a relation. Starr and

Rudman,[1] for example, speak of the "strength" (instead of the "quality") of a technology and suggest an equation similar to (1) for it. Their time constant depends on three factors. One is the potential payoff of the technology, another is the priority that society assigns to realizing improvement, and the third is the level of resources available for development. They do not quantify these influences, but they do show that the resulting time constant is, indeed, a constant.

Such influences certainly are reflected in the rate of n-folding and therefore in the time constant (as Starr and Rudman assert). But since these influences are hard to quantify, we shall turn our attention directly to the single interpretable parameter, n. Let us next see whether or not equation (1) fits existing data and, if it does, what values of n result.

Examples

Most of Starr and Rudman's examples are drawn from recent times. All examples for which they provide supporting data are drawn from the last century. Therefore we must first develop some new examples drawn generally from earlier history.

The Hydrocarbon-fueled Steam Power Plant

The *thermal efficiency* of stationary plants is defined as the ratio of useful work delivered to the heating value of fuel consumed. It is clearly a quantity that anyone who must pay for fuel will be strongly motivated to improve.

Table 1 includes thermal efficiencies of power plants, dating from Newcomen's engine to the present. The older sources, lacking a First Law of Thermodynamics to convert heating value to work, report the "duty" of engines in foot-pounds-force (ft-lb_f) per bushel of coal. Without knowing the exact heating value of English coals we shall use the figure 13,500 Btu/pounds-mass (lb_m). This is typical for high-grade coal and should be within 5 percent of the correct value. A "bushel" of coal is an imprecise measure of weight, but it is usually taken to be 84 lb_m. We shall note any deviations from this. In the 19th century, after Watt had standardized the horsepower-hour (hp-hr) at 1.98×10^6ft-lb_f, we find the performance given in terms of lb_m coal/hp-hr. Table 1 gives both the reported figure and the equivalent thermal efficiency.

The efficiency data are plotted as a function of time in figure 1. Equation (1) with the reference efficiency, Q_o, equal to 0.57 in 1742, is

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[1] C. Starr and R. Rudman, "Parameters of Technological Growth," *Science* 182 (1973): 358–64.

included. This prediction, based on a 2½-fold ($n = 2.5$) increase of efficiency every thirty years, fits the data as well as any line could. After about 1850 the data flatten away from the prediction since the basic invention has been "completed." Subsequent development of steam power is limited by materials and by the approach to the limit set by the Second Law of Thermodynamics.

The Mechanical Clock

Steam power provides about a 120-year record of evolution, or four working lifetimes, but the mechanical clock evolved over a period five times as long. Between the invention of the crude weight-driven foliot-and-verge mechanism is about 1335 and the best mechanical clocks in the 1920s, the error of clocks plummeted through almost six orders of magnitude.

TABLE 1

THERMAL EFFICIENCY OF HYDROCARBON-FUELED STATIONARY STEAM POWER PLANTS

Machine	Date	lb_m Coal/ hp-hr	ft-lb_f/ Bushel Coal	Thermal Efficiency(%)
Newcomen engine[a]	1718–67	...	5,590,000	.63
Newcomen-Smeaton engine[b]	1775	...	9,500,000	1.08
Watt's double-acting engine[c]	1784	8.4	...	2.24
Same, with cutoff[c]	1784	6.26	...	3.01
Watt's Truro engine[d]	1792	...	33,000,000	3.74
Hornblower engine[e]	1804	...	30,000,000	3.4
"Within Watt's lifetime"[d]	1819	...	~50,000,000	5.67
St. Anstell mine, cornwall[f]	1835	...	112,000,000	12.7
Taylor's engine[g]	1842	...	128,000,000	10.9
Alban's engine[h]	1843	1.325	...	14.23
3-expansion binary cycle[i]	1902	...	...	26.8
Parson's turbine[i]	1912	...	...	24.8
Modern evolution[j]	1915–60	...	...	See dashed line in fig. 1

[a] The first reliable measurements of performance that we have are those John Smeaton made on existing Newcomen engines in Newcastle in 1767. Presumably these were models made between 1718 and 1767 (see R. H. Thurston, *A History of the Growth of the Steam Engine*, 5th ed. [London, 1895], p. 7).

[b] One of Smeaton's first redesigned Newcomen engines (ibid., p. 69).

[c] A. P. Usher, *A History of Mechanical Inventions* (Cambridge, Mass., 1970), pp. 355–56.

[d] H. W. Dickinson, *James Watt, Craftsman and Engineer* (Fairfield, N.J., 1967), pp. 168–70.

[e] Thurston, p. 138.

[f] D. Lardner, *The Steam Engine Familiarly Explained and Illustrated*, 2d American ed. from 5th English ed., ed. E. L. Carey and A. Hart (Philadelphia, 1836), pp. 304–5. The figure is Lardner's compromise between two figures.

[g] H. W. Dickinson, *A Short History of the Steam Engine* (Cambridge, 1939), p. 101. The value given here is based on a 94 lb_m-bushel.

[h] Thurston, pp. 327–28.

[i] C. F. Hirshfeld and W. N. Barnard, *Elements of Heat Power Engineering*, 2d ed. (London, 1915), pp. 355 and 394b.

[j] B. G. A. Strotzki and W. A. Vopat, *Power Station Engineering and Economy* (New York, 1960), p. 248, figs. 12–19.

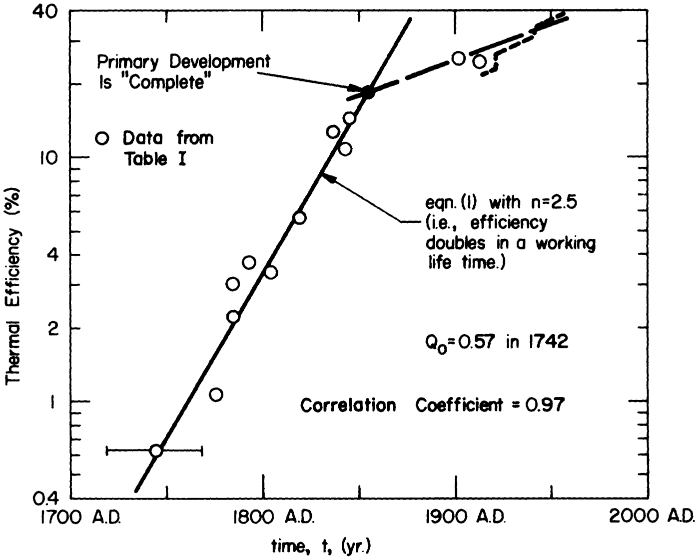

FIG. 1.—Increase of thermal efficiency with time for hydrocarbon-fueled stationary steam power plants. H. W. Dickinson, *A Short History of the Steam Engine* (Cambridge. 1939).

We shall take inverse error, or accuracy—the number of days a clock will run with only 1-second error—as the measure of quality that technologists have strived to improve. Values of "error" and "accuracy" during the clock's history are tabulated in table 2 and plotted in figure 2. Equation (1), based upon a doubling model, is again included in the figure. It is interesting to note that while the 18th-century preoccupation with clockwork results in some data that deviate upward, subsequent data relax back toward the line. The simple doubling model is quite good over the five- or six-century history.

Speed of Mechanical Transport of Humans

People have always been highly motivated to move about as rapidly as possible. Until the 18th century this meant approaching as closely as possible to the natural speed of horses or of the wind. During the 18th century there was an enormous motivation to apply the steam engine to transportation. The first 18th-century steam cars that were built did not improve upon the speed of a comfortable walk. Table 3 showing the speeds of mechanical transportation therefore begins with Murdoch's steam car (1784)[2] which moved between 6 and 8 miles per hour.

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[2] R. H. Thurston, *A History of the Growth of the Steam Engine,* 5th ed. (London, 1895), chap. 4

TABLE 2

ACCURACY OF MECHANICAL CLOCKS

Clock	Date	Error $\left(\frac{\text{Sec}}{\text{Day}}\right)$	Accuracy $\left(\frac{\text{Day}}{\text{Sec}}\right)$
Usher's speculation[a]	1335–1450	900–3,600	.00111–.00028
Britannica speculation[b]	1335–1450	1,800	.00056
Quote from Tycho Brahe[a]	ca. 1580	~30	~.0333
Usher's estimate for land-based deadbeat escapements[a]	1715	~.4	2.5
Harrison's prizewinning seagoing timepiece[a]	1759	.143	7.0
LeRoy's prizewinning seagoing timepieces[a]	1763	.826	1.21
		.158	6.34
Bradley's clock[a]	1758	.102	9.80
Greenwich Observatory[a]	1850	.149	6.7
Berlin Observatory[b]	1877	~.025	~40.0
Leyden Observatory[a]	1900	.028	35.7
U.S. Naval Observatory[a]	1904	.015	66.7

[a] A. P. Usher, *A History of Mechanical Inventions* (Cambridge, Mass., 1970), chaps. 8 and 12.
[b] *Encyclopaedia Britannica* (1970), 5:934.

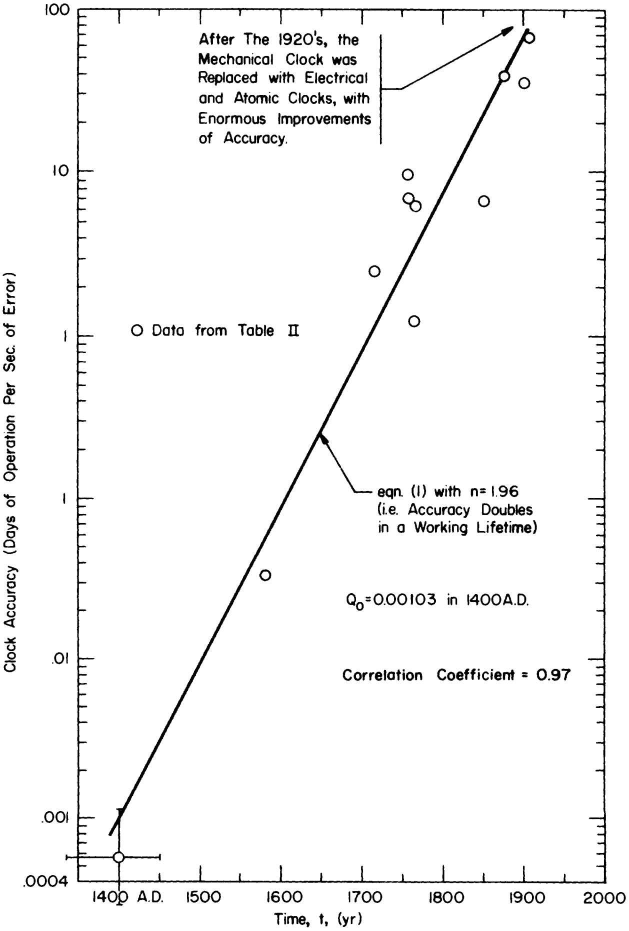

FIG. 2.—Increase of accuracy of mechanical clocks with time

TABLE 3

SPEED OF MECHANICAL TRANSPORT OF HUMANS

Class and Machine	Date	Speed (mph)
Steam car:		
Murdoch's car[a]	1784	6–8
Trevithick's car[b]	1803	17
Ogle and Summers[a]	1831	32–35
Stanley Steamer[a, c]	1906, 1907	127.7, 150+
Railroad:		
Trevithick's R.R.[a]	1808	20
The "Rocket"[a]	1829	29
The "Northumbrian"[a]	1830	36
Lucifer Engine[c]	1839	57
American type of locomotive[c]	1878	80–100
Empire State Express[c]	1893	112.5
Siemens und Halse Electric[c]	1903	130.6
(20th-century locomotives could no longer move as fast as other transport)		
Automobile:		
M. Campbell[c]	1935	301
C. Breedlove[d]	1965	614
Lighter-than-air flight:		
Eight airships[e]	1852–1908	See data in fig. 3
Heavier-than-air flight:		
Wright Brothers[f]	1905	39.5
British War Office trials[g]	1912	75
BE2C[h]	1914–15	80
Bristol fighter[h]	1916–17	115
Martinsyde F4[h]	1918–19	145
Spad XIII[g]	1917	134
Nieuport airplane[c]	1921	210.6
Curtiss R3C-2[h]	1925	232.6
Schneider Trophy[h]	1931	407
He176[c]	1939	525
ME 262[h]	1944	585
Bell X S 1[c]	1948	967
Lockheed YF-12A[d]	1965	2,070
Douglas-Skyrocket[c]	1951	1,241
Bell X-1A[c]	1953	1,612
Fixed-wing rocket[c]	1960–67	See data in fig. 3

[a] R. H. Thurston, *A History of the Growth of the Steam Engine,* 5th ed. (London, 1895), chap. 4.
[b] *Encyclopaedia Britannica* (1970), 2:866.
[c] N. and R. McWhirter, *Guinness Book of World Records* (New York, 1973).
[d] *Encyclopaedia Britannica* (1970), 21:56A,B.
[e] Ibid., 11th ed. (1911), 1:299.
[f] *Compton's Encyclopedia* (Chicago, 1968), 1:172.
[g] C. J. Biddle, *Fighting Airman* (New York, 1968), p. 271.
[h] *Encyclopedia Britannica,* 12th ed. (1922), new vol.: 22.

These data are plotted in figure 3, where it is immediately clear that flight is a replacement technology for land transport. Land transport approximately follows a simple doubling model ($n = 1.86$) for two centuries. The one-century history of flight begins with very sluggish, powered balloons in the late 19th century and increases 10-fold per working lifetime. Flight catches up with ground transport after World War I.

It is interesting that ground transport continued to follow the $n = 1.86$ pattern *after* it was displaced. Apparently the motivation to improve ground-transport speed has remained active in its own right—quite unaffected by air-speed records. Perhaps the ground-transport curve will continue to rise with such surface vehicles as vacuum-conduit transport capsules driven by linear motors. At the same time it seems unlikely that there remains much motivation to continue increasing air speeds. They have now reached such enormous values that problems of starting, stopping, and turning determine how fast a person can be taken from one place to another.

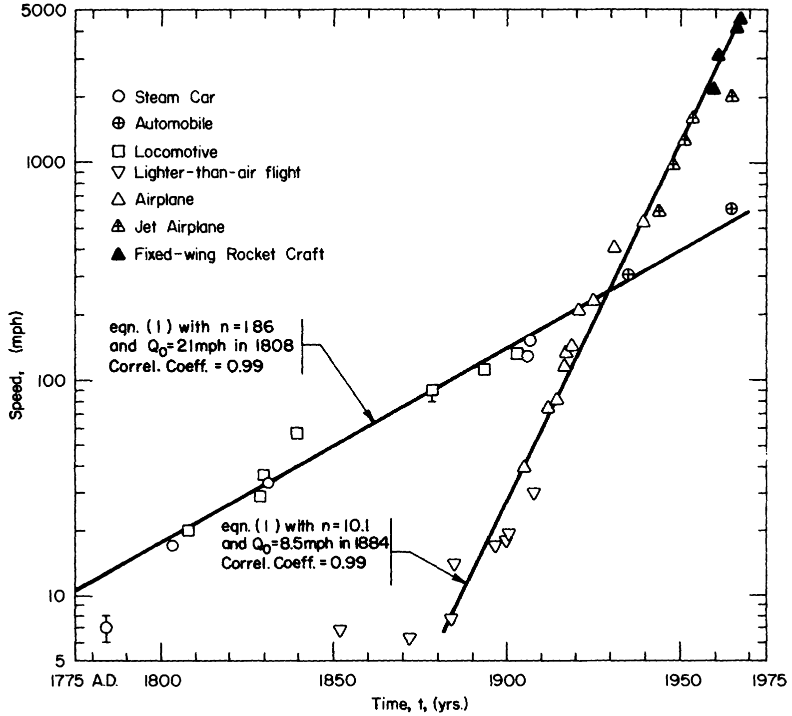

FIG. 3.—Increase of speed of transportation with time

TABLE 4

LOW TEMPERATURES ACHIEVED BETWEEN 1860 AND 1937

Development	Date	T°K	$(1/T - 1/298)$°K_{-1}
Carre's absorption system[a]	1860	233.2	.000932
Cailletet condensed air[b]	1877	82.	.00884
Cracow lab produced liquid O_2[b]	1883	77.4	.00956
Dewer produced liquid H_2[b]	1898	20.3	.0459
Ohnes produced liquid He[b]	1908	4.22	.234
Keesom's method[c]	1932	.7	1.425
Giaugue and McDougal, adiabatic demagnetization	1933	.287	3.48
deHaas, adiabatic damag.[b, c]	1933–37	.09–.0044	11.1–227

[a] R. C. Jordan and G. B. Priester, *Refrigeration and Air Conditioning*, 2d ed. (Englewood Cliffs, N.J., 1956), p. 6.
[b] R. Barron, *Cryogenic Systems* (New York, 1956), chap. 1.
[c] P. S. Epstein, *Textbook of Thermodynamics* (New York, 1971), p. 43.

Low Temperature Technology

Serious attempts to reach temperatures below the coldest natural thermal reservoir began in the late 18th century. However the first functioning refrigerators were developed in the middle 19th century. Table 4 begins with the earliest one whose low temperature can be documented. It progresses through three-quarters of a century until adiabatic demagnetization enters as a replacement technology.

The appropriate measure of quality of low temperature technology should probably be the inverse absolute temperature, or "temper" as it has been called.[3] This is a more fundamental measure of thermodynamic behavior, and it has the advantage of increasing without bound as the absolute temperature, T, goes to zero. Accordingly we choose the difference between the temper at the lowest achievable temperature, and its value at standard conditions, as the measure of quality: $Q_{\text{low temp. tech.}} = [1/T - 1/298]\ °K^{-1}$.

This measure is listed in table 4 and plotted against time in figure 4. It follows the n-folding model extremely well, but in this case n is 21.5! This rate of improvement is the highest one we have yet encountered, but it is small in comparison with those that occur in the 20th century.

The Guinness Book of World Records provides a wealth of data from which to build additional examples.[4] Four are included in figure 5. They are *the depth of drilled deep wells* between 1841 and 1972, which yields $n = 2.52$, *the maximum depth reached by a man in the ocean* from Bazin's diving sphere in 1845 to Piccard's bathyscaphe in 1960, which

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[3] C. L. Tien and J. H. Lienhard, *Statistical Thermodynamics* (New York, 1971), p. 43.
[4] N. and R. McWhirter, *Guinness Book of World Records* (New York, 1973).

yields $n = 3.46$, *the maximum height reached by liquid-fueled rockets*[5] from 1932 to 1957, which yields $n = 807$; and *the maximum height reached by man* between 1923 and 1957 when orbital vehicles constituted a replacement technology, which yields $n = 2.64$. The latter example lingered from 1783 to 1923 as an essentially physically limited technology. The balloon experiments of Rozier in Paris during 1783 yielded altitudes from 84 feet on October 15 to 9,000 feet on December 1. For the next century and a half not much more could be done. Higher altitude flight had to await the development of breathing equipment for fliers in the 20th century.

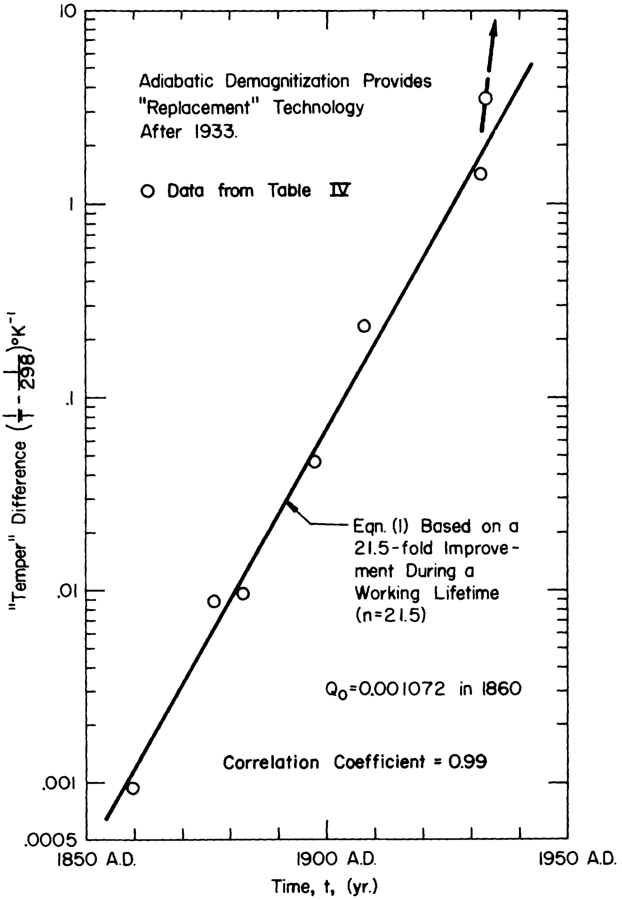

FIG. 4.—Improvement in coldness with time

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[5] The solid-fueled rocket goes back to antiquity, but the appearance of the liquid-fueled rocket represents the beginning of serious attempts to reach high altitude with rocketry.

Several examples (some of which would have been favorable to the present arguments) were not used although they appeared in Guinness. Several of them clearly were not strongly motivated technological improvements. These included the maximum span of bridges, the maximum height of buildings, and the maximum weight and/or length of ships. The maximum depth reached by divers wearing only breathing gear was also excluded, since the depth is restricted more by the frailty of the human body than by that of the human intellect.

Summary of n*-Folding Rates*

Starr and Rudman present several curves (similar to figs. 1 through 5) for modern devices. These are drawn from a variety of prior sources. Table 5 lists four values of *n* that we have scaled from their

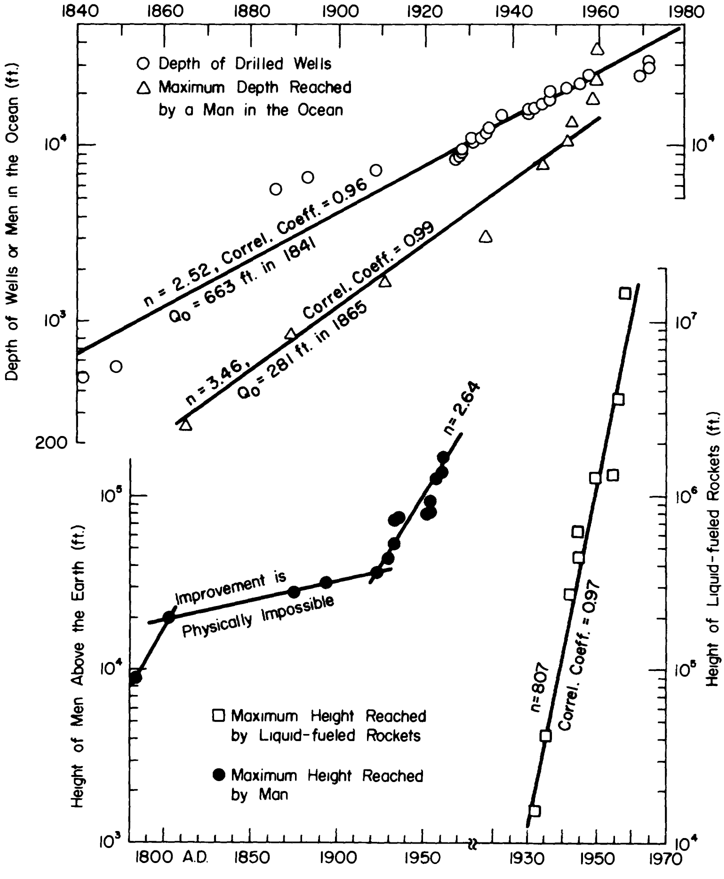

FIG. 5.—Four examples from the *Guinness Book of World Records*

TABLE 5

RATES OF n-FOLDING OF TECHNOLOGICAL IMPROVEMENT DURING MOTIVATED GROWTH

Technology	Quality	Inclusive Dates	n	Time Constant, T ($30/\ln n$) Yrs
Examples from the present study:				
Mechanical clock	Accuracy	1400–1920	1.95	45.1
Steam power	Thermal efficiency	1742–1850	2.5	32.6
Land transport	Speed	1803–1965	1.86	48.5
Low temperatures	Difference in temper	1860–1936	21.5	9.8
Air transport	Speed	1884–1967	10.1	13
Examples from the *Guinness Book of World Records:*				
Well drilling	Depth	1841–1962	2.52	32.5
Diving vehicles	Depth	1865–1960	3.46	24.2
Flight	Maximum height	1792–1961	2.64	31.0
Liquid-fueled rocket	Maximum height	1926–57	807	4.5
Examples from Starr and Rudman's paper:				
Incandescent light	Lumens per watt	1880–60	6.4	16.1
Radio	Broadcast frequency	1896–60	1.85×10^4	3.1
Particle accelerators	Particle energy	1930–60	10^5	2.6
Computers	Bits/add time	1945–70	10^{12}	1.1
Example from Noyes's paper:				
Printed circuits	No. of components per circuit	1959–76	2×10^9	1.4

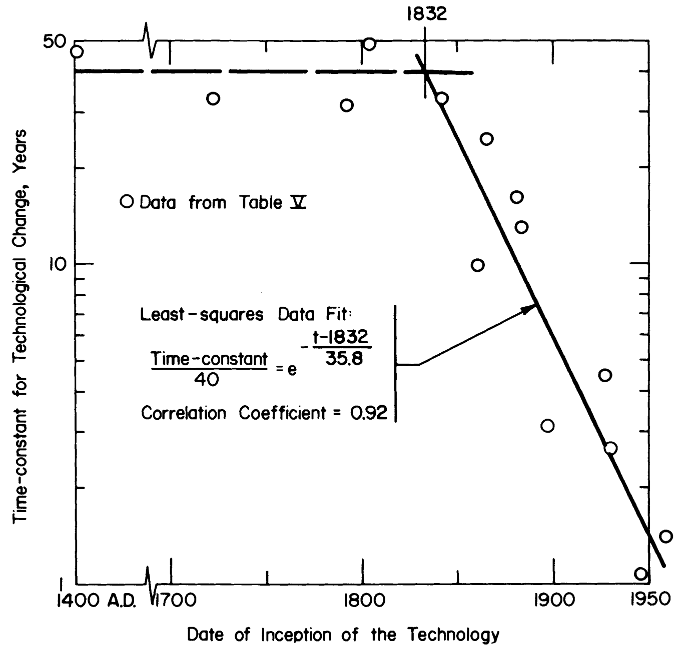

FIG. 6.—Historical variation of time constants for technological change

curves, along with the nine we have just developed. In addition to these four examples, Starr and Rudman also present curves for the magnitude of power generated by various power sources. We ignore these because we do not believe that there is real *motivation* to improve upon size for its own sake.

Finally, table 5 includes one more data point for the number of components per circuit in integrated circuits from a very recent paper by Noyes.[6]

A Radical Change in Technological Growth

Table 5 reveals that the rate of change of technological growth increased dramatically in the middle of the 19th century. The last column presents the time constant, T, for improvement of each technology, calculated from the observed values of n. These time constants are plotted against the appropriate date of inception of the technology in figure 6.

Figure 6 shows that the time constants remain at around forty years through the first third of the 19th century. Then the time constants

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[6] R. N. Noyes, "Microelectronics," *Scientific American* 237, no. 3 (1977): 63–69.

themselves begin to decrease exponentially. A least-squares data fit of the points representing technologies between 1830 and the present gives the line and the equation shown in figure 6. The correlation coefficient for that equation is .92, which is quite high. The equation tells us that, since 1832, the time constant which dictates the acceleration of technological improvement is only thirty-six years. That represents a remarkable acceleration of technological change. If the trend continues, devices invented today should "improve" by a factor of e every eight months; they should improve by a factor of 5 million every decade.

The fact that the history of technological time constants can be so accurately represented by an exponential equation suggests in turn that the basic behavior can be described by the differential equation

$$\frac{dT}{dt} = \begin{bmatrix} \text{O} & \text{before} & 1832 \\ -T/35 & \text{after} & 1832 \end{bmatrix} . \tag{2}$$

Thus the time constant did not change until 1832. Then it began to drop at a rate proportional to its own magnitude.

Equation (2) constitutes an explanation of the character of the 19th-century shift in technological growth. Suddenly technology began to breed more technology. Prior to the 1830s, society (the public and the technologists who served the public) demanded and provided improvement at a constant rate. But new technology began to respond to itself in a new way; it began to set the pace for itself. The faster technologists saw technology improving, the faster they would require the rate of improvement to increase.

The historian might well ask by what means an assertion of this importance is justified, because his standards of verification are typically quite different from those presumed here. The assertion is the direct consequence of quantitative analysis of data. The historian will typically want to reach such a conclusion by an entirely different road—from a study of correspondence among engineers, of the character of public writings, etc. Such investigations are surely needed because the precise human interactions underlying equation (2) should be understood. However equation (2) is an empirical fact developed from an enormous amount of data. It tells us unequivocally that technology has fed upon itself since the end of the first third of the 19th century but it did not do so earlier.

Clarification of the mechanism of the change is suggested by many historians. Cardwell typically discusses the evolution of Western technology in terms of "turning points,"[7] the last of which he places in the mid-19th century. This was the turning point between the phase of the industrial revolution and the phase which he identifies with the establishment of industrial research laboratories: "The conspicuous feature of the period" he observes "was the rapid convergence of science and technology considered as social institutions . . ." He goes on to note that "Whitehead . . . expressed the point very succinctly when he wrote: 'The greatest invention of the 19th century was the invention of the method of inventions. . . .' The phrase . . . refers . . . to the devising of institutions to ensure technological progress: the research laboratory, . . . the design/development department, the technical sales and services. . . . The main agents of this change have been the increasingly numerous classes of highly trained professional engineers and scientists. . . ."

This is precisely the kind of "self-consciousness" and attendant self-excited growth that equation (2) shows arising in the technology of the mid-19th century. Of course it also implies the increasing abundance of those resources that Starr and Rudman indicate should cause the time constant to shrink: potential payoff, priority, and resources for development.

A second empirical fact which we have heretofore taken for granted, but which the data show to be unwaveringly true, is that the rate of improvement of a particular technology, once established, does not change. The rate of increase of the speed of human ground transport started with $n = 1.86$ and $T = 48.5$ years at the turn of the 18th century, and it stayed the same after the 1830s right down to the present time. This is even borne out by balloon ascents despite their being "put-on-the shelf" for 120 years. The implication is that a kind of technological conservatism is established very quickly in any domain. Society will only claim (or perhaps only tolerate) a more rapid growth rate in new technologies—but never in established ones.

Conclusions

Within the limitations of the fourteen examples developed or reproduced here, we find the following. (1) Technologies *improve* in quality at an exponential rate until they are either *replaced* or *completed,* as long as they are both *motivated* and only *ingenuity-limited.* (The italicized terms are defined in the Introduction section.) (2) The time constant for improvement of such a technology does not change after

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[7] D. S. L. Cardwell, *Turning Points in Western Technology* (New York, 1972), chaps. 5 and 6.

motivated growth begins. (3) Before the mid-19th century technology was not *self-excited.* Technology roughly doubled in quality with each technologist's working lifetime. Afterward it was self-excited.[8] Therefore the time constants of growth of new technologies have decayed exponentially (with a secondary time constant of thirty-six years) since the 1830s.

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[8] During the review process, S. J. Kline presented data which support this conclusion in a less formal way ("Toward the Understanding of Technology in Society," *Mechanical Engineering* 99, no. 3 [1977]: 40–54). Kline sees the transition as occurring "before 1850" and identifies it as the "start of purposeful R and D" which is comparable with Whitehead's "invention of the method of the inventions."