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Productivity Growth and Machinery Investment: A Long-Run Look, 1870-1980

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Abstract

Over the past century in six major economies economic growth has been strongly associated with machinery investment, as is the case for a larger group of nations since 1950. The macroeconomic patterns and narratives of the history of technology both suggest that this association is causal—that a high rate of machinery investment appears a necessary prerequisite for rapid long-run growth—and points away from the possibilities that rapid growth is the cause of high machinery investment, or that a high rate of machinery investment is a good proxy for other factors that are important causes of growth.

JEL nos:

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INTRODUCTION

Machinery investment and productivity growth have been strongly associated over the past century in six industrial nations for which data are available: Canada, Germany, Italy, Japan, the United Kingdom, and the United States. A similar association holds since World War II for a broader sample of nations.[1] Narratives of individual nations' economic histories have frequently noted such an association.[2] Moreover, there are signs that a large part of this association is *causal:* high machinery investment appears to generate rapid growth.

This article begins by sketching some issues at stake in the debate over the role of machinery accumulation in growth. I then presents the data used, and raise some questions about their reliability before documenting the association of machinery investment and growth. Later sections address issues of causality—does high machinery investment cause fast growth, or does fast growth lead to high machinery investment?—and fit the macro patterns found here to the micro patterns found in the narratives written by historians of technology.

Economic historians have long stressed the role of mechanization in the multiplication of productivity over the past two centuries. The industrial nations are today more than eight times as wealthy as they were a century ago because they can and have poured resources into making the machines that embody the technologies of the Industrial Revolution. Factors supporting high machinery

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[1]See De Long and Summers, "Equipment Investment and Economic Growth."

[2]For example, Hayn, "Capital Formation and Argentina's Price Cost Structure"; and Díaz-Alejandro, *Essays on the Economic History of the Argentine Republic* argued that Argentina's extraordinarily poor performance since World War II was due to a low rate of machinery investment in machinery resulting from counterproductive policies. Hill, "Growth and Investment According to International Comparisons," found a strong bivariate association between machinery investment and growth between 1954 and 1962 in OECD countries. De Long and Summers, "Equipment Investment and Economic Growth," found a strong association between machinery investment and growth between 1950 and 1985 for a broad sample of nations, as did Jones, "Economic Growth and Producer Durables Prices."

investment are given a prominent role in historians' narratives and are in the foreground of the pictures drawn by Rostow, Gerschenkron, Rosenberg, Landes, Pollard, and many others.[3]

Development and growth economists have tended to take another direction. They have often concluded that the role of accumulation has been overstressed and other factors—such as widespread formal education, the exploitation of economies of scale, appropriate terms of trade, the overcoming of structural rigidities, and the repairing of market failures—are more central to growth and development.[4] Studies in the growth-accounting tradition of Solow have been interpreted as revealing that capital deepening is responsible for only a small part of productivity growth.[5] The general drift of this line of thought is that rapid machinery accumulation is neither sufficient nor necessary for economic growth: investing in formal education, overcoming bottlenecks, and removing inefficiencies in the use of resources are more strategic tolong-run growth than accumulating machinery.

This article reaffirms the Gerschenkronian and Rostovian view. The macro patterns it finds suggest that machinery investment is a very good candidate for the starring role of strategic factor in economic growth. Moreover, the macro pattern fits well with the micro narratives of technological historians. Rosenberg is only one of many who argue, on the basis of micro studies of innovation, that the construction, acquisition, and installation of machines is a key link in

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[3]See Rostow, *Stages of Economic Growth*; Gerschenkron, *Economic Backwardness in Historical Perspective*; Rosenberg, "Capital Goods, Technology, and Economic Growth"; Landes, *The Unbound Prometheus*; Pollard, *Peaceful Conquest*; and Blanqui, *Histoire de l'Economie Politique in Europe*.

[4]Rostow, *Theorists of Economic Growth* , surveys the development of theories of economic growth. Clark, *Conditions of Economic Progress* was among the first to argue that capital deepening was *not* responsible for the bulk of growth.

[5]For example, see Datta-Chadhuri's claim in "Market Failure and Government Failure" that "Solow ...demonstrated that only a small part of...growth...can be explained by...physical capital." Solow's "Technical Change and the Aggregate Production Function" is more restrained. See also Denison, *Why Growth Rates Differ*.

economic development.[6] I suggest here that the pictures of trees sketched by technological historians give a good view of the forest as well.

DATA

This study covers six nations—Canada, Germany, Italy, Japan, the United Kingdom, and the United States—over eight periods—1870 to 1885, 1885 to 1900, 1900 to 1913, 1913 to 1929, 1929 to 1938, 1938 to 1950, and 1950 to 1965, and 1965 to 1980.[7] The fifteen-year frequency of observation, with some dates offset to better match the cycle and the eras of war and peace, was chosen to reveal long-run shifts in growth rates instead of short-run cyclical fluctuations.[8]

The nations were chosen on the basis of data availability. Long-run national product estimates of the necessary quality are rare; these six countries had the best data. They make up a substantial part of the industrial world, accounting for roughly 60 percent of total world economic product today and perhaps 40 percent in 1870.[9]

In choosing among the different estimates of growth rates and investment shares, I stayed as close as possible to the estimates compiled by Maddison, whose database has had a substantial influence on conceptions of long-run

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[6]See Rosenberg, "Technological Change in the Machine Tool Industry."

[7]The data for Canada are relatively poor before 1929, and are not used. The German data used cover only West Germany after World War II.

[8]The 1913 to 1929 period ends on the eve of the Great Depression, thus containing all of World War I and subsequent business cycles leading up to the end of the 1920s boom. And the 1938 to 50 period ends when post-World War II reconstruction had been substantially completed.

[9]A seventh once-rich nation, Argentina, is of extraordinary interest as discussed in the text. Inclusion of Argentina would help to control for a potential sample selection problem—since all of the nations in the sample have done well, perhaps they are unrepresentative. But Argentina cannot be reliably included in the statistical analysis. If it were included, the coefficients estimated for the regressions would be very similar, but the standard errors of the coefficients would be much smaller.

growth in a comparative perspective.[10] Thus my estimates of output per capita were drawn from his *Phases of Capitalist Development*. Those estimates of relative past output levels were derived by extrapolating growth rates as given by nation-specific studies backward from a current benchmark. Growth was measured using different price vectors: for example, the prices in which Japanese growth from 1965 to 1980 was calculated were *not* the relative prices in which German growth from 1900 1913 was calculated. There is no good reason to believe that the different output growth rates reported by Maddison are fully consistent with each other.

The estimates of machinery investment were compiled from individual national sources.[11] The same potential inconsistencies are thus present in the

[10]Out of those cross-country estimates available, Maddison's database one of the most comprehensive and certainly the best documented. See Angus Maddison, *Phases of Capitalist Development*, and *Economic Growth in the Twentieth Century*. However, Maddison's estimates are not immune from challenge. See Jan de Vries, "The Decline and Rise of the Dutch Economy," for a convincing argument that Maddison's estimates of Dutch nineteenth century growth are substantially awry. J. Bradford De Long, "Productivity Growth, Convergence, and Welfare: Comment," makes some skeptical observations on some of the estimates in *Phases of Capitalist Development*, particularly for Japan and Scandinavia. Nevertheless, future challengers and revisors of Maddison must begin where his work leaves off—and his work has made that of potential revisionists much easier. For estimates of comparative living standards made via wage levels compared using contemporary purchasing power parity benchmarks, see Jeffrey Williamson, "The Evolution of Global Labor Markets." Williamson's estimates find sufficiently large discrepancies to be worrisome, but not large enough to fully invalidate Maddison's database. On the other hand, Mulhall's *Industries and Wealth of Nations* contains contemporary estimates of the industries and wealth of nations that have a correlation for the sample used here (excluding Japan) of 0.98 with Maddison's estimates.

[11]Sources of pre-World War II data on capital stock estimates and investment shares are as follows. For Canada, only official post-1929 data are available. A more detailed picture of earlier growth could be constructed by extrapolating from the individual years covered by Firestone, *Canada's Economic Development*, but the data will not bear the weight of such extrapolation. For Germany, the estimates used are Maddison's revisions in *Phases of Capitalist Development* of W.G. Hoffman et al.'s estimates in *Das Wachstum der deutschen Wirtschaft*. Before 1929, the underlying estimates of the German capital stock are "net concept" estimates. All other estimates used are "gross concept" estimates. Italian machinery and equipment data are derived from Fua, ed., *Lo Sviluppo Economico in Italia*, for the pre-World War II period, and from Summers and Heston, "The Penn World Table, Version V," thereafter. Japanese data are derived from Ohkawa, *Estimates of Long-Term Economic Statistics of Japan since 1868*, for the pre-World War II period, and from "Penn World Table V" for the post-World War II period. United Kingdom data are taken from Feinstein, *National Income, Expenditure, and Output in the United Kingdom*. For the United States, the estimates for the post-1929 period are the official Department of Commerce estimates; the estimates for the pre-1929 period are derived from Kuznets, *Capital in the American Economy*.

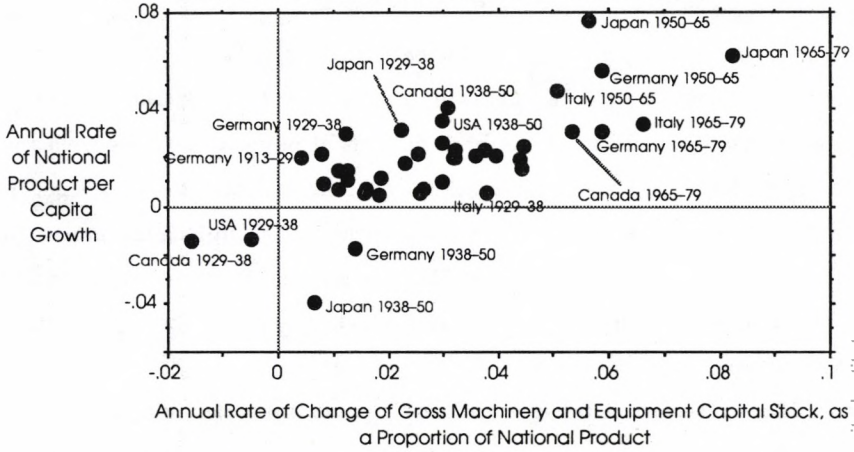
investment estimates as well. Prices used differ across countries and in some cases across periods. I gambled that such inconsistencies do not corrupt the conclusions, but my findings cannot be used to draw strong lessons about characteristics and patterns of growth in any one country relative to others in the sample. Statements about the deviations of national patterns from the average pattern found in the sample, derived from the data used in this paper, may well be misleading. But I hope that conclusions about long-run growth in the "typical" industrialized nation will be more secure: errors made in describing the quantitative shape of growth in individual nations to some degree cancel when averages are considered.

The investment estimates used in this paper are typically equal to gross investment less retirements. The result is larger than "net investment," which subtracts depreciation on existing capital, but it is smaller than "gross investment." The concept I use is appropriate for aggregate production functions: it measures the change in physical capital for use in production.

MACHINERY ACCUMULATION AND PRODUCTIVITY

Figure 1 plots machinery investment shares and output per capita growth. The association is strong, capturing more than half of the variance of output per capita growth. The machinery coefficient is large: each percentage point rise in machinery investment as a share of output is associated with an increase of more than 0.5 percent per year in output per capita growth.

Figure 1
Machinery Investment and Output per Capita Growth



The highest-growth, highest-investment points come after World War II. This "great Keynesian boom" saw more rapid growth than any previous era. Perhaps it was a structural break, and the association of machinery and growth in the sample as a whole reflects this break. But this is not the case: post-1950 growth has been no more rapid on the average than what would have been predicted from pre-1950 relations.[12]

[12]Little of rapid post-1950 growth in output or the pace of investment in machinery can be attributed to replacement of wartime losses. Only Japan and Germany were below their pre-World War II growth paths by 1950, and they were not far below. By 1965, all six of the countries were above not only their pre-World War II but also their pre-Great Depression growth paths. See Milward, *The Reconstruction of Western Europe*.

Table 1
GDP per Capita Growth Regressed on Machinery and non-Machinery Investment Rates

Specification	Machinery Investment	Non-Residential Construction Investment.	Extra Effect of Machinery: T-Statistic	Population Growth Rate	Output/Capita Level Relative to U.S.	R^2	SEE
Full	0.561	0.192	1.47	-0.481	-0.011	0.587	0.0139
	(0.157)	(0.117)		(0.504)	(0.009)		
Full	0.624	0.167	1.91	-0.543		0.572	0.0140
	(0.147)	(0.115)		(0.504)			
Full	0.599	0.127	2.10		-0.011	0.577	0.0139
	(0.151)	(0.094)			(0.009)		
Full	0.675	0.101	2.07	-0.373	-0.049	0.665	0.0135
Nation Dummies*	(0.169)	(0.129)		(0.609)	(0.021)		
Full	0.736	0.175	1.80	-0.741	-0.003	0.640	0.0144
Era Dummies**	(0.225)	(0.138)		(0.644)	(0.011)		
Full	1.227	0.046	3.35	-2.212	-0.031	0.758	0.0130
Nation & Era***	(0.266)	(0.140)		(0.907)	(0.026)		

*The U.S. alone has a significant nation dummy: +0.0208.
**None of the era dummies are significant.
***The 1965–79 era coefficient has a significant negative coefficient, the Canada and the U.S.A. nation coefficients are significant and positive.

Table 1 reports regressions of output per capita growth on investment in machinery and on additional variables: the level of output per capita relative to America (to take account of possible "convergence," as follower countries more quickly retrace the steps of leaders), the rate of population growth (to take account of the burdens of capital widening), the share of non-residential construction investment in national product (to control for the increase in productivity produced by other forms of investment besides equipment), and separate indicator variables for each nation and era.[13] Such nation and era

[13]"Random effects" estimation, assuming that each nation and each era has its own random effect that is in addition to the residual for individual observations, leads to coefficient estimates very similar to those with the nation and era indicator variables omitted. The regression

indicator variables partially control for a host of additional influences that are nation- and era-specific on the rate of economic growth.[14]

Table 1 also reports T-statistics on the difference between the coefficient on investment in machinery and the coefficient on investment in general. This reveals the significance of the partial correlation between growth and machinery investment that remains even controlling the correlation between growth and investment in general. Consider just the first regression, with the lowest such T-statistic: 1.47. An observer thinking the odds were even between machinery investment having a stronger or a weaker association with growth than other investment, but having no view about the magnitude of the differential would, if this regression in Table 1 came as completely new information, believe afterward that the odds were 14 to 1 that machinery had the stronger association.

The bottom left corner of the scatter in Figure 1 consists of points—such as in the United States from 1929 to 1938, or in Japan from 1938 to 1950—in which slow growth or decline in output per capita levels resulted principally not from low machinery investment but from the Great Depression, and devastation and defeat in war. However, adding additional variables to capture the effect of those historical episodes had little effect on the machinery investment coefficient. In results not shown, the addition of both Great Depression and war loss indicator variables reduced the machinery investment coefficient by only 0.07—half of a standard deviation.

The nation and era indicator variables included in the lower regressions of Table 1 rarely achieve statistical significance.[15] It is interesting that there are

estimates that the nation- and era-specific components of the residual are small.

[14]Still other additional variables were also included in results not shown. Direct measures of education are noted below. "Defeat in war" indicator variables did not have a noticeable effect on the machinery investment coefficient; neither did crude variables measuring the orientation of exports toward primary products as opposed to manufactures.

[15]Nation effects are measured relative to Germany. Era effects are measured relative to the initial 1870–85 period. The U.S. indicator is one of the few that is significant: the U.S. has grown over the past century about two percent per year faster than would be expected given its level of

not significant nation and era effects. They would proxy for important variables—like rates of education, impacts of economic policies, or the functioning of the international regime—with differential effects across nations and eras. There are surely important determinants of growth other than population growth, machinery and other forms of investment, and "catch-up." But such determinants appear to be neither persistent for any nation—not even Japan—nor pervasive in any one era—not even in the Great Depression.

Regressions with both nation and era indicator variables included produced very large coefficients on the machinery investment variable, as well as implausible estimates of the relationship between population and output per capita growth. Including both sets consumed much of the regression's identifying variance, producing coefficient estimates that were potentially untrustworthy. For this reason I relied more on the regressions without nation and era-specific indicator variables. Their omission might be justified by their small and statistically not significant estimated coefficients.

Political Stability

Political stability—an absence of coups, insurrections, and confiscations—and a high rate of investment in formal education are two factors featured prominently in studies of comparative determinants of growth in the post-World War II period.[16] It is conceivable that political stability is a key to growth, and

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per capita national product relative to the other industrial nations and its rate of equipment investment. When the level of output per capita relative to the U.S. is dropped from the independent variables, then the U.S. indicator variable loses its significance. The U.S. is an exception to the "convergence" toward average productivity levels for the set of industrial nations as a whole that is exhibited by other industrial economies. The U.S. has managed to maintain its productivity lead for an astonishingly long time. See Abramovitz, "Catching Up, Forging Ahead, and Falling Behind," and Baumol, Blackman, and Wolff, *Productivity and American Leadership*. The positive U.S. indicator reveals not that the U.S. has grown faster than expected given its rate of machinery investment, but that it has grown faster than expected given its relative wealth.

[16]See Barro, "Economic Growth in a Cross Section of Nations."

that the strong association of machinery investment and growth comes about because a high rate of machinery investment is a result of political stability. It is also conceivable that a high rate of investment in formal education is a key to growth, and that a high rate of machinery investment is a good indicator that other forms of investment are high. The sample contained little evidence to support either possibility, however.

The first regressions of table 2 report coefficients estimated when a political stability dummy variable is added to the basic specification reported in table 1. Political stability comes close to having a statistically significant effect: in the specification used in the first line of Table 2, a country without unconstitutional changes of government over an era sees GDP per capita grow faster by one percentage point per year. Of course, it is not clear to what degree this relation is cause and to what degree it is effect. Stagnant living standards can be the result of political instability, or they prepare the ground for coups: but for the Great Depression, it is unlikely that the Nazis would have come to power in Germany.

However, including a political stability indicator variable in the regressions does not materially affect the coefficient on machinery investment. No substantial part of the association between machinery investment and economic growth arises because political instability both causes slow productivity growth and induces economic dislocation.

Table 2
Additional Variables—Political Stability and Investment in Education

Additional Variable	Machinery Investment	Construction Investment.	Population Growth Rate	Output/Cap Level Relative to U.S.	Coefficient on the Additional Variable	R^2	SEE
Political Stability	0.510	0.173	-0.447	-0.016	0.010	0.611	0.0137
	(0.158)	(0.116)	(0.497)	(0.009)	(0.006)		
Political Stability	0.612	0.147	-0.539		0.006	0.582	0.0140
	(0.148)	(0.117)	(0.505)		(0.006)		
Log Secondary Sch	0.552	0.208	-0.460	-0.011	0.002	0.609	0.0146
Education Rate*	(0.167)	(0.125)	(0.533)	(0.012)	(0.003)		
Log Secondary Sch	0.594	0.184	-0.527		0.003	0.597	0.0146
Education Rate*	(0.162)	(0.122)	(0.529)		(0.002)		
Log Primary Sch	0.587	0.182	-0.475	-0.010	0.001	0.598	0.0143
Education Rate*	(0.181)	(0.127)	(0.540)	(0.010)	(0.008)		
Log Primary Sch	0.666	0.148	-0.569		0.004	0.585	0.0143
Education Rate*	(0.165)	(0.123)	(0.533)		(0.008)		

*Independent variable is the residual from a regression on the log level of GDP/capita.

Investment in Education

In the post-World War II cross-section of nations, a country's secondary school enrollment rate—the proportion of its total population enrolled in secondary school—is one of the aggregate education investment indicators most strongly associated with economic growth.[17] The lower rows of Table 2 report coefficients estimated by adding the log of primary and secondary school enrollment rates to the list of independent variables. Because education rates have an upward secular trend as incomes increase, the independent variable

[17]See Mankiw, Romer, and Weil, "A Contribution to the Empirics of Economic Growth."

used is the residual from a regression of log enrollment rates on log GDP per capita.

The primary school enrollment variable is not associated with growth. The sample of nations is a bad one from the perspective of identifying the effects of primary school enrollment. Near-universal primary education was established in most of the nations of the sample by the interwar period, so there is relatively little identifying variance.

Secondary school education is only weakly associated with growth once machinery investment share is included in the regression: a doubling of the secondary school enrollment rate is associated with an increase in GDP per capita growth of only 0.3 percent per year.

Moreover, once again adding an independent variable has no noticeable impact on the estimated machinery investment share coefficient. There is no sign that the strong association between machinery investment and growth arises because machinery investment is a good indicator that other kinds of investment, like investment in classroom-educated people, are high as well.[18]

Thus, adding direct measures of education rates does not reduce the magnitude or significance of the coefficient on machinery investment. This may be entirely due to the inadequacy of official measurements of education rates as proxies for the stock of human capital produced by formal education. It is far from proof that the formal education received in classrooms is necessarily less important for productivity growth than the informal hands-on education gained by using the capital goods of the industrial revolution. But it does suggest such a possibility.

[18]Experimentation with other specifications, including the fraction of the school-age population in school, did not lead to significantly different results.

CAUSALITY

Few would argue that machinery investment is not to a degree dependent on output growth. Any influence generating faster growth will raise future profits. If firms anticipate such an increase they will invest in machinery to capture those future profits. Whether causation runs from machinery investment to growth or from growth to machinery investment is impossible to say with complete confidence. Nevertheless, three pieces of evidence suggest that a substantial share of causation runs from higher machinery investment to faster growth, not the reverse.

The first piece exploits the distinction between output growth and output per capita growth. If faster growth leads to higher investment because of the expectation of profits, investment might well respond equally to increases in output generated by productivity and to those generated by population. It should not matter much whether larger demand comes from having more consumers or richer consumers.[19]

Table 3
Machinery Investment Regressed on Output per Capita Growth and Population Growth

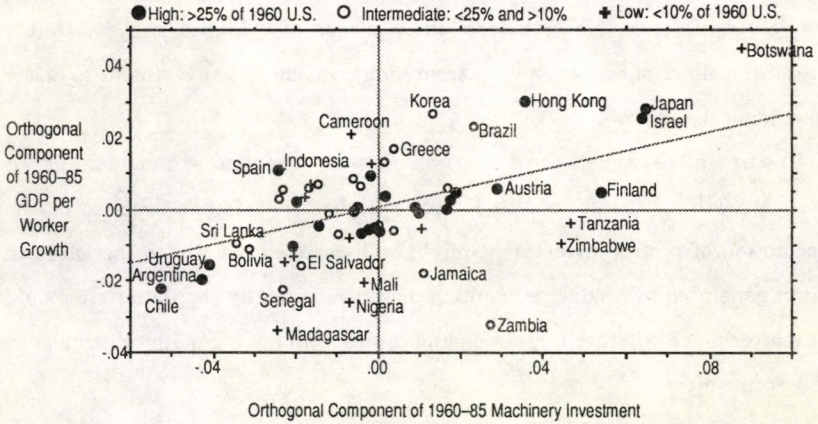
Dependent Variable	Output per Capita Growth	Population Growth	Non-Residential Construction investment	R^2	SEE
Machinery Investment	0.710	0.319		0.556	0.0137
	(0.104)	(0.383)			
Machinery Investment	0.513	-0.459	0.265	0.627	0.0127
	(0.121)	(0.458)	(0.098)		

Table 3 regresses machinery investment rates on output per capita and

[19]This insight is due to Barry Bosworth, who suggested it to Lawrence Summers. De Long and Summers have used it to try to identify causality between machinery investment and growth in the post-World War II period.

population growth rates. It shows a strong association between output per capita growth and machinery investment and a weaker and imprecisely estimated association between population growth (holding output per capita constant) and machinery investment. *Intensive* growth that raises productivity and income levels is especially strongly associated with machinery investment.

Figure 2
Post-World War II Growth and Machinery Investment Shares of Output



A second piece of evidence is the recent, post-World War II experience assessed by De Long and Summers, and by Jones.[20] Today carries information about yesterday: the evidence of the present allows us to "write history backwards" if we believe that structural relationships change slowly.[21] The relationship between machinery investment and growth in the post-World War II period is as strong as the relationship in the longer-run sample considered here, as Figure 2 shows. And there is a strong case to be made that the post-

[20]"Equipment Investment and Economic Growth," and Jones, "Economic Growth and Producer Durables Prices." See also Dowrick and Nguyen, "OECD Comparative Catchup and Convergence."

[21]See Kelley and Williamson, "Writing History Backwards: Meiji Japan Revisited."

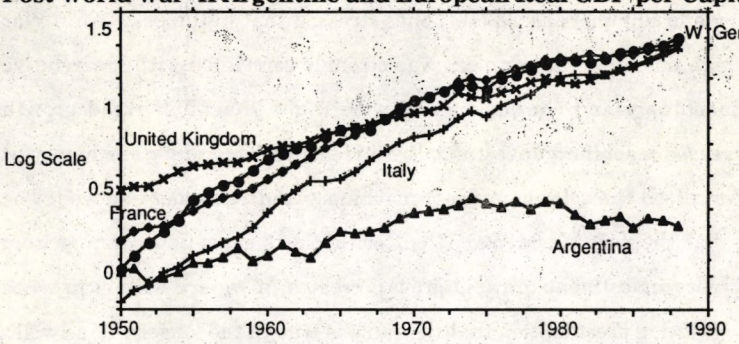
World War II association between machinery investment and growth is causal.

De Long and Summers as well as Jones stressed that in the post-World War II period, high machinery investment was strongly correlated with low relative prices of machinery and equipment and with rapid growth. If rapid growth caused increased machinery investment by increasing demand for machinery, it should have raised the relative price of machinery and equipment as well. The likelihood that the post-World War II pattern reflects causation running from high machinery investment to rapid growth creates, if we are willing to write history backward, a presumption that the same is true in the longer run as well.

National Experiences

The third piece of evidence comes from narrative histories of policy and growth in individual nations. Of these histories, perhaps the most powerful and disturbing is the case of Argentina. Argentinean long-run national income accounts are not sufficiently reliable to include it in the database for the regressions underlying Table I. Neverthless, it is worth considering. Up to the late 1950s it was as rich as continental Europe, and had grown rapidly since large-scale settlement began in the mid-nineteenth century. In 1929 Argentina was perhaps fifth in the world in terms of automobiles per capita. In 1913 Buenos Aires was in the top 20 among cities of the world in terms of telephones per capita. Yet today Argentina is a Third-World nation. Figure 3 plots the relative erosion of Argentinean ouput per capita from levels comparable to Europe's at the end of World War II.

Figure 3
Post-World War II Argentine and European Real GDP per Capita Levels



Carlos Díaz-Alejandro's *Essays on the Economic History of the Argentine Republic* provides a powerful—albeit controversial—analysis of Argentina's relative decline.[22] The Depression had left Argentina justly suspicious of the free-trade order: its trading partners had shut it out of markets to preserve domestic employment. Political cleavages had deepened as landowner and exporter elites showed an eagerness to abandon democracy to stunt the welfare state. In this environment Juan Perón gained support for a program of national assertion and populist redistribution.

Perón sought rapid economic growth and the redistribution of wealth to urban workers who had not received their fair share. His program of stimulation, price controls, and wage raises produced almost half a decade of growth, but then agricultural production and exports fell as the disincentives implicit in his program made themselves felt.

The resulting foreign exchange shortage gave Perón only unattractive options: devaluation and borrowing from abroad, thus betraying his nationalist commitments; internal austerity, causing unemployment and reversing his

[22]A somewhat different interpretation, dating Argentinean decline from the World War I-era cutoff of large-scale British capital investment, is provided by Taylor, "External Dependence, Demographic Burdens, and Argentine Economic Decline After the *Belle Époche*."

redistributions; or controls on imports to balance foreign payments by rationing imported goods. Perón chose this third alternative, believing that growth, a continuation of redistribution, and a reduction in dependence on the world economy was good. According to Díaz-Alejandro first priority for foreign exchange went to raw materials to keep factories operating, second priority to consumption goods to keep workers' living standards high, and last priority to imports of capital goods for investment.

As a result, the early 1950s saw Argentina's relative prices of producer durables rise to more than twice world levels. Each percentage point of output saved and committed to the purchase of machinery produced less than one-half a percentage point's worth of real machinery investment. Even though the 1945 to 1955 government had boasted of its role in encouraging industrialization, Díaz Alejandro calculated that "[r]emarkably, the capital stock in electricity and communications increased by a larger percentage during the depression years 1929-39 than during 1945-55."

Subsequent governments moderated but did not roll back Perónist policies. The interest groups that benefitted from them had loud voices, and shaky governments shrank from policy moves that would redistribute wealth away from urban workers back out to the countryside. In spite of a healthy national savings rate, Argentinean rates of machinery investment have been low since World War II. And the economy has stagnated.

The case of post-World War II Argentina finds its opposite in post-World War II West Germany. Post-World War II Argentina was thought to have a bright economic future. Post-World War II West Germany was seen as likely to require a generation to regain its previous relative economic position. Yet as Figure 3 also shows, between 1950 and 1960 West German national product per capita gained 35 percent relative to France and 45 percent relative to Britain, leaving it in 1960 with a productivity level halfway between the two.

During this decade of the *Wirtschaftswunder,* real returns on the German stock market averaged 24 percent per year. Such high rates of stock price growth indicate that Germany's growth leap of the 1950s was a surprise: had investors foreseen rapid economic growth, they would have bid stock prices up to higher levels in the early 1950s in anticipation. Belief in rapid growth of the magnitude seen in the *Wirtschaftswunder* was the exception, not the rule, in post-World War II Germany. Thus it is not possible to claim that high machinery investment in Germany between 1950 and 1965 was induced by a high demand for machinery by firms anticipating rapid economic growth: by and large Germans—at least Germans investing in the stock market—did not anticipate the bright future that in fact lay ahead. If Germany's high machinery investment in the early post-World War II period is related to its growth miracle, it is as cause, not as consequence.

TECHNOLOGY AND PRODUCTIVITY

The macro pattern sketched above is of a strong association between machinery investment and economic growth, an association that some evidence suggests reflects a strong causal chain running from the former to the latter. This macro pattern is consistent with a picture of the micro structure of innovation that historians of technology have been drawing for generations.[23] As Nathan Rosenberg puts it, "...inventions are relatively crude and inefficient [at first]....They are, of necessity, badly adapted to many of the[ir] ultimate uses...they offer only small advantages, or perhaps none at all." Rosenberg concludes that "the pace at which... improvements are made will be a major determinant of the rate of diffusion....[I]mproving a process contributes even

[23]Rosenberg, "The Historiography of Technical Progress," excellently surveys work on the history of technology. Rosenberg's survey was written before, and thus omits, Hounshell's superb *From the American System to Mass Production.*

more to technological progress than does its initial development."[24]

Consider three classic and exemplary studies. First, Fishlow's study of American railroad productivity found that over the forty years from 1870 to 1910 the lion's share of cost reduction was contributed by incremental changes in the design of freight cars and locomotives; one by one, these changes were small and barely noticed, but over 40 years they doubled the effective power of locomotives and to a tripling of the effective capacity of freight cars.[25]

Second, a similar pattern holds in the past two decades in the computerized tomography industry: initial invention had relatively small benefits, but the subsequent explosion of innovation and adaptation changed a curiosity into a very valuable diagnostic device. The wave of small innovations—themselves separate from, though unthinkable without the initial invention—contributed most of the value of the innovation.[26]

Third, recall Hunter's famous study of the development of the steamboat. Both the engine and the principles of ship design were borrowings from Britain, yet the developed American steamboat had a different kind of engine, a different strength of frame, a different shape of hull, a different form of superstructure—no feature of the original British design was kept without major modification.[27]

Case studies cannot prove a general pattern. Nevertheless, it is worth noting that historians who have examined the process of technological development have for the most part stressed the process of feedback and incremental improvements in operation and design. A similar stress on incremental improvements can be found in studies of technology adaptation by countries not

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[24]Rosenberg, *Perspectives on Technology* .

[25]Fishlow, "Productivity and Technological Change in the Railroad Sector."

[26]See Trajtenberg, *Economic Analysis of Product Innovation.* Similar patterns can be found even in technologies that appear at first glance stable, as Rosenberg's *Perspectives on Technology* stresses.

[27]Hunter, *Steamboats on the Western Rivers.*

at the forefront of invention and innovation. How are such incremental improvements made? Clearly they can only be made by those who are already very familiar with the technology and its uses. Without workers and managers with hands-on experience, the process of technology transfer and technological adaptation becomes impossibly difficult. Feedback from users and small adaptations of machines and organizations lies at the heart of the stories of productivity growth narrated by technological historians. Such a pattern strongly suggests that rapid productivity growth requires intimate experience with—and abundant accumulation of—the machinery in which the technologies that need to be adapted are embodied.

Thus the macro association of machinery investment and growth and the micro studies in the history of technology may be pieces of the same puzzle. On the macro side, rapid machinery accumulation is associated with rapid productivity growth and appears to yield large social benefits to the economy in terms of higher productivity. Benefits of the magnitude suggested by the machinery investment coefficients in Table 1—fifty percent per year or more—dwarf the profits that the investors in the capital goods are able to directly appropriate. On the micro side, active experience with technologies is a necessary prerequisite to developing them further, or to using them productively.

CONCLUSION

The association between machinery investment and growth in this sample is very strong. The estimated coefficients suggest that each additional percentage point of total output devoted to investment in machinery raises output per worker growth by more than half a percentage point per year. This might be taken to imply a gross social rate of return on equipment investment of more than fifty percent per year—or a net social payback period of three years or less,

even allowing for the rapid depreciation of machinery. Investors' profits earned from the purchase and use of machinery are an order of magnitude lower than these possible social returns.

This high estimate may be too high, however. The nations in the sample are, today, wealthy and successfully industrialized economies. Circumstances have broken in their favor over the past century. The high coefficient may to some degree be capturing the good luck that these economies in the sample have had; a different sample might well have led to different conclusions.[28]

One obvious addition to the sample that would have done so is the Soviet Union: since Stalin took absolute power at the end of the 1920's, the Soviet Union's five-year plans called for extraordinarily heavy rates of investment in machinery. Yet the Soviet Union achieved very poor productivity growth rates by the standards of the industrial West. The inefficiency of the Soviet economy in translating inputs into outputs is one of the most fascinating and heartbreaking stories of twentieth-century economic history. Yet its experience serves as a warning to governments seeking to industrialize and accelerate growth: the type of machinery investment that leads to rapid growth appears to be the type generated by private firms and market allocation processes, not by central planners.

Nevertheless, the experience of the past century is that those countries that have grown most rapidly have been those that have invested very heavily in machinery. There is a case that their rapid growth is in large part due to this investment: it enabled their workers and firms to gain experience with and thus to master the technologies of the Industrial Revolution embodied in machinery. This is a vision of the process of economic growth is familiar to economic historians. The fit between their micro narratives and the macro patterns should

[28]The strong post-World War II association of machinery and growth suggests that more than "good luck" is at work. However, in the post-World War II cross-section the association between machinery investment and growth is stronger for the richer than for the poorer nations.

lead them to place more confidence in their narratives of machinery investment and innovation—and to be more confident that they have much to teach other economists about long-run growth.

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