# Transition Dynamics in Vintage Capital Models: Explaining the Postwar Catch-Up of Germany and Japan*

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**Abstract**

We consider a neoclassical interpretation of Germany and Japan's rapid postwar growth that relies on a catch-up mechanism through capital accumulation where technology is embodied in new capital goods. Using a putty-clay model of production and investment, we are able to capture many of the key empirical properties of Germany and Japan's postwar transitions, including persistently high but declining rates of labor and total-factor productivity growth, a U-shaped response of the capital-output ratio, rising rates of investment and employment, and moderate rates of return to capital.

Keywords: putty-clay, embodied technology, productivity growth, convergence

JEL Classification: D24, E22, N10, O41

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# 1 Introduction

Per capita GDP increased by over 5 percent per year in Germany in the 1950s and 1960s and over 8 percent per year in Japan; the corresponding figure for the United States was 2 percent. What accounts for the remarkable performance of these "economic miracles"? A variety of explanations have been put forward, many of which emphasize the roles played by cultural, institutional, and political factors. Another strain of the literature, which we pursue in this paper, has emphasized the more prosaic processes of capital accumulation and technological change as driving forces for the rapid postwar growth of the German and Japanese economies.[1] Outside of growth-accounting exercises, however, there has been little quantitative research evaluating this explanation in light of the empirical evidence.

One hypothesis that has been subjected to scrutiny and been founded wanting is that the postwar growth experiences of Germany and Japan are consistent with the predictions of a simple optimizing growth model where the initial capital stock is well below its steady-state level. In his study of Japanese saving behavior, Hayashi (1989) documents the U-shape of the time series of the wealth-to-income ratio in postwar Japan and argues that it is inconsistent with the simple capital accumulation hypothesis. Christiano (1989) further argues that one can explain neither the delayed response of Japanese saving and growth rates nor the long duration of the catch-up process without substantial modifications to the baseline growth model. Finally, King and Rebelo (1993) note that if capital accumulation is an important contributor to Germany and Japan's postwar growth, a standard growth model implies either extremely high real interest rates or extraordinarily high values of installed capital in the early stages of development; neither prediction appears to hold true in either country.

The rates of investment, unemployment, and productivity growth in postwar Germany and Japan also are at odds with the predictions of a standard optimizing growth model with a low initial capital stock. According to such a model, the investment share of GDP should initially soar and then decline monotonically as capital deepening takes place. In Germany and Japan, however, investment rates started low and then rose. The standard optimizing model also implies that the effects of low labor productivity and a high return to capital will have offsetting

[1] See, for example, Maddison (1964), Ohkawa and Rosovsky (1968), Denison and Chung (1976), and Hulten (1991).

influences on employment during the early stage of development, with the result that employment remains near its steady-state level during the transition. In fact, the West German unemployment rate exceeded 10 percent in 1950, before gradually falling to below 2 percent by 1960. The situation was similar in Japan, where a significant degree of underemployment – manifested by relatively high employment in traditional agricultural and craft sectors – persisted through the 1950s (Denison and Chung (1976)). Finally, an explanation based solely on an initial shortfall of capital predicts that labor productivity growth occurs simultaneously with growth in the capital-labor ratio. This contradicts the empirical finding that the peak in labor productivity growth preceded that in capital deepening in both countries.

A second, more promising, hypothesis is that Germany and Japan's postwar transitions reflected the closing of a gap in technology between these countries and the United States. Total factor productivity (TFP) in German manufacturing was about half that in the United States in 1950, and manufacturing TFP in Japan was only a third the U.S. level in 1955 (van Ark and Pilat (1993)). This gap narrowed considerably over the next three decades: By 1980, TFP in German manufacturing had risen to 80 percent of the U.S. level and in Japan it had reached 60 percent of the U.S. level. Christensen, Cummings and Jorgenson (1981) find similar results using TFP measured on the basis of the entire economy. We argue that a significant portion of the initial technology gap resulted from the use of prewar and wartime industrial machinery and production processes far less efficient than modern technologies available in the United States. In our view, German and Japanese postwar investment in capital goods embodying modern production technologies gradually closed this "machine gap."[2] A natural outcome of this process of capital accumulation with embodied technology is a gradual diffusion of productivity gains over time.

We argue that the observed patterns of investment, employment, and productivity growth in Germany and Japan in the 1950s and 1960s are consistent with a growth model based on a putty-clay production technology and capital accumulation with embodied technological change. The process of technological catch-up was slowed by the putty-clay nature of capital. The relative fixity of existing

[2]An alternative explanation for this transformation is that an "idea gap" that was not embodied in the capital stock existed at the end of the war, and that this gap eroded over time. For example, Parente and Prescott (1994) and Eaton and Kortum (1997) argue that the postwar pattern of initially high, then falling, TFP growth results from the gradual diffusion of technological and organizational knowledge from the United States to Germany and Japan.

capital-labor ratios intrinsic to putty-clay capital implies that it is costly to rapidly increase employment and production. As a result, capital accumulation initially occurs through a process of "capital widening" that expands employment and productive capacity with relatively low rates of investment. During this phase of the transition, productivity growth is high, owing to the effects of embodied technology, but the rate of capital accumulation is relatively low, and, as a result, the capital-output ratio falls. Over time, the economy builds sufficient capacity to engage in standard capital deepening. During this latter phase of the transition, productivity growth slows while the rate of capital accumulation rises.

The remainder of the paper is organized as follows. Section 2 provides a discussion of the German and Japanese economic performance in the three decades following the Second World War. Section 3 presents a dynamic general equilibrium model that incorporates putty-clay capital and embodied technology. In section 4 the transition dynamics of the model are analyzed and compared to the empirical evidence documented in section 2. Section 5 concludes.

# 2 Germany and Japan's Postwar Growth Experiences

Germany and Japan's postwar growth experiences can be divided into three distinct periods: an initial phase of immediate postwar reconstruction; an early stage of technological catch-up marked by rapid increases in productivity and relatively low rates of capital accumulation; and a later phase of technological catch-up marked by declining rates of productivity growth and high rates of capital accumulation.

## 2.1 Stages of Growth

In the immediate postwar period of reconstruction, the economies of Germany and Japan experienced rapid growth as they recovered from wartime conditions, damage and destruction to the capital stock and infrastructure, and the influx of millions of refugees. Although estimates of overall war-related capital destruction are inherently imprecise and mask the unequal distribution across sectors – for example, German heavy industry was particularly hard hit and Japan's shipping fleet was devastated – a reasonable estimate is that about 20 to 25 percent of Germany's and Japan's capital stocks were destroyed or dismantled (Wolf (1993), Denison and Chung (1976)). In addition to capital destruction, both Germany and Japan experienced large population inflows owing to wartime displacement and postwar repatriation. From 1945 to 1953, about 10 million people migrated into West Germany; this represented a 25 percent increase in its 1945 population (Wolf (1993)). Some 8 million people repatriated to Japan, adding about 10 percent to the population (Denison and Chung (1976)). Combining the effects of capital destruction and immigration in the immediate postwar period, and taking into account investment during this period, the capital shortfall in each country was probably on the order of 20 percent as of the early 1950s.

The period of immediate postwar reconstruction ended around 1950 in West Germany, and a few years later in Japan.[3] Because this phase of immediate postwar reconstruction is so unusual and owing to the limited quality of available data, we exclude this period from the analysis in this paper. Instead, we limit ourselves to the two decades that follow, when both the German and Japanese economies had largely recovered from the immediate effects of wartime disruption and dislocation, but nonetheless experienced tremendous growth.

In the early stage of the process of technological catch-up, aggregate TFP growth in Germany and Japan was very rapid, while capital-output ratios actually fell. Table 1 shows the growth rates of economywide TFP and the those of the capital-labor and capital-output ratios over three periods for Germany, Japan, and the United States.[4] For the present purposes, we define the early stage of catch-up as taking place in the 1950s. Although the capital-labor ratio grew moderately during the 1950s in both Germany and Japan, with TFP growing at nearly 5 percent per year, the pace of output growth exceeded that of the capital stock. In contrast, over the same period, TFP growth in the United States was the same as in the following decade and the capital-output ratio was close to flat.

In the later stage of catch-up – occurring during the 1960s and 1970s – the earlier patterns of TFP growth and capital accumulation are reversed. TFP growth slowed in Germany and Japan during this stage, while the pace of capital accumulation

[3]In the case of Germany, fundamental economic and monetary reform was instituted in 1948, and the Federal Republic of Germany was established in 1949. By 1950 industrial production in Germany had reached its prewar peak and the process of repair and reconstruction of the damaged capital and infrastructure was mostly complete. This initial phase took somewhat longer in Japan, but was largely completed around 1953: Economic and monetary reform was initiated in 1949, and Japan regained its independence in 1952. Japanese industrial production reattained its prewar peak in 1954. In addition to the sources listed in the first footnote of this paper, references on the immediate postwar periods of Germany and Japan include Wallich (1955), Cohen (1958), Giersch, Paqué and Schmieding (1993), and Hamada and Kasuya (1993).

[4]Christensen, Cummings and Jorgenson (1980) follow a somewhat different methodology, but find the same basic features of the data as shown in Table 1.

Table 1: Productivity Growth and Capital Deepening

| Growth Rate | 1950-60 | 1960-73 | 1973-89 |
|---|---|---|---|
| TFP | | | |
| Germany | 4.8 | 2.1 | 1.0 |
| Japan | 4.9 | 4.0 | 0.8 |
| United States | 1.6 | 1.6 | 0.5 |
| | | | |
| Capital-Labor Ratio | | | |
| Germany | 4.5 | 7.5 | 4.1 |
| Japan | 1.5 | 11.6 | 5.9 |
| United States | 2.2 | 1.9 | 1.6 |
| | | | |
| Capital-Output Ratio | | | |
| Germany | -2.1 | 2.4 | 1.5 |
| Japan | -4.0 | 2.9 | 2.7 |
| United States | -0.3 | -0.5 | 0.5 |
| Source: Wolff (1996) | | | |

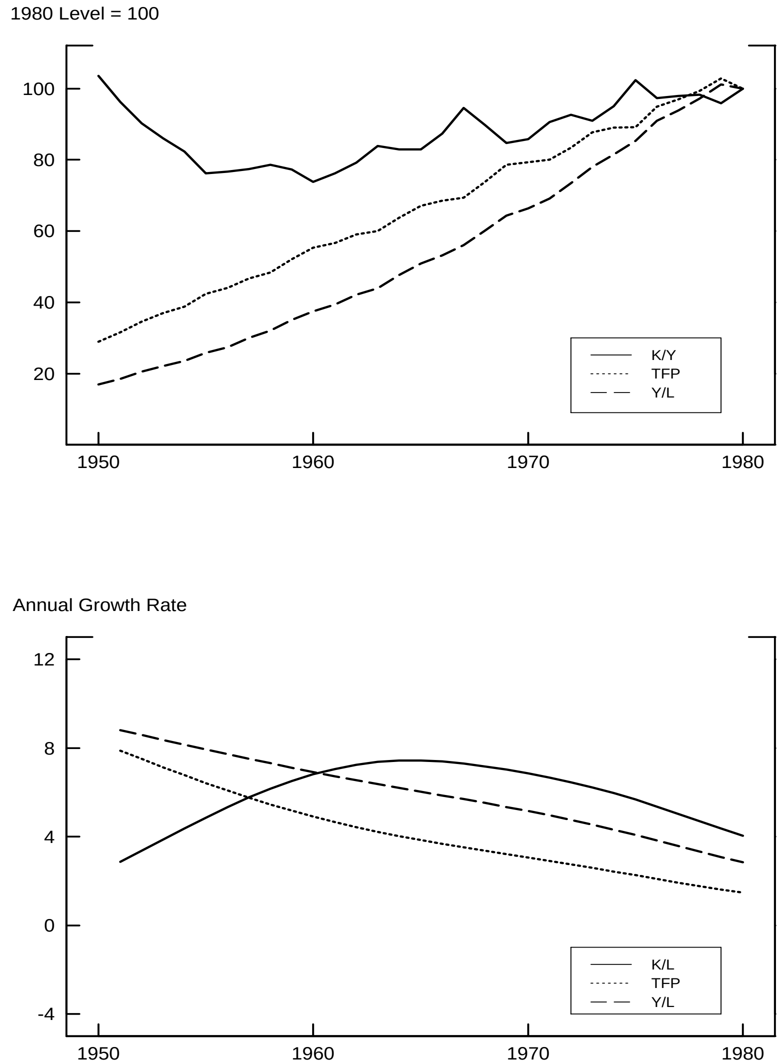
rose sharply in both countries. The pickup in the pace of capital accumulation in Germany and Japan is also evident in the investment flows. Private investment as a share of GDP was relatively low in the early 1950s, especially in Japan. In each country the investment share climbed over the 1950s, before peaking in the 1960s (Germany) or early 1970s (Japan).

Figures 1 and 2 provide additional graphical evidence for two distinct phases of catch-up for Germany and Japan.[5] For each country, the upper panel shows the levels of the capital-output ratio (K/Y), TFP, and output per hour (Y/L) in the manufacturing sector. These series are normalized to 100 in 1980. The lower panel of each figure shows the smoothed growth rates for the capital-labor ratio (K/L), TFP, and output per hour in the manufacturing sector. To reduce the higher frequency fluctuations in the growth rate series, we fit a spline approximation to the level data and compute growth rates from these spline approximations.

In the early phase of catch-up, German manufacturing experienced high rates of labor and total factor productivity growth, but the capital-output ratio *declined* reflecting the relatively subdued pace of capital accumulation. This early period

[5]We thank Bart van Ark and Dirk Pilat, who kindly provided us with their data for these two figures.

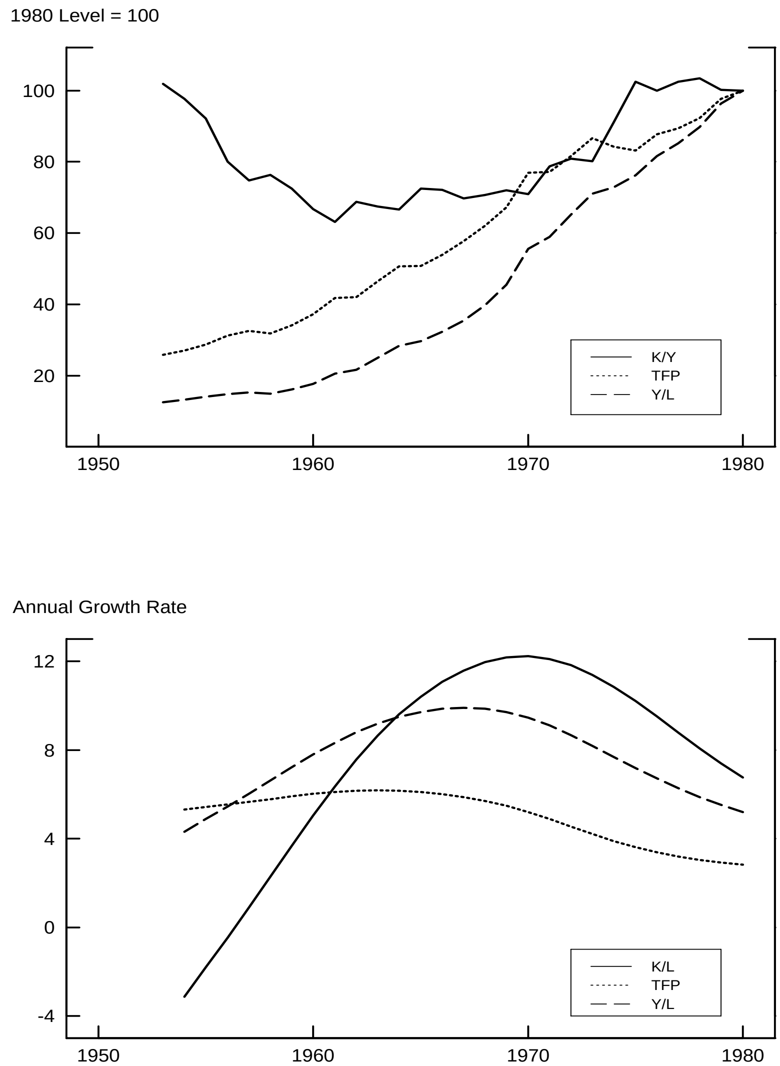
Figure 1: Manufacturing Sector in Germany




lasted for about the decade of the 1950s, over which time the capital-output ratio fell by nearly 30 percent from its 1950 level. Consistent with the economywide data documented in Table 1, productivity growth peaked well in advance of the peak in the rate of growth in the capital-labor ratio. During the later stage, beginning in about 1960, productivity growth in German manufacturing slowed, while the capital-output ratio increased as the pace of capital deepening accelerated.

The patterns of productivity and capital deepening in Japanese manufacturing are similar to that in Germany. As shown in Figure 2, the decline in the capital-output ratio is much more pronounced in Japan and the initial rise in productivity

Figure 2: Manufacturing Sector in Japan




growth rates occurs later than in Germany. Again, the rate of productivity growth peaks well in advance of the peak rate of increase in the capital-labor ratio.

## 2.2 Sources of Growth

A key factor contributing to the low level of productivity in the early postwar period is that Germany and Japan had fallen further behind the technological frontier represented by the United States during the war years.[6] The technological isolation

[6]German labor productivity fell from 46 percent of the U.S. level in 1938 to only 30 percent in 1950, a 35 percent drop in the level of relative productivity. The percent decline in Japan's relative productivity was of the same magnitude. Germany and Japan did not regain their prewar positions

experienced by Germany and Japan during both the prewar military build-up and the war itself contributed to the slow diffusion of new technologies. Ohkawa and Rosovsky (1968, p.42) summarize the situation in Japan as follows:

> The war and its aftermath produced a long interruption of normal Japanese private sector investment, and hence an especially large gap or pool of untapped modern technology. This was further enlarged by the acceleration of productivity growth in industrialized countries generally.

Another factor contributing to Germany and Japan's growth opportunities at the end of the war was the lack of widespread application of mass-production techniques in both countries during the prewar period. Relatedly, the absence of industries producing modern consumer durables on a wide scale afforded additional opportunities for rapid growth in the postwar period. Finally, sectoral transformations yielded productivity gains as both economies shifted away from military-related activities and the agricultural and craft sectors toward private industrial production.[7]

For each of these contributing factors, the adoption of new techniques and the development of new industries required substantial amounts of new investment in plant and equipment. Because they share the characteristic that the productivity improvement is embodied in investment, we lump these different factors together under the general rubric of "embodied technological change."

## 3 The Model

Previous research on the postwar catch-up of Germany and Japan has focussed on production technologies that feature a high degree of substitutability between capital and labor. Putty-clay capital provides an alternative view, in which capital-labor ratios on existing machines are rigid.[8] As a consequence, in the early stage of

relative to the United States again until around 1960 (Maddison (1991)).

[7]Interestingly, increases in human capital do not appear to have contributed much to Germany and Japan's postwar productivity catch-up relative to the United States (see Denison (1967), Denison and Chung (1976), and Maddison (1995)). Nevertheless, the existence of a well-educated workforce and sizable pools of scientists and engineers in both Germany and Japan was key to those countries' ability to adopt and adapt new production methods and technologies. More generally, following the immediate postwar reconstruction phase, both countries benefitted from legal and institutional structures and monetary regimes that constituted a "social capability" for growth, in the terms of Abramovitz (1995).

[8]The putty-clay model was originally introduced by Johansen (1959). For further references to the putty-clay literature and a more detailed description of the model described below, see Gilchrist and Williams (2000).

catch-up, investment is directed at adding new machines with relatively low capital intensity. As emphasized by Maddison (1964), such "capital widening" expands the employment and output capacity of industry, but dampens the growth rate of capital relative to labor. Over time, the catch-up process switches from one of capital widening to one of capital-deepening, that is, raising the quantity of capital per worker. During this latter stage, capital serves as a substitute for labor in production, and the capital-labor ratio increases rapidly.

We evaluate Germany and Japan's transition dynamics in an optimizing general equilibrium model based on putty-clay technology developed in Gilchrist and Williams (2000). This framework naturally admits a distinction between capital widening and capital deepening – that is, between investment on the extensive and intensive margins – that is entirely absent from the standard putty-putty model. In the putty-clay model, capital goods embody the level of technology and the choice of capital intensity made at the time of their creation. Ex ante, the choice of capital intensity – the amount of capital to be used in conjunction with one unit of labor – is based on a standard Cobb-Douglas production function. Ex post, the production function is of the Leontief form with a zero-one utilization decision. Over time, as the leading-edge technology improves, older, less efficient vintages of capital become too costly to operate and are scrapped.

### 3.1 The Production Technology

Each period a set of new investment "projects" becomes available. Constant returns to scale implies an indeterminacy of scale at the level of projects, so without loss of generality, we normalize all projects to employ one unit of labor at full capacity. We refer to these projects as "machines." The productive efficiency of a machine initiated at time $t$ is affected by four terms: the economywide level of disembodied technology $A_t$, the economywide level of vintage technology, $\theta_t$, an idiosyncratic shock to productivity, $\mu_t$, and the amount of capital invested per machine, $k_t$. We assume that capital goods require one period for initial installation and fail at the exogenous rate $\delta$.

The economywide levels of disembodied and vintage (embodied) technologies follow stochastic processes described in the next section. We assume that the trend level of embodied technology increases over time with gross growth rate $(1+g)^{1-\alpha}$, while disembodied technology has no trending component.[9] The idiosyncratic shock $\mu_t > 0$ is drawn from a log-normal distribution

$$\log \mu_t \sim N(-\frac{1}{2}\sigma^2, \sigma^2),$$

where the mean correction term $-\frac{1}{2}\sigma^2$ implies $E(\mu_t) = 1$. The realized level of combined vintage and idiosyncratic efficiency $\mu_t\theta_t$ is assumed to be permanent and thus embodied in the machine.

Final-goods output produced at time $t$ by a machine built in period $t-j$ with embodied technology $\mu_{t-j}\theta_{t-j}$ and capital $k_{t-j}$ is given by

$$Y_t(\mu_{t-j}\theta_{t-j}k_{t-j}^{\alpha}) = A_t \; 1\{L_t(\mu_{t-j}\theta_{t-j}k_{t-j}^{\alpha}) = 1\} \; \mu_{t-j}\theta_{t-j}k_{t-j}^{\alpha}, \tag{1}$$

where $L_t(\mu_{t-j}\theta_{t-j}k_{t-j}^{\alpha})$ is labor employed at the machine and the zero-one indicator function $1\{L_t(\mu_{t-j}\theta_{t-j}k_{t-j}^{\alpha}) = 1\}$ reflects the Leontief nature of machine production with unit labor capacity. Let

$$X_t \equiv \mu_t\theta_t k_t^{\alpha} \tag{2}$$

denote the efficiency level of a particular machine, and let $\bar{X}_t = \theta_t k_t^{\alpha}$ denote the mean efficiency of such machines. To characterize the production possibilities of this economy, we note that, once produced, machines are distinguished only by their efficiency level $X$. Let $H_t(X)$ denote the quantity of machines of efficiency level $X$ that are available for use at time $t$. Integrating over $X$ yields expressions for aggregate output

$$Y_t = A_t \int_0^{\infty} 1\{L_t(X) = 1\} X H_t(X) dX \tag{3}$$

and aggregate labor input

$$L_t = \int_0^{\infty} L_t(X) H_t(X) dX. \tag{4}$$

The quantity of machines with efficiency $X$ available for production at time $t+1$ equals the quantity of machines that survive from period $t$ plus the quantity of new machines with efficiency $X$ that are put into place at time $t$. The log-normal distribution for $\mu_t$ implies that $X_t$ is also log-normally distributed with

[9] This distinction between the underlying sources of trend productivity growth is of no consequence for the analysis in this paper.

$E(\log X_t|\bar{X}_t) = \log \bar{X}_t - \frac{1}{2}\sigma^2$. Hence, the quantity of machines of a given efficiency $X$ evolves according to

$$H_{t+1}(X) = (1-\delta)H_t(X) + (\sigma X)^{-1}\phi(\frac{1}{\sigma}(\log X - \log \bar{X}_t + \frac{1}{2}\sigma^2))Q_t \tag{5}$$

where $\phi()$ is the standard normal probability distribution function and $Q_t$ is the aggregate quantity of new machines that are put in place at time $t$. The term $(\sigma X)^{-1}\phi(\frac{1}{\sigma}(\log X - \log \bar{X}_t + \frac{1}{2}\sigma^2))$ thus is the density of new machines with efficiency level $X$.

In the absence of government spending or other uses of output, aggregate consumption, $C_t$, satisfies

$$C_t = Y_t - k_t Q_t, \tag{6}$$

where $k_t Q_t$ equals aggregate investment expenditures.[10]

Preferences of the representative household are given by

$$\frac{1}{1-\gamma} E_t \sum_{s=0}^{\infty} N_{t+s}\beta^s \left(\frac{C_{t+s}(N_{t+s} - L_{t+s})^{\zeta}}{N_{t+s}}\right)^{1-\gamma}, \tag{7}$$

where $0 < \beta < 1, \gamma > 0$, and $\zeta > 0$. The labor endowment, $N_t$, is assumed to grow at a constant rate $n$, $N_t = N_0(1+n)^t$. The social planner chooses contingency plans for factor utilization, $\{L_t(X), \forall X > 0\}$, and investment decisions, $\{k_t, Q_t\}$, to maximize welfare subject to the labor endowment and equations 2 – 6. The information set at time $t$ includes the current and past levels of economywide disembodied technology, $A_t$, and embodied technology, $\theta_t$. However, the idiosyncratic shock to individual machines $\mu_t$ is revealed only after period $t$ allocations are made.

### 3.2 The Utilization and Investment Decisions

Each period the social planner chooses which machines to utilize and which machines to leave idle. Given the Leontief structure of production and the assumption of no machine startup or shutdown costs, this decision problem is static in nature and is equivalent to to the choice of a cutoff value, $W_t$, whereby machines with productivity $A_t X \geq W_t$ are run at capacity, while those less productive are left idle. Let

$$z_t^s \equiv \frac{1}{\sigma}\left(\log W_t - \log A_t \bar{X}_s + \frac{1}{2}\sigma^2\right) \tag{8}$$

[10]We abstract from international trade. In principle, the process of catch-up can be accelerated by borrowing from abroad. For Germany and Japan, the trade balance tended to be roughly in balance on average over the 1950s and 1960s, suggesting that the closed-economy assumption is not a bad approximation for the purposes of this paper.

measure the productivity difference between the efficiency of the marginal machine in use at time $t$ and the mean efficiency of a vintage $s$ machine.

Capacity utilization of the set of vintage $s$ machines at time $t$ – the ratio of actual output produced by all vintage $s$ machines to the amount of output that would be produced if all such machines were operated at full capacity – is given by $(1 - \Phi(z_t^s - \sigma))$, where $\Phi(\cdot)$ denotes the standard normal cumulative distribution function. Equation 3 then implies that aggregate output may be expressed as a function of current capacity utilization rates and past investment decisions

$$\begin{aligned} Y_t &= A_t \int_{A_t X > W_t}^{\infty} X H_t(X) dX \qquad (9) \\ &= \sum_{j=1}^{\infty} \left(1 - \Phi(z_t^{t-j} - \sigma)\right) (1-\delta)^j Q_{t-j} A_t \bar{X}_{t-j}. \end{aligned}$$

Similarly, aggregate labor may be expressed as

$$\begin{aligned} L_t &= \int_{X > W_t}^{\infty} H_t(X) dX \qquad (10) \\ &= \sum_{j=1}^{\infty} \left(1 - \Phi(z_t^{t-j})\right) (1-\delta)^j Q_{t-j}, \end{aligned}$$

where $1 - \Phi(z_t^s) = \Pr(A_t X_s > W_t | A_t, W_t)$ is the share of vintage $s$ machines in use at time $t$.

The social planner's problem may now be restated in terms of the choices of the cutoff, $W_t$, the capital intensity for new machines, $k_t$, and the number of new machines, $Q_t$, produced at time $t$. Formally, the social planner chooses contingency plans for the sequence $\{W_{t+s}, k_{t+s}, Q_{t+s}\}_{s=0}^{\infty}$ to maximize equation 7 given the stock of existing machines and the labor endowment, and subject to equations 2, 5, 6, 8, 9, and 10.

Let $U_{c,t+s}$ denote the marginal utility of consumption and $U_{L,t}$ denote the marginal utility associated with an incremental increase in work (decrease in leisure). The optimal cutoff $W_t$ satisfies

$$U_{c,t} W_t + U_{L,t} = 0. \qquad (11)$$

The optimal choice of capital intensity, $k_t$, satisfies the condition

$$U_{c,t} = E_t \left\{ \sum_{j=1}^{\infty} \beta^j (1-\delta)^j U_{c,t+j} \left(1 - \Phi(z_{t+j}^t - \sigma)\right) \right\} \left( \alpha \frac{A_{t+j} \bar{X}_t}{k_t} \right). \qquad (12)$$

The final term in the right-hand side of this expression equals the marginal gain to production associated with an incremental increase in $k_t$, taking into account expected future rates of capital utilization implied by equation 11.[11] Similarly, the optimal quantity of new machines, $Q_t$, satisfies

$$U_{c,t}k_t = E_t\Big\{\sum_{j=1}^{\infty}\beta^j(1-\delta)^j\left(U_{C,t+j}(1-\Phi(z_{t+j}^t-\sigma)A_{t+j}\bar{X}_t - U_{L,t+j}(1-\Phi(z_{t+j}^t))\right)\Big\}. \tag{13}$$

The left-hand side of this expression equals the forgone utility associated with producing a new machine with capital intensity $k_t$. The right-hand side of this expression equals the incremental gain in the present discounted value of the future utility associated with the additional output from such a machine less the disutility of labor associated with operating such a machine.

In the next section we compare the transition dynamics of the putty-clay model to the more standard putty-putty vintage capital model initially introduced by Solow (1960). This model is obtained from the above framework by relaxing the restriction that ex post capital-labor ratios are fixed. For the Solow putty-putty model, define the capital aggregator $K_t$

$$\begin{aligned} K_t &\equiv \sum_{j=1}^{\infty}\theta_{t-j}^{1/\alpha}(1-\delta)^j I_{t-j} \\ &= (1-\delta)K_{t-1}+\theta_{t-1}^{1/\alpha}I_{t-1}, \end{aligned} \tag{14}$$

where $I_t$ denotes gross aggregate capital investment. In the Solow vintage model, embodied technological change enters the model through the capital accumulation equation and is equivalent to a reduction in the economic cost of new capital goods. Aggregate production in the Solow vintage model is given by

$$Y_t = \exp(\frac{1-\alpha}{\alpha}\frac{\sigma^2}{2})A_t K_t^{\alpha} L_t^{1-\alpha}, \tag{15}$$

where the first term is a scale correction that results from aggregating across machines with differing levels of idiosyncratic productivity.

[11] An increase in $k$ has a direct effect on output through its effect on $\bar{X}_s$. It also potentially has an indirect effect through utilization rates – a higher $k$ implies increased utilization. The marginal utility associated with the least efficient machine is, however, zero; that is,

$$\frac{1}{\sigma}\phi(z_t^s-\sigma)\bar{X}_s - \frac{1}{\sigma}\phi(z_t^s)W_t = 0,$$

and hence the indirect effect vanishes at the optimum.

We calibrate both models using standard parameter values from the literature (e.g., Kydland and Prescott (1991) and Christiano and Eichenbaum (1992)). Each period in the model corresponds to one year. The calibrated parameters are $\beta = 0.97$, $\gamma = 2$, $\zeta = 3$, $g = 0.024$, $n = 0.01$, $\delta = 0.1$, $\alpha = 0.36$. Trend growth in labor is chosen to match the German and Japanese postwar data; trend productivity growth is set equal to its average rate in the United States over 1950–80. The results reported in this paper are not sensitive to reasonable variations in these parameters. Following Gilchrist and Williams (2000), we set $\sigma = 0.15$ in the putty-clay model.

# 4 Model Experiments

In this section, we examine the transition dynamics of the putty-clay model in response to destruction of the capital stock and to the availability of new, more productive technologies. We start by considering the effects of capital destruction. This experiment highlights the importance of putty-clay capital in explaining key aspects of labor and capital transition dynamics. In the next two experiments, we consider increases in disembodied and embodied technology. Finally, the fourth experiment combines both capital destruction and increases in embodied technology in an empirically plausible manner, and evaluates the model's ability to match features of Germany and Japan's postwar experiences along a number of dimensions.

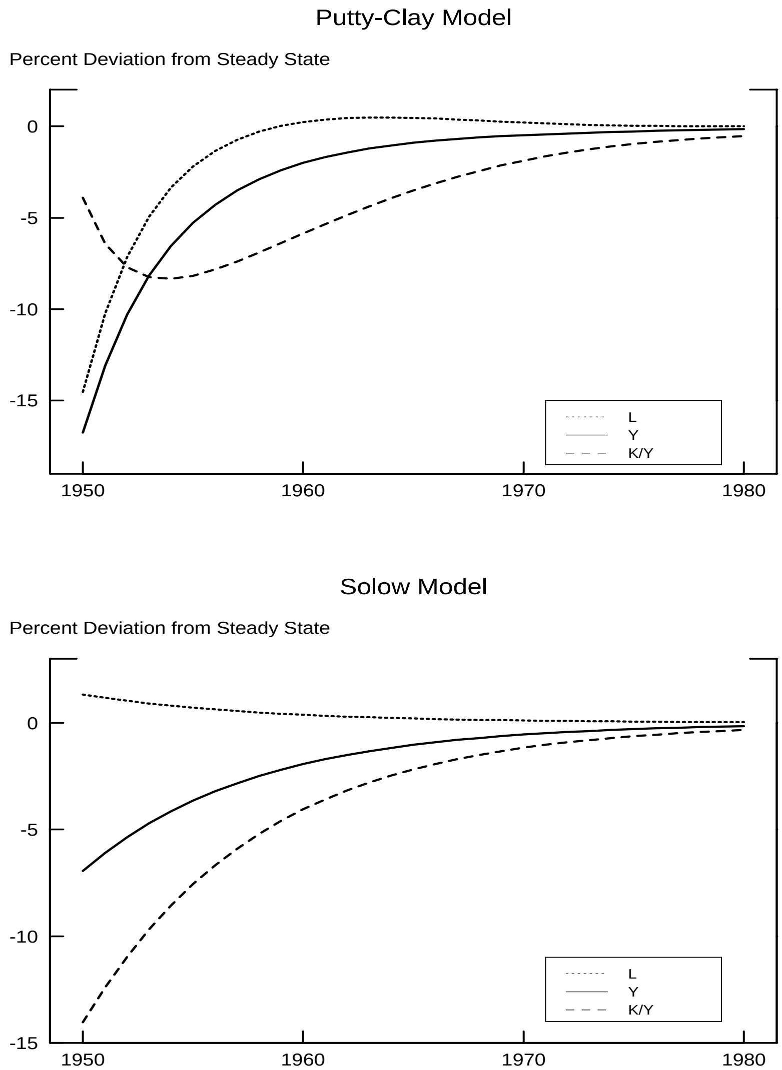
## 4.1 Capital Destruction

We begin our model experiments by considering the effects of destroying 20 percent of the capital stock.[12] The magnitude of the simulated shock is roughly consistent with estimates of the effects of war-related destruction and population inflows, as discussed in section 2. The results from this experiment are shown in Figure 3, which plots the dynamic responses of the percent deviations of labor, output, and the capital-output ratio from their respective steady-state values. The upper panel shows the response for the putty-clay model, while the lower panel shows the response for the Solow putty-putty model.

In the putty-clay model, capital destruction has an immediate large negative effect on employment and output, owing to the short-run complementarity between capital and labor implied by the Leontief nature of production. Employment initially

[12]We simulate the model using an extended path algorithm based on Fair and Taylor (1983). For the simulations, we truncate the maximum lifespan of machines at 45 years.

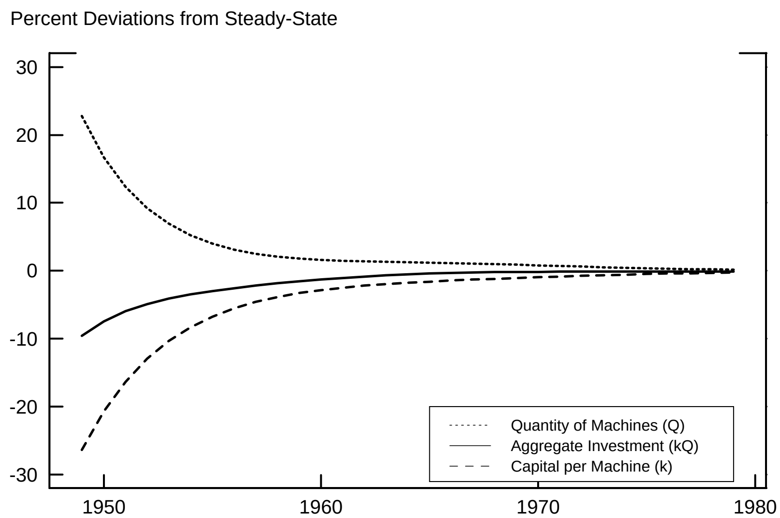
Figure 3: Destruction of 20 Percent of the Capital Stock




falls by 15 percent and output falls by 17 percent. Along the transition path, output, capital, and employment all rise monotonically. The capital-output ratio exhibits a U-shaped response: After a small initial drop, the capital-output ratio declines for several years before gradually returning to its steady-state value.

In the Solow putty-putty model, employment actually *rises* in response to the destruction in capital. As a result, the initial drop in output is 7 percent – less than half as large as in the putty-clay model. This decline in output roughly equals the product of the capital share times the amount of capital destroyed. The modest rise in employment occurs because the high rate of return on savings offsets the low marginal product of labor. Along the transition path, employment gradually falls while output and the capital stock rise. After a sharp initial drop of 14 percent, the capital-output ratio rises monotonically back to its steady-state value.

Figure 4: Putty-Clay Investment Dynamics Following Capital Destruction




The two models imply very different transition dynamics for employment and the capital-output ratio, with the predictions of the putty-clay model more consistent with the data along these dimensions. Figure 4 decomposes the response of aggregate investment in the putty-clay model into capital per machine and the quantity of new machines. Investment along the extensive margin (machine quantity) increases sharply, reflecting the process of capital widening. Given this rapid pace of machine creation, if the capital-labor ratio of new machines were to remain constant, the implied rate of investment would be very high. Such high rates of investment would entail either a sharp rise in the marginal cost of production or a large reduction in consumption. By reducing capital per machine, productive capacity is quickly restored while investment rates are kept low, as seen in the figure. With additions to capacity, investment along the intensive margin increases and capital per machine gradually returns to its steady-state level. This initial phase of capital widening followed by one of capital deepening underlies the U-shaped response of the capital-output ratio in the putty-clay model.

### 4.2 An Increase in Disembodied Technology

Although capital destruction alone can explain some of the features in the German and Japanese data, it cannot account for the magnitude of the decline in the capital-output ratio or the patterns in productivity growth experienced by Germany and Japan during the postwar period. To explain these phenomena, we now consider transition dynamics in response to permanent increases in technology. We begin by considering the effect of an increase in disembodied technology for the putty-clay model.[13]

Figure 5 shows the transition dynamics following an immediate permanent rise in the level of disembodied technology. The upper panel of the figure reports the levels of the capital-output ratio, TFP, and labor productivity; the lower panel shows the growth rates of the capital-labor ratio, TFP, and labor productivity. These variables correspond to the data plotted in Figures 1 and 2. In the exercises reported in the remainder of the paper, the magnitude of the productivity shock is calibrated to roughly match the degree of catch-up in economywide TFP for Germany relative to the United States achieved by 1980.

The transition dynamics implied by a one-time increase in disembodied technological change are clearly at odds with the data for Germany and Japan. This shock generates a monotonically increasing capital-output ratio and virtually no growth in total-factor productivity following the initial increase.[14] In addition, the growth rate in the capital-labor ratio declines monotonically over time, in contrast to the hump-shaped pattern observed in the data.

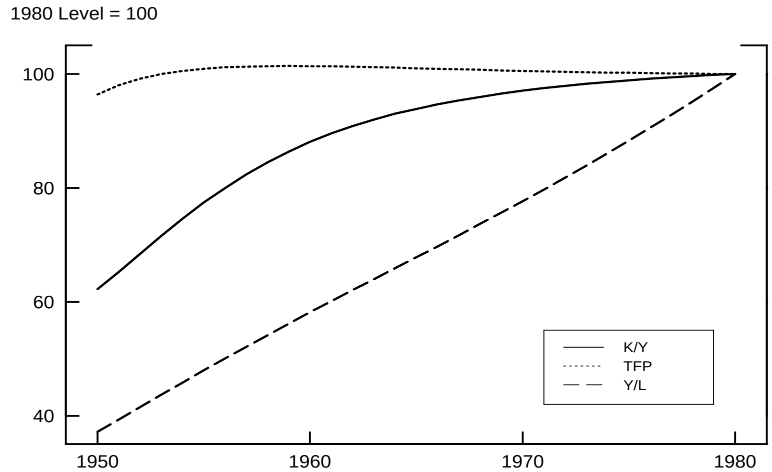
### 4.3 An Increase in Embodied Technology

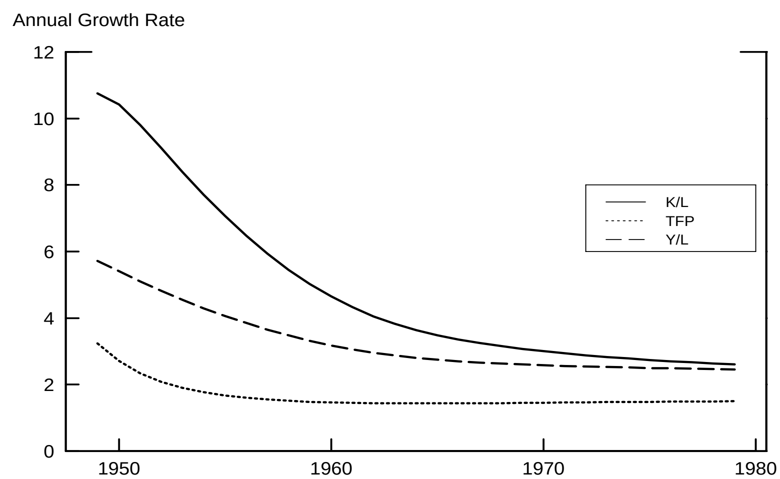
The transition dynamics implied by an immediate increase in embodied technology provide a much better fit to the historical data than do those implied by an immediate increase in disembodied technology. Figure 6 reports the effects of an immediate permanent rise in $\theta_t$ – the mean level of technology determining the productivity of

[13]Because production possibilities are immediately expanded in response to disembodied technological change, the relative fixity of factor proportions has little effect on transition dynamics in this experiment, and we obtain very similar results with the Solow putty-putty model.

[14]We compute TFP as a Solow residual from the Cobb-Douglas production function given in equation 15, where the "capital stock" is calculated according to equation 14. Because the putty-clay model deviates from both of these assumptions, this measure of TFP differs from the true level of disembodied technology. The relatively small variation in measured TFP growth shown in the figure is a result of this mismeasurement.

Figure 5: Immediate Increase in Disembodied Technology



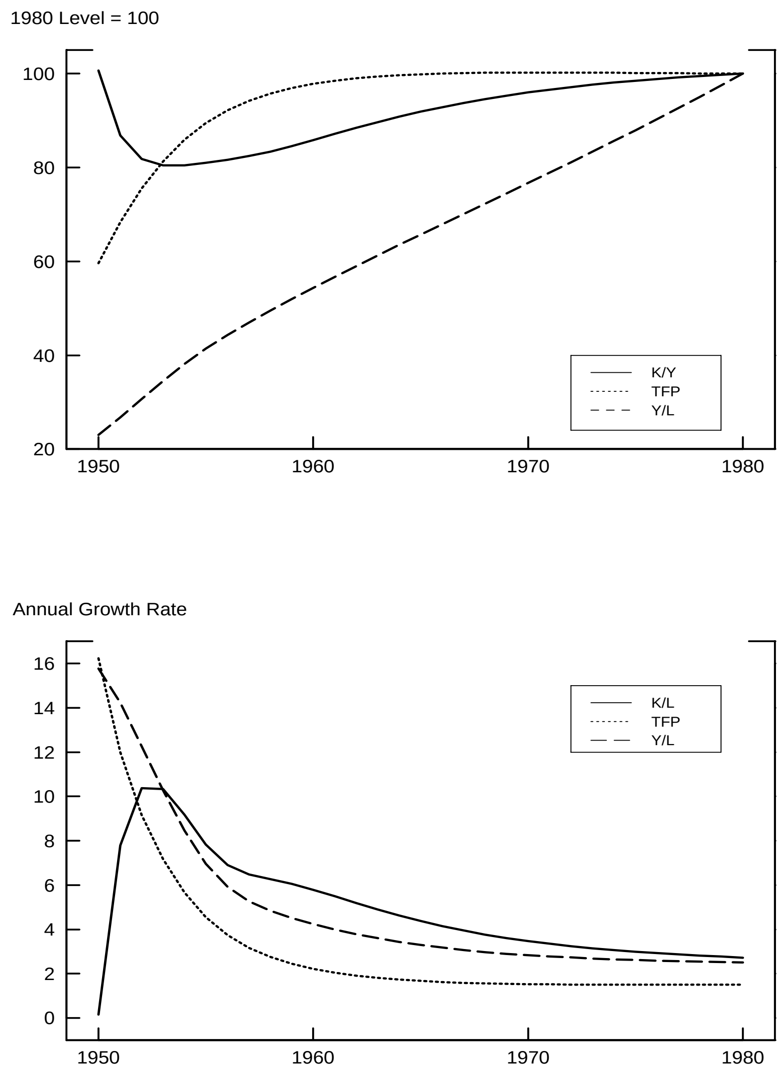




new machines – in the putty-clay model.[15]

The productivity gains associated with an increase in embodied technology occur only as the leading-edge technology is incorporated in the existing capital stock. As in the case of capital destruction, investment is limited by rapidly rising marginal costs of production in the short run. As a result, the initial expansion of output, hours, and investment is muted. This gradual adoption of new technology through investment explains the high but declining growth rates of total-factor and labor

[15]Qualitatively, the results from this experiment are similar to those in a putty-putty model. Quantitatively, the putty-putty model implies a stronger comovement between productivity and capital deepening that is less compatible with the empirical evidence.

Figure 6: Immediate Increase in Embodied Technology




productivity.[16]

An increase in embodied technology also provides a natural explanation for the U-shaped response of the capital-output ratio. Because there is no direct effect of the increase in technology on measured productivity, neither output nor capital shows much response in the initial period. The initial phase of the expansion is then

[16]If the capital stock were measured in efficiency units, all the productivity gains resulting from an increase in embodied technology would be ascribed to capital accumulation rather than TFP. Throughout this paper, we assume that changes in embodied technology are not reflected in the data for investment and capital stocks. We believe this approach is appropriate for comparisons of simulated to actual data. Greenwood, Hercowitz and Krusell (1997) argue that the U.S. data in the postwar period incorporate only a fraction of the improvements in embodied technology. The national accounts of Germany and Japan are computed in a similar fashion.

characterized by a period of capital widening as productive capacity is increased at low cost. This period of declining capital-output ratios lasts for several years, after which the economy begins the process of capital deepening. During this latter phase, the capital-output ratio rises monotonically as the economy converges to the new steady state.

The process of capital widening followed by capital deepening also explains the hump-shaped response of the growth rate in the capital-labor ratio observed in the data. With the rapid expansion in machine quantity, labor is growing nearly as rapidly as capital. As productive capacity is established, the growth rate of the capital-labor ratio increases. This growth rate peaks a few years after the start of the transition. During the capital-deepening phase, the growth rate of the capital-labor ratio remains above its steady-state rate but declines monotonically over time.

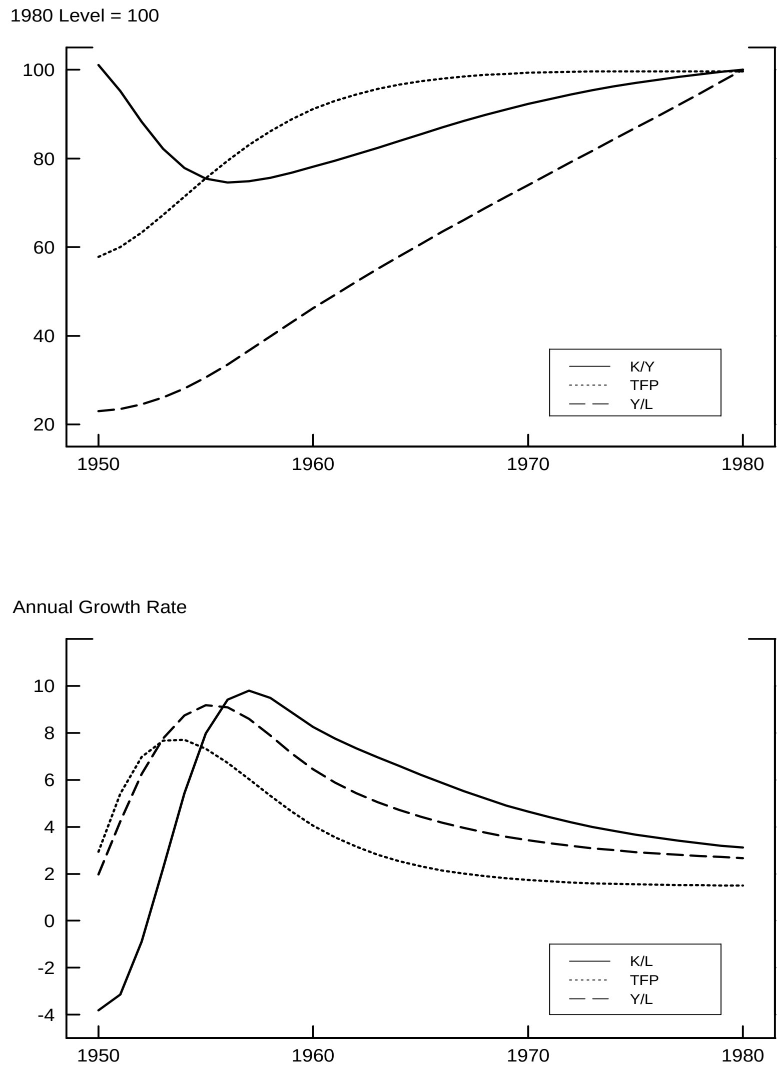
### 4.4 A Gradual Phase-In of Embodied Technology

The preceding simulations suggest that both capital destruction and embodied technological change are key elements in explaining the transition dynamics of post-war Germany and Japan. In this section we consider the combined implications of capital destruction and technological change. In doing so, we also introduce a reasonable delay in obtaining complete access to the leading-edge technology associated with new capital goods. Arguably, it takes some time for producers to identify and purchase new capital goods and put into place production processes that are most appropriate for their industry. Early in the process, capital goods may not be used in the most efficient manner, but once in place, it is difficult to change their use.

We model the gradual phase-in of technology as a series of anticipated increases in $\theta_t$, where the ultimate increase in the level of embodied technology is the same as in the preceding experiment. Our goal in this exercise is to emphasize the process of capital accumulation rather than diffusion as the primary driving force behind the catch-up process. Accordingly, we assume that the technology diffuses relatively rapidly. Specifically, the increase in the level of embodied technology is assumed to be $(1 - 0.75^t)$ in period $t$, which implies that 25 percent of the ultimate rise in $\theta$ occurs within one year, and 75 percent within five years. We further assume that the economy starts with a capital stock that is 20 percent below its steady-state level. The transition dynamics for the combined simulation are plotted in Figure 7.

The gradual phase-in of embodied technology provides an incentive to delay

Figure 7: Phased-in Increase in Embodied Technology with 20% Capital Destruction



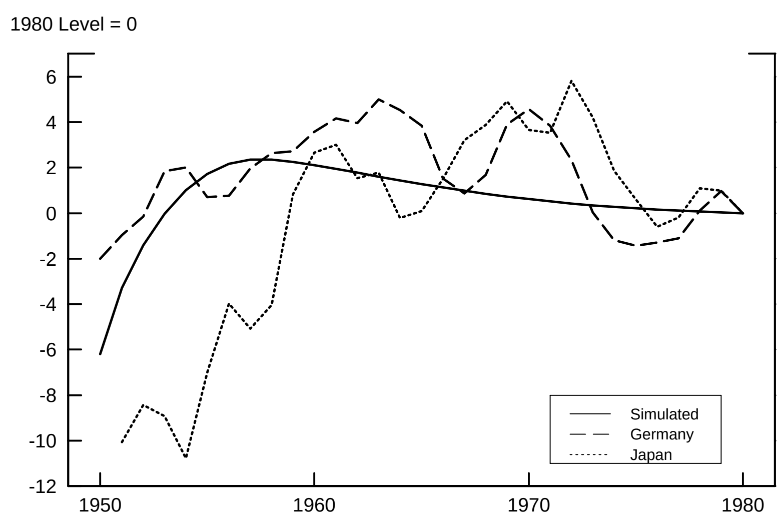

investment in order to take advantage of additional improvements in technology yet to come. In addition to delaying the investment process, the gradual phase-in implies that productivity growth rates are initially low and rising, peaking several years out. This pattern reflects both the direct effect of the path of technology and the indirect effect of delayed capital expenditures relative to the case of an immediate increase in technology.

The U-shaped response of the capital-output ratio in the model is now more pronounced and provides a close match to those observed in the data. In terms of growth rates, we again observe a hump-shaped response of the capital-labor growth rate. Initially, labor is growing even more rapidly than capital. The peak response of the capital-labor growth rate occurs a few years after the peak response in productivity, a finding that again is in broad agreement with the data.

### 4.5 Implications for Employment, Investment, and Interest Rates

The gradual phase-in of embodied technology combined with capital destruction captures the major features of capital and productivity dynamics during Germany and Japan's postwar transition. We now focus on the dynamic responses of investment, employment, and the real rate of return to capital. As noted, in a putty-putty model, investment and the real rate of return surge while employment remains persistently high along the transition path following either capital destruction or an increase in technology. All three of these predictions are inconsistent with the empirical experiences of Germany and Japan. We now consider the implications of our combined experiment for each of these three variables.

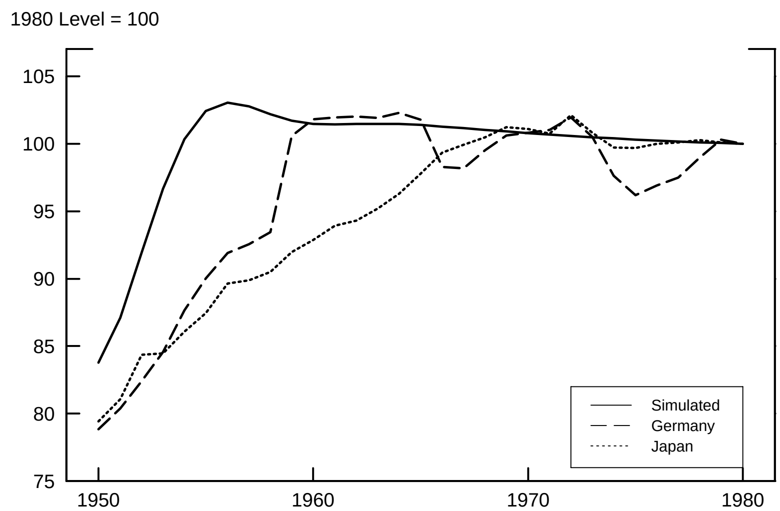
Figure 8: Investment Share of GDP




The combination of capital destruction and a gradual increase in embodied technology causes the investment share initially to drop, but then rise steadily over most of the 1950s. Loss of capacity combined with some delayed access to frontier technologies dampens investment for several years. Figure 8 plots the investment shares of GDP for Germany and Japan, along with the investment share implied by the model simulation with capital destruction and gradual phase-in of embodied technology. The investment share in Germany rises about 5 percentage points over the

1950s, while that in Japan climbs about 12 percentage points. The model simulation does a nice job of capturing this pattern of investment – the investment share rises about 8 percentage points over the 1950s.

Figure 9: Detrended Employment




The model also predicts a sharp rise in employment in the 1950s. Figure 9 plots detrended employment for Germany and Japan, along with employment implied by the model simulation.[17] The employment patterns for Germany and Japan are remarkably similar – employment starts 20 percent below trend and rises monotonically throughout the 1950s, with Germany reaching its trend level somewhat more rapidly than Japan. In the model simulation, employment begins 16 percent below trend and rises monotonically over most of the decade. Although the model's employment dynamics are more rapid than those apparent in the data, the model succeeds in matching the magnitude of the employment response, which is governed by the putty-clay features of the model.

Table 2 considers the model's implications for real interest rates. We again consider the effect of the combined experiment of capital destruction and embodied technological change, with and without a gradual phase-in of technology. Without phase-in, real interest rates are initially nearly 60 percent, declining to 20 percent

[17]To detrend employment, we first estimate a log-linear trend over the period 1965-1990. We then extrapolate this trend backwards and subtract it from the full sample of data, starting in 1950. This procedure allows us to capture labor movements associated with transition dynamics rather than more general demographic forces and trends in participation rates that are relevant in the full sample period.

after five years. This initial spike in real interest rates reflects the large investment opportunities available at the start of the transition. Although substantially lower than the 500 percent rate of return obtained by King and Rebelo (1993) in their study of transition dynamics applied to Germany and Japan, such returns are high by historical standards.

Table 2: Simulated Annual Real Rates of Return to Capital

| Increase in Embodied Technolgy with Capital Destruction | | | | | |
|---|---|---|---|---|---|
| | 1950 | 1955 | 1960 | 1965 | 1970 |
| Immediate | 57 | 21 | 13 | 10 | 9 |
| Phased-in | 4 | 23 | 18 | 13 | 11 |

With the gradual phase-in of embodied technology, real rates of return are plausible and consistent with historical estimates of the return to capital. The real rate of return now starts below its steady-state level of 8 percent, as investors wait for additional improvements in technology. After five years, the real return to capital has risen to 23 percent, but then gradually converges to its long-run value. Using stock market returns, Maddison (1964, page 55) estimates a 23 percent return on capital in Germany and a 32.5 percent return in Japan over the period 1955-1961. Overall, the model succeeds at resolving the puzzling issue as to why employment, investment, and rates of return were relatively low in the early stages of transition, despite the tremendous growth opportunities that these countries faced at the time.

# 5 Conclusion

In this paper we consider a neoclassical interpretation of the postwar growth experiences of Germany and Japan. Unlike research that has focussed exclusively on the role of capital accumulation in a standard growth model, we emphasize the importance of the gap in the level of technology embodied in capital goods and its effect on capital accumulation and productivity growth. In the postwar period, Germany and Japan regained access to advanced technologies embodied in capital goods available from the United States and elsewhere. According to this view, Germany and Japan's "economic miracles" reflected a closing of the gap in "machines." This process was slowed by the putty-clay nature of capital, which necessitated an early stage of capital widening to expand productive capacity before capital deepening could fully take place. In the putty-clay model, an empirically plausible combination of capital destruction and increases in embodied technology can explain the patterns of productivity, capital accumulation, employment, and rates of return to capital during Germany and Japan's postwar transition.

Germany and Japan's postwar growth experiences provide prime examples of economic transitions determined by embodied technology and putty-clay capital. The postwar patterns of productivity and capital accumulation in Italy, and to a lesser extent, France, share similar qualities with those of Germany and Japan, although the scale of the transition is smaller. These factors are also likely to have been key influences on transitions in post-communist and other newly industrializing countries. Finally, embodied technological change is an important source of growth in the United States and a key ingredient in the U.S. productivity acceleration in the late 1990s.[18] This paper contributes to our understanding of the medium-run dynamics that we should expect from such growth opportunities.

[18]See, for example, Greenwood et al. (1997), Oliner and Sichel (2000), and Greenwood and Jovanovic (2001)).

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