The 'embodiment' controversy:  
A review essay

Zvi Hercowitz*

E. Berglas School of Economics, Tel Aviv University, Tel Aviv 69978, Israel

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1. Introduction

The 'embodiment' controversy between Jorgenson and Solow in the 1960s centered on the importance of capital-embodied technological change. If technological change is 'disembodied', it affects output growth independently of capital accumulation. In contrast, 'embodied' technological change requires investment in order to affect output. Hence, diagnostics about the relative importance of the two forms of technological change is crucial for learning about the transmission mechanism of technological progress to output growth. Solow (1960) argued that embodied technological change is dominant, hence, investment is the key mechanism; while Jorgenson (1966) argued that from the data available then, one could not provide an answer about its relative importance. This controversy between Jorgenson and Solow is still actual, perhaps now more than in the 1960s, given the rapid development of new technologies in the production of capital goods since the middle 1970s. The appearance of Jorgenson's (1995) collected papers, which have greatly influenced ideas about the measurement of technical change, represents an important opportunity to review this debate and its implications.

Jorgenson's and Solow's modelling of embodied technological change have dramatically different implications. The two specifications are presented in Section 2 as special cases of a more general framework. Section 3 addresses the empirical implications of the two frameworks and reviews the relevant empirical

* Tel.: 972 3 6409916; fax: 972 3 6409908; e-mail: zvih@econ.tau.ac.il.

1 See Greenwood and Yorukoglu (1997) and Horstein and Krusell (1996).
evidence. The discussion is based on Greenwood et al. (1996). Finally, Section 4 concludes, addressing the question: How important is 'embodiment'?

2. The framework of analysis

Consider the following aggregate production technology:

\[ y_t = f(k_t, l_t)z_t = c_t + i_t + R(z_t, q_t; x_t), \]
\[ i_t^* = q_t, \]
\[ k_{t+1} = k_t(1 - \delta) + i_t^* = \sum_{s=0}^{\infty} i_{t-s} q_{t-s}(1 - \delta)^s, \quad 0 < \delta < 1. \]

Eq. (2.1) is the resource constraint; output, \( y_t \), produced with capital, \( k_t \), and labor, \( l_t \), is used in consumption, \( c_t \), investment, \( i_t \), and expenditures, \( R \), required to achieve or maintain a level of technology defined by \( z_t \) and \( q_t \), given other variables, \( x_t \). The factor \( z_t \) is a standard index of total factor productivity, and \( q_t \) represents the quality of new capital per unit of investment cost. Note in Eq. (2.1) that \( i_t \) is investment in consumption units, and hence it represents the cost of investment in terms of consumption, while \( i_t^* \) in Eq. (2.2) is investment in efficiency units. Eq. (2.3) is the evolution equation for capital, which adds up existing vintages adjusted for quality and for physical depreciation at the rate \( \delta \). Hence, \( k_{t+1} \) 'embodies' the current and past \( q_t \)'s, and from here that the \( q \)-type of technological change is usually denoted as 'embodied'. The \( z \)-type of technological change is referred to as 'disembodied' since it affects output in Eq. (2.1) for any given level, and composition in terms of vintages, of \( k_t \).

An aggregate version of the specification adopted by Solow (1960) is Eqs. (2.1), (2.2) and (2.3) with \( R(\cdot) = 0 \). Here, technological change of both types evolves exogenously and without cost. Jorgenson (1966) (reproduced in Jorgenson, 1995, Chapter 2, vol. 1) criticizes Solow's specification:

'Solow assumes that investment goods of a given vintage progress technologically over time but only in the production of investment goods' (p. 10).

Jorgenson's statement can be interpreted, using Eqs. (2.1), (2.2) and (2.3), as saying that given the current \( k_t \) (and, in general, given all factors of production), a higher-\( q \), affects the production of investment goods, by virtue of Eq. (2.2), in a similar way as \( z_t \) affects total output. Hence, if the criterion for technological change to be 'disembodied' is to have an impact on current production given the current capital stock (or, in general, given all current factors of production), then \( q \) also qualifies as 'disembodied'. The key issue in this criticism is the fact that in Solow's specification \( q \) evolves free of cost, similar to \( z \). Jorgenson (1966) proposes a way for resolving this ambiguity regarding \( q \):

'To avoid the implication that disembodied technological change occurs for investment goods of a given vintage, at least in the production of new investment
goods, it is necessary to adjust the quantity of investment goods produced as well" (p. 10).

Jorgenson then advocates replacing Solow's

$$c_t + i_t = y_t = f(k_t, l_t)z_t$$

(2.4)

with

$$c_t + i^*_t = y_t = f(k_t, l_t)z_t,$$

(2.5)

in which the output of investment goods is adjusted for quality. Unlike z, increasing q does involve resources now, i.e., it requires either more labor input or less consumption. Formulation of Eq. (2.5), along with Eq. (2.1), implies that

$$R(z, q; x) = iq - i,$$

which does not include z reflecting the definitional asymmetry that z evolves free of cost - and x = i.

2.1. Semantics

The comparison of Solow's Eqs. (2.2), (2.3) and (2.4) framework with Jorgenson's Eqs. (2.2), (2.3) and (2.5) framework involves theoretical as well as empirical considerations. Let us start, though, with a semantic aspect. The 'embodied/disembodied' distinction has different meanings in the two frameworks. For both, the two types of technological change evolve exogenously, with 'embodied' technological change affecting investment only and 'disembodied' affecting all production. However, as mentioned above, Jorgenson's framework has the additional requirement that 'embodiment' involves a resource cost. Given this ambivalence regarding the 'embodied/disembodied' distinction, the discussion here follows Greenwood, Hercowitz and Krusell (1996), who use the 'investment-specific/neutral' distinction for q and z. A growing q is 'investment-specific' regardless of whether it requires resources or not, and z is (sector) 'neutral', given that it affects all produced goods in a parallel way. Therefore, the 'investment-specific/neutral' distinction applies to both frameworks as well as to the general formulation in Eqs. (2.1), (2.2) and (2.3).

2.2. Equivalence between models of investment-specific and neutral technological change

The distinction between the two forms of technological change is empirically meaningful only if data can be used to distinguish a model incorporating q from one with z. Jorgenson establishes a proposition of equivalence between these two models, which can be stated in the present notation as follows. Assume that the data available consist of \(\{c_t, i_t, l_t\}_{t=1}^{T}\) (consumption, investment in consumption cost units, and labor input) where T is the sample size, along with the capital stock \(k_0\) and investment \(i_0\) in the period prior to the sample, and \(\delta\), the rate of physical depreciation of capital. Jorgenson shows that this data set does
not allow us to distinguish which form of technological change is operating, hence, models with one form or the other are equally capable of generating the observed data. To illustrate Jorgenson's equivalence, it is sufficient to assume the structure of Eqs. (2.2), (2.3) and (2.4). (see footnote 2, below, for the Eqs. (2.2), (2.3) and (2.5) case).

From Eqs. (2.2), (2.3) and (2.4) and the available data, the following system of equations can be formed:

\[ c_t + i_t = f(k_t, l_t)z_t, \quad t = 1, 2, \ldots, T, \quad (2.6) \]

where

\[ k_t = \sum_{s=1}^{t} i_{t-s} q_{t-s}(1-\delta)^{t-s} + k_0(1-\delta)^t. \]

The system in (2.6) contains \( T \) equations with \( 2T \) unknowns: \( \{z_t, q_{t-1}\}_{t=1}^{T} \). Hence, the system is underidentified, implying that the above data set cannot distinguish which form of technological change, or combination of both, is operating.\(^2\) Solow (1960) assumed that \( z \) is constant and identified the growth rate of \( q \). Alternatively, one can do the opposite, set \( q = 0 \), and compute the resulting growth in \( z \), which is the procedure usually followed in standard growth accounting.

It is important to stress here that Jorgenson's equivalence was stated in the 1960s, and that data collection has since improved to an extent that enables making a reasonable inference on the \( q \) series, as discussed below in Section 3. Hence, another \( T \) equations can be added to the system in Eq. (2.6), and, accordingly, the equivalence proposition ceases to apply.

3. Jorgenson's specification vs. Solow's specification

3.1. Implications of the two frameworks

Jorgenson's \( c_t + i_t^* = y_t \) and Solow's \( c_t + i_t = y_t \), both combined with \( i_t^* = i_t q_t \) and \( k_{t+1} = k_t(1-\delta) + i_t^* \), have sharply different theoretical and empirical implications. Eq. (2.2), shared by both frameworks, can be expressed as

\[ TC(i_t^*) = i_t = i_t^*/q_t. \]

\(^2\) If the technology is described by Eqs. (2.2), (2.3) and (2.5), instead of Eqs. (2.2), (2.3) and (2.4), \( c_t + i_t \) on the left-hand side of Eq. (2.1) is replaced by \( c_t + i_t q_t \). Hence, \( q_T \) becomes an additional unknown. Given that the equivalence between the models follows from having too many unknowns, the situation is unchanged by adding another one.
which describes the total consumption cost of $i^*$ efficiency units of investment. Then, $1/q_t$ is the marginal cost, $MC$, of an efficiency unit of investment; hence, in competitive equilibrium,

$$MC(i^*) = \frac{1}{q_t} = p_t,$$

(3.1)

where $p_t$ is the relative price of such unit in terms of consumption. The strong implication of Jorgenson's resource constraint $c_t + i^*_t = y_t$ is that consumption and investment in efficiency units are assumed to be perfect substitutes in production. Hence, if perfect competition is a good approximation, $p_t = 1$ should hold in equilibrium and, from Eq. (3.1), it then follows that $q_t = 1$ for all $t$. Therefore, internal consistency of the specification requires that there be no investment-specific technological change! In other words, if Jorgenson's $c_t + i^*_t = y_t$ is correct, there is no need to look at data to gauge the importance of investment-specific technological change: It should not exist.

In contrast, Solow's resource constraint $c_t + i_t = y_t$ does not impose any pattern on the relative price $p_t$, since it includes investment in terms of the consumption cost. Hence, within this framework, it is meaningful to use data on the relative price of investment in efficiency units, in the context of $p_t = 1/q_t$ from Eq. (3.1), in order to identify the process of investment-specific technological change. Given that this type of technological change is concentrated in new equipment, the relevant relative price is that of the equipment component of investment. Thus, looking at the behavior of $p_t$ serves two purposes: the first is to observe which framework is supported; the second is to identify the $q$ process. The following section addresses the observed behavior of the relative price.

3.2. The relative price of equipment

The empirical counterpart of the relative price of equipment $p$ can be computed by dividing the equipment deflator by the consumption deflator. The appropriate deflator is a price index that refers exactly to the same good over time; and therefore, quality improvements that change the nature of the good should be controlled. In the case of investment, the price index should refer to an efficiency unit. In practice, however, it is very hard to control for quality, because it is reflected in a wide range of dimensions. If quality is not well accounted for, then the computed investment price-index grows faster than it should, due to the incorrect inclusion of the unaccounted part of quality improvement. Correspondingly, the computed $q$ grows slower than it should.

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3 In the case of imperfect competition, a constant price would also imply a constant $q$, provided there is no long-term trend in markups.
Gordon (1990) constructed a price index of production equipment that deals with quality improvement in much greater detail than in NIPA. His sample is 1947–1983. The empirical counterpart of $p$ can then be computed by dividing Gordon’s equipment price index by the deflator of consumption of nondurables and services (excluding housing). This consumption deflator excludes components of total consumption that can be considered household investment. Fig. 1 displays two measures of the relative price $p$, one using the equipment deflator in NIPA and the other using Gordon’s index. Since Gordon’s series was computed through 1983 only, it was linked from 1984 onwards to NIPA’s index, hence, the two series coincide for this part of the sample. The figure displays two main features. First, the relative price from NIPA is stable until the early 1980s, after which it starts to decline rapidly – at an annual rate of 3.6% in the 1983–1994 period. In contrast, Gordon’s relative price displays a strong negative trend from the beginning of the sample, declining at an annual rate of 2.6% in the 1947–1983 period. The different behavior of the two series until 1983 is clearly due to Gordon’s more detailed treatment of quality improvement. From 1984 onwards, however, only the NIPA series is available. The faster decline of the relative price since the early 1980s can be explained by either an acceleration in investment-specific technological change, or by an improvement in NIPA’s procedures in the computation of the equipment price index, or both. For the entire 1947–1994 period, Fig. 1 displays a dramatic decline of the relative price at the annual rate of 2.8% that, according to Eq. (3.1), corresponds to the annual growth rate of $q$.

This evidence clearly supports Solow’s specification, not Jorgenson’s.
4. Conclusion: How important is 'embodiment'?

From the discussion above it follows that (a) there is an empirically meaningful distinction between $q$-technological change and $z$-technological change (Section 2.2), and (b) the relative price evidence supports the Solow framework and, at the same time, it reveals the $q$-process. This implies that one can proceed and address the main question at the center of the ‘embodiment controversy’: How important is ‘embodiment’? This question can be given operational content by considering: How much of actual economic growth is due to investment-specific technological change?

This issue was studied by Greenwood et al. (1996), who found that in the postwar US period, about 60% of output growth per unit of labor could be attributed to $q$-technological change, and the remaining 40% to $z$-technological change.\(^4\)

The 60% figure can be decomposed into a direct effect, i.e., the increasing quality of given flows of investment in consumption units, and an indirect effect, i.e., the stimulus for further investment in consumption units. To compute the latter component, Greenwood, Hercowitz and Krusell solved the general equilibrium of the model in order to isolate the share of $q$-technological change in total capital accumulation.

In the 1947–1994 period, output per hour of work, or labor productivity, grew in the United States at an average rate of 1.27%. Holding investment in consumption units constant, in order to isolate the direct effect, Eq. (2.3) implies that the stock of equipment grows at the growth rate of $q$, i.e., 2.8%. When using the equipment share of 0.17, computed by Greenwood et al., this translates into 0.48% of annual growth in labor productivity. Hence, the direct effect of $q$-growth can be accounted responsible for 38% of labor productivity growth, and the remaining 22% (adding up to 60%) can be explained by $q$-induced capital accumulation.

The conclusion is that ‘embodiment’ is the main transmission mechanism of technological progress to economic growth.

References


\(^4\) Focusing on output per unit of labor controls for labor input growth as a source of output growth and thus simplifies the present analysis.