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3 Productivity and Economic Growth

Dale W. Jorgenson

3.1 Introduction

The purpose of this chapter is to commemorate fifty years of research on economic measurement. I have chosen a theme—economic growth and its sources—that has played a highly significant and continuing role in the Conference on Research in Income and Wealth. Economic growth was a major professional concern of Simon Kuznets, the founder of the conference. During the last quarter of his life, Kuznets (1971) devoted much of his prodigious energy and talent to the study of economic growth. A sizable portion of the research on economic growth that I will review first appeared in the conference proceedings, Studies in Income and Wealth. Finally, growth is currently undergoing a dramatic resurgence in interest among economists. This interest is motivated in large part by practical concerns arising from the great slowdown in economic growth that occurred during the 1970s and has continued to the present.

Until very recently the study of sources of economic growth has been based on the notion of an aggregate production function. This concept is one of those masterful simplifications that make it possible to summarize a welter of detailed information within a single overarching framework. It is also a concept that seems tailor-made for the interpretation of data on output, input, and productivity of the type compiled in national product accounts. At the same time the concept of an aggregate production function is highly problematical, requiring very stringent assumptions on production patterns at the level of individual sectors of the economy. Intuitively speaking, the technology of each sector must contain a replica of the aggregate production function. It will be useful to spell out the assumptions underlying the aggregate production function and their implications in more detail below.

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The origins of the concept of an aggregate production function can be clearly identified in the work of Paul H. Douglas and his associates. It is important to distinguish carefully between the notion of an aggregate production function and Douglas's more frequently cited contribution, the linear logarithmic or Cobb-Douglas functional form. Douglas did not make this distinction himself, but the existence of an aggregate production function is implied by the way he used the Cobb-Douglas function. Douglas introduced the aggregate production function in 1928 and pursued its empirical implementation with single-mindedness and determination until his election as U.S. senator from Illinois in 1948. He returned to the topic after his retirement from the Senate. His last contribution, published posthumously in 1976, appeared almost half a century after his initial paper. Douglas's body of empirical research is one of the major achievements in economic measurement of the first half of the twentieth century.

At first, Douglas and his collaborators worked in isolation, but their work gradually attracted the interest of other economists. The starting point for our discussion of economic growth is a notable but neglected article by the great Dutch economist, Jan Tinbergen, published in German in 1942.[1] Tinbergen's contribution is clearly recognizable as one of the earliest formulations of what we now call the neoclassical theory of economic growth. The supply side of the model was based on an aggregate production function. However, Tinbergen took a critical step beyond the conception employed by Douglas. He added a time trend to the function of capital and labor inputs, representing the level of "efficiency." Tinbergen's work languished in obscurity until the mid-1950s, when it was revived by Stefan Valavanis-Vail (1955). In the meantime, the notion of efficiency or total factor productivity was introduced independently by George J. Stigler (1947) and became the starting point for a major research program at the National Bureau of Economic Research.

The National Bureau program involved such pioneers of economic measurement as Moses Abramovitz and Solomon Fabricant and culminated in the epoch-making monograph by John W. Kendrick, *Productivity Trends in the United States*, published in 1961. Kendrick's work focused on the United States and employed an explicit system of national production accounts, including measures of output, input, and productivity for national aggregates and individual industries. The production account incorporated data on outputs from earlier studies by the National Bureau, especially the work of Kuznets (1961) on national product. The input side employed data from other research work at the National Bureau, including data on capital from Raymond Goldsmith's (1962) system of national wealth accounts. However, much of the data was generated by Kendrick himself. Kendrick's achievement is an important milestone in the progress of economic measurement during the second half of the twentieth century.

The contributions of Douglas and Tinbergen were integrated with the national product accounts generated by Kendrick (1956) in Robert Solow's frequently cited 1957 article, "Technical Change and the Aggregate Production Function." This article unified the economic theory of production, econometric methods for fitting production functions, and the generation of production accounts at the national level. Solow's work is solidly within the tradition of production modeling established by Douglas and extended by Tinbergen, but it goes beyond this tradition by generating index numbers appropriate to econometric modeling. Solow's approach was instrumental in the further extensions of Douglas's framework by Arrow, Chenery, Minhas, and Solow (1961), introducing the elasticity of substitution as a parameter to be estimated by econometric methods.

An excellent overview of research on sources of economic growth, including alternative data sources and methodologies, is provided by the Rees Report to the National Research Council (1979). Christensen, Cummings, and Jorgenson (1980) and Maddison (1987) have reviewed international comparisons of sources of economic growth among industrialized countries, while Kravis (1976) has surveyed international comparisons of productivity. Griliches (1984), Mansfield (1984), and Nelson (1981) have reviewed research on productivity at the level of the individual firm. Detailed surveys of the literature on productivity have been presented by Kennedy and Thirlwall (1972), Link (1987), and Nadiri (1970, 1972).

3.1.1 Sources of U.S. Economic Growth.

The conceptual framework developed by Kendrick, Solow, and other pioneers in the study of economic growth can be illustrated by the results presented in table 3.1. At the aggregate level, output is represented by the quantity of value added, which is expressed as a function of capital and labor inputs and the level of productivity. Growth rates for the period 1947–85 are given for output and the two inputs in the first column of table 3.1. Value added grows at the rate of 3.28% per year, while capital grows at 3.88% and labor input grows at 1.81%. The contributions of capital and labor inputs are obtained by weighting the corresponding growth rates by the shares of the inputs in value added. This produces the familiar allocation of growth to its sources: capital input is the most important source of growth in output by a substantial margin, accounting for 44.2% of economic growth during the period. Labor input accounts for 34.1% of growth. Capital and labor inputs together account for almost four-fifths of economic growth, while productivity accounts for only 21.6%.

The findings summarized in table 3.1 are not limited to the period as a whole. In the first panel of table 3.1 the growth of output is compared with the contributions of the two primary factor inputs and productivity growth for eight subperiods—1947–53, 1953–57, 1957–60, 1960–66, 1966–69, 1969–73, 1973–79, and 1979–85. The end points of the periods identified in table 3.1, except for the last period, are years in which a cyclical peak occurred. The growth rate presented for each subperiod is the average annual growth

Table 3.1 **Aggregate Output, Inputs, and Productivity: Rates of Growth, 1947–85**

Variable	1947–85	1947–53	1953–57	1957–60	1960–66	1966–69	1969–73	1973–79	1979–85
Value-added	.0328	.0529	.0214	.0238	.0472	.0360	.0306	.0212	.0222
Capital input	.0388	.0554	.0401	.0229	.0367	.0437	.0421	.0392	.0262
Labor input	.0181	.0251	.0037	.0124	.0248	.0226	.0128	.0219	.0146
Contribution of capital input	.0145	.0215	.0149	.0083	.0142	.0167	.0149	.0140	.0098
Contribution of labor input	.0112	.0153	.0022	.0077	.0151	.0140	.0082	.0139	.0089
Rate of productivity growth	.0071	.0160	.0043	.0078	.0179	.0053	.0074	−.0067	.0034
Contribution of capital quality	.0058	.0126	.0069	.0016	.0053	.0058	.0054	.0045	.0022
Contribution of capital stock	.0088	.0090	.0080	.0067	.0089	.0108	.0095	.0095	.0077
Contribution of labor quality	.0039	.0060	.0038	.0084	.0041	.0030	.0018	.0024	.0026
Contribution of hours worked	.0073	.0093	−.0016	−.0007	.0110	.0110	.0065	.0114	.0063
Rates of sectoral productivity growth	.0088	.0142	.0083	.0112	.0190	.0060	.0097	−.0012	.0029
Reallocation of value added	−.0019	.0007	−.0044	−.0021	−.0021	−.0007	−.0023	−.0053	.0006
Reallocation of capital input	.0005	.0003	.0013	.0005	.0009	.0001	.0006	−.0001	.0009
Reallocation of labor input	−.0003	.0009	−.0009	−.0019	.0001	−.0002	−.0005	−.0000	−.0010

rate between cyclical peaks. The contributions of capital and labor inputs are the predominant sources of U.S. economic growth for the period as a whole and all eight subperiods.

I have found that the contribution of capital input is the most significant source of output growth for the period 1947–85 as a whole. The contribution of capital input is also the most important source of growth for seven of the eight subperiods, while productivity growth is the most important source for only one, 1960–66. The contribution of capital input exceeds the contribution of labor input for seven subperiods, while the contribution of labor input is more important only for the period 1960–66. The contribution of labor input exceeds productivity growth for four of the eight subperiods.

In 1985 the output of the U.S. economy stood at almost three-and-a-half times the level of output in 1947. My overall conclusion is that the driving force behind the expansion of the U.S. economy between 1947 and 1985 has been the growth in capital and labor inputs. Growth in capital input is the most important source of growth in output, growth in labor input is the next most important source, and productivity growth is least important. This perspective focuses attention on the mobilization of capital and labor resources rather than advances in productivity.

The findings just summarized are consistent with a substantial body of research. For example, these findings coincide with those of Christensen and Jorgenson (1973a) for the United States for the period 1929–69 and the much earlier findings of Tinbergen (1942) for the period 1870–1914. Maddison (1987) gives similar results for six industrialized countries, including the United States, for the period 1913–84. However, these findings contrast sharply with those of Abramovitz, Kendrick, and Solow, which emphasize productivity as the predominant growth source. At this point it is useful to describe the steps required to go from these earlier findings to the results summarized in table 3.1.

The first step is to decompose the contributions of capital and labor inputs into the separate contributions of capital and labor quality and the contributions of capital stock and hours worked. Capital stock and hours worked are a natural focus for input measurement since capital input would be proportional to capital stock if capital inputs were homogeneous, while labor input would be proportional to hours worked if labor inputs were homogeneous. In fact, inputs are enormously heterogeneous, so that measurement of input aggregates involves compiling data on components of each input and weighting the growth rates of the components by the corresponding value shares. Capital and labor quality have growth rates equal to the differences between the growth rates of input measures that take account of heterogeneity and measures that ignore heterogeneity. In the Kendrick-Solow approach these components are ignored, since inputs are treated as homogeneous.

The results presented in table 3.1 reveal that the assumption of homogeneous capital and labor inputs is highly misleading. We find that growth in the quality of capital stock accounts for two-fifths of the growth of capital input during the period 1947–85. This quantitative relationship also characterizes the eight subperiods. For the period as a whole we find that the growth of labor quality accounts for more than one-third of the growth of labor input. The growth in hours worked actually falls below the growth in the quality of hours worked for the period 1953–60. For the period 1966–79 the contribution of hours worked accounts for almost two-thirds of the contribution of labor input. The relative proportions of growth in hours worked and labor quality are far from uniform. Although these proportions vary greatly from period to period, there is a decline in the relative importance of labor quality after 1960.

The development of measures of labor input reflecting heterogeneity is one of the many pathbreaking contributions of Edward F. Denison (1961, 1962b) to the analysis of sources of economic growth. Table 3.1 is based on an extension and revision of the measures of labor input presented by Jorgenson, Gollop, and Fraumeni (1987). Hours worked are cross-classified by age, sex, education, and employment status and weighted by wage rates.[2] A total of 160 types of labor input are distinguished at the aggregate level. Denison (1969, 1972) continues to adhere to capital stock as a measure of capital input. This approach ignores the heterogeneity among components of capital input reflected in the growth of capital quality in table 3.1. In this table, capital stocks are cross-classified by type of asset and legal form of organization and weighted by rental prices. At the aggregate level, a total of 169 components of capital input are measured separately. Assets of different ages are weighted in accord with profiles of relative efficiency constructed by Hulten and Wykoff (1981a).

The point has come where it is necessary to be more precise about the concept of an aggregate production function. In technical jargon the existence of an aggregate production function requires that the technology of each sector is separable in value added and that value added is a function of capital and labor inputs and the level of technology. Moreover, the sectoral value-added functions must be identical for all sectors, while the functions relating labor and capital inputs to their components must also be identical for all sectors. Finally, each component of these input aggregates must receive the same price in all sectors.

The assumptions just enumerated are well known to aggregation theorists and have achieved broader recognition as a consequence of the "reswitching controversy" initiated by Samuelson (1962). The lack of surface plausibility in this set of assumptions has not deterred economists from applying the concept of an aggregate production function in analyzing the sources of economic growth. The obvious question is, why? To attempt to answer this question we can decompose the rate of aggregate productivity growth into its sources at the level of 37 sectors of the U.S. economy. Fortunately, the data for production patterns in these sectors can be generated in a way that avoids the assumptions that underly the aggregate production model. This makes it possible to test the assumptions of the model and assess the importance of departures from these assumptions empirically.

Aggregate productivity growth can be represented as a weighted sum of sectoral productivity growth rates with weights given by ratios of the value of output in each sector to value added in all sectors. In addition, the aggregate productivity growth rate depends on reallocations of value added, capital input, and labor input among sectors. The growth rates of the reallocations are the differences between growth rates of aggregate indexes of value added, capital input, and labor input and the corresponding indexes obtained by weighting each of the components by prices specific to each sector. For example, the index of aggregate labor input involves weighting up the 160 components of labor input. The reallocation of labor input is the difference between this index and an index that separately weights the 5,920 types of labor input, cross-classified by the 37 sectors of the U.S. economy as well as the characteristics of labor input distinguished at the aggregate level.

Reallocations of value added, capital input, and labor input are measures of departures from the assumptions that underly the aggregate production model. Reallocations of value added incorporate differences in value-added functions among sectors and departures from the separability assumptions required for the existence of a value-added function in each sector. Reallocations of capital and labor inputs include differences in capital and labor aggregates among sectors, departures from separability assumptions required for the existence of these aggregates, and differences in prices of individual capital and labor inputs among sectors.

For the period 1947–85 as a whole the rate of aggregate productivity growth is somewhat lower than the weighted sum of sectoral productivity growth rates. The reallocations of value added, capital input, and labor input are small but not negligible, so that the model of production based on an aggregate production function provides a valuable and useful summary of the data. However, we find that the reallocations, especially the reallocation of value added, are very large for the periods 1953–57 and 1973–79. The contributions of the reallocations during the 1973–79 period contribute to a precipitous drop in the aggregate productivity growth rate.

I have already noted that the growth rate of output in the U.S. economy averaged 3.28% per year during the postwar period, 1947–85. During the subperiod 1973–79 the average growth rate is only 2.12%, a decline of 1.16%. The contribution of capital input declined by only 0.05% per year between the two periods, while the contribution of labor input actually increased by 0.27%. The decline in the rate of productivity growth was 1.38%, more than the decline in the growth rate of output. In the last panel of table 3.1 we can see that the weighted sum of sectoral productivity growth rates was negative for the period 1973–79 at 0.12% per year. The 1% decline in this sum is almost sufficient to account for the slowdown in U.S. economic growth. The decline in productivity growth at the sectoral level was augmented by a negative contribution of 0.53% per year from the reallocation of value added.

My conclusion from table 3.1 is that the aggregate production model used in analyzing economic growth by Denison, Kendrick, Kuznets, Maddison, Solow, Tinbergen, and a long list of others is appropriate for studying long-term growth trends. However, this model is highly inappropriate for analyzing the sources of growth over shorter periods. In fact, the aggregate production model has become a serious obstacle to understanding the causes of the slowdown in economic growth in the United States and other industrialized countries during the period 1973–79. There is a real danger that the analysis of economic growth will remain wrapped in the straitjacket of the aggregate production model. A disaggregated data set, like that presented in table 3.1, shows that the assumptions underlying this model are clearly inconsistent with the empirical evidence.

3.1.2 Sources of Sectoral Growth

The major accomplishment of recent research on the sources of U.S. economic growth is the integration of the growth of intermediate, capital, and labor inputs at the level of individual industrial sectors into an analysis of the sources of growth for the economy as a whole. This integration makes it possible to attribute U.S. economic growth to its sources at the level of individual industries. In table 3.1 the sources of U.S. economic growth are allocated among contributions of growth in capital and labor inputs, changes in productivity at the sectoral level, and intersectoral shifts of outputs and inputs.

The analysis of sources of growth at the industry level is based on the decomposition of the growth rate of sectoral output into the sum of the contributions of intermediate, capital, and labor inputs and the growth of productivity. The contribution of each input is the product of the value share of the input and its growth rate. In table 3.2 I compare the growth rate of output with the contributions of the three inputs and the growth of productivity for the period 1947–85. The sum of the contributions of intermediate, capital, and labor inputs is the predominant source of growth of output for 33 of the 37 sectors included in table 3.2.

Comparing the contribution of intermediate input with other sources of output growth, we find that this input is by far the most significant source of growth. The contribution of intermediate input exceeds productivity growth and the contributions of capital and labor inputs. If we focus attention on the contributions of capital and labor inputs alone, excluding intermediate input from consideration, we find that these two inputs are a more important source of growth than changes in productivity.

The findings presented in table 3.2 are based on the symmetrical treatment of intermediate, capital, and labor inputs.[3] To provide additional insight into

Table 3.2 Growth in Sectoral Output and Its Sources, 1947–85 (Average Annual Rates)

		Contributions to Growth in Output			
Industry	Rate of Output Growth	Intermediate Input	Capital Input	Labor Input	Rate of Productivity Growth
Agriculture, forestry & fisheries	.0192	.0068	.0014	−.0051	.0161
Metal mining	.0012	.0067	.0067	−.0071	−.0051
Coal mining	.0078	.0090	.0071	−.0098	.0015
Crude petroleum & natural gas	.0187	.0149	.0160	.0061	−.0182
Nonmetallic mineral mining	.0234	.0099	.0061	−.0003	.0077
Construction	.0308	.0182	.0028	.0086	.0012
Food & kindred products	.0228	.0160	.0010	.0001	.0057
Tobacco manufactures	.0033	.0065	.0017	−.0011	−.0039
Textile mill products	.0201	.0111	.0009	−.0022	.0103
Apparel & other textile products	.0245	.0106	.0012	.0010	.0118
Lumber & wood products	.0199	.0128	.0039	−.0014	.0046
Furniture & fixtures	.0299	.0150	.0024	.0046	.0078
Paper & allied products	.0318	.0189	.0049	.0034	.0047
Printing & publishing	.0299	.0185	.0040	.0070	.0004
Chemicals & allied products	.0457	.0217	.0080	.0041	.0119
Petroleum refining	.0288	.0169	.0021	.0010	.0088
Rubber & plastic products	.0453	.0272	.0015	.0083	.0084
Leather & leather products	−.0150	−.0118	.0005	−.0063	.0026
Stone, clay & glass products	.0252	.0142	.0040	.0030	.0040
Primary metals	.0032	.0038	.0010	−.0009	−.0007
Fabricated metal products	.0228	.0112	.0035	.0048	.0033
Machinery, except electrical	.0398	.0184	.0058	.0058	.0098
Electrical machinery	.0534	.0222	.0057	.0092	.0164
Motor vehicles	.0351	.0233	.0040	.0014	.0064
Other transportation equipment	.0441	.0273	.0039	.0105	.0024
Instruments	.0505	.0186	.0072	.0123	.0123
Miscellaneous manufacturing	.0204	.0090	.0023	−.0016	.0107
Transportation & warehousing	.0223	.0105	.0021	−.0006	.0103
Communication	.0637	.0113	.0223	.0083	.0218
Electric utilities	.0543	.0189	.0164	.0043	.0147
Gas utilities	.0398	.0285	.0075	.0017	.0020
Trade	.0354	.0113	.0074	.0062	.0104
Finance, insurance, & real estate	.0405	.0142	.0118	.0134	.0011
Other services	.0388	.0183	.0081	.0137	−.0013
Government enterprises	.0330	.0175	.0081	.0098	−.0025
Private households	.0489		.0494	−.0006	
Government, excluding government enterprises	.0316			.0316	

the sources of economic growth at the sectoral level, we can decompose the growth rate of intermediate input into growth of an unweighted index of intermediate input and growth in intermediate input quality. As before, we can decompose the growth of capital input into growth in capital stock and capital quality. Finally, we can decompose the growth of labor input into growth in hours worked and labor quality. In table 3.3 this decomposition is presented for 37 sectors for the period 1947–85.

We find that growth in quality is not an important component of growth in intermediate input. Inferences about the predominant role of intermediate input would be unaffected by the omission of changes in quality. Excluding intermediate input from consideration, however, we find that the relative importance of productivity growth and the contributions of capital and labor inputs would be reversed by using measures that omit changes in input quality. The incorporation of intermediate input is an important innovation in the methodology employed in generating the data presented in tables 3.2 and 3.3. The second major innovation is the measurement of changes in the quality of capital and labor inputs at the sectoral level.

The perspective on U.S. economic growth suggested by the results presented in tables 3.2 and 3 emphasizes the contribution of mobilization of resources within individual industries. The explanatory power of this perspective is overwhelming at the sectoral level. For 33 of the 37 industrial sectors included in tables 3.2 and 3.3, the contribution of intermediate, capital, and labor inputs is the predominant source of output growth. Changes in productivity account for the major portion of output growth in only four sectors.

3.1.3 Summary

The findings on the sources of U.S. economic growth summarized in tables 3.1, 3.2, and 3.3 have been generated by a truly massive empirical research effort. In section 3.2 I describe the sources and methods for construction of data on labor input. These data have incorporated all the annual detail on employment, weeks, hours worked, and labor compensation published in the decennial Census of Population and the Current Population Survey. Similarly, the data on capital input described in section 3.3 have incorporated all the available detail on investment in capital goods by industry and class of asset and on property compensation by legal form of organization from the U.S. national income and product accounts (NIPA). Finally, the data on intermediate input and output described in section 3.4 have incorporated all of the available annual data by industry from the U.S. national income and product accounts and the U.S. interindustry accounts.

The application of the theory of index numbers to the measurement of labor input requires weighting the components of labor input by wage rates. This was carried out at the aggregate level by Denison (1962b) and implemented for all industrial sectors of the U.S. economy by Gollop and Jorgenson (1980, 1983). Similarly, the measurement of capital as a factor of production involves weighting the components of capital input by rental rates. The conceptual basis for imputing rental prices for capital goods was established by Jorgenson (1963). These rental prices were employed in aggregate productivity measurement by Jorgenson and Griliches (1967). The rental price concept was further elaborated by Hall and Jorgenson (1967). This concept was implemented at the aggregate level by Christensen and Jorgenson (1969) and at the sectoral level by Fraumeni and Jorgenson (1980, 1986) and Gollop and Jorgenson (1980).

The model of capital as a factor of production originated by Walras (1954) was extended to encompass quality change for capital goods and relative efficiencies for capital goods of different vintages by Hall (1971). Hall's methodology generalizes the "hedonic technique" for measuring quality change of capital goods employed by Griliches (1961b). This methodology has been exploited by Hulten and Wykoff (1981b) in measuring depreciation of capital goods from vintage price data. Griliches (1964), Stone (1956), and Triplett (1983a, 1986) have discussed the rationale for incorporating quality-corrected price indexes into systems of national accounts.

The final step in developing the methodology for analyzing sources of economic growth is to aggregate over individual industrial sectors. This step is critical in integrating the analysis of sources of growth for individual industries into the analysis of growth for the economy as a whole. The methodology for aggregation over sectors originated by Domar (1961) has been generalized by Hulten (1978) and Jorgenson (1980). This methodology was implemented for the U.S. by Fraumeni and Jorgenson (1980, 1986) and underlies the data on aggregate productivity change presented in table 3.1. I describe sources and methods for construction of data on aggregate output, input, and productivity in section 3.5.

At a methodological level the integration of data generation and econometric modeling is an important achievement of recent research on the sources of economic growth. The extensive data development described in sections 3.2, 3.3, and 3.4 is firmly rooted in the economic theory of production. The conceptual basis for the measures of intermediate, capital, and labor inputs in Tables 3.1, 3.2, and 3.3 is provided by the theory of exact index numbers employed by Diewert (1976). Diewert showed that the index numbers utilized, for example, by Christensen and Jorgenson (1969) could be generated from the translog production function introduced by Christensen, Jorgenson, and Lau (1971, 1973).

The integration of the analysis of sources of economic growth with econometric modeling of producer behavior has suggested two alternative modeling strategies. The first is based on an aggregate production function, originally introduced by Cobb and Douglas (1928) and developed by Tinbergen (1942) in the form used for the analysis of sources of growth for the economy as a whole. A second strategy for modeling producer behavior is to disaggregate to the level of individual industrial sectors and replace the aggregate

Table 3.3 **Contributions of Input Quality to Growth in Sectoral Output: Rates of Growth, 1947–85**

	Average Annual Rates of Growth						
Industry	Quality of Intermediate Input	Unweighted Intermediate Input	Quality of Capital Stock	Capital Stock	Quality of Hours Worked	Hours Worked	Rate of Productivity Growth
Agriculture, forestry & fisheries	−.0004	.0071	.0023	−.0009	.0020	−.0071	.0161
Metal mining	−.0001	.0068	.0026	.0041	.0013	−.0083	−.0051
Coal mining	.0012	.0078	.0000	.0070	.0012	−.0110	.0015
Crude petroleum & natural gas	−.0010	.0159	.0007	.0152	.0013	.0048	−.0182
Nonmetallic mineral mining	.0000	.0099	.0001	.0060	.0011	−.0014	.0077
Construction	.0003	.0179	.0005	.0024	.0009	.0077	.0012
Food & kindred products	−.0005	.0165	.0002	.0007	.0005	−.0004	.0057
Tobacco manufactures	.0005	.0060	−.0001	.0017	.0006	−.0017	−.0039
Textile mill products	.0002	.0110	.0004	.0006	.0005	−.0027	.0103
Apparel & other textile products	.0008	.0098	.0002	.0010	.0005	.0004	.0118
Lumber & wood products	.0008	.0120	.0006	.0033	.0009	−.0023	.0046
Furniture & fixtures	.0000	.0150	.0003	.0021	.0008	.0038	.0078
Paper & allied products	.0000	.0189	.0014	.0034	.0012	.0022	.0047
Printing & publishing	.0001	.0184	.0012	.0028	.0014	.0056	.0004
Chemicals & allied products	−.0004	.0222	.0027	.0053	.0013	.0028	.0119
Petroleum refining	.0020	.0149	.0002	.0019	.0004	.0005	.0088

Rubber & plastic products	.0001	.0271	.0005	.0009	.0012	.0071	.0084
Leather & leather products	.0006	−.0124	−.0009	.0014	.0005	−.0068	.0026
Stone, clay & glass products	.0002	.0140	.0010	.0029	.0015	.0015	.0040
Primary metals	.0002	.0036	−.0009	.0020	.0008	−.0016	−.0007
Fabricated metal products	.0000	.0112	.0002	.0033	.0011	.0038	.0033
Machinery, except electrical	.0005	.0179	.0006	.0051	.0014	.0044	.0098
Electrical machinery	.0010	.0211	.0002	.0055	.0019	.0073	.0164
Motor vehicles	.0003	.0231	−.0008	.0048	.0007	.0007	.0064
Other transportation equipment	.0004	.0269	.0025	.0014	.0018	.0087	.0024
Instruments	.0000	.0186	.0004	.0068	.0021	.0102	.0123
Miscellaneous manufacturing	.0001	.0089	.0003	.0020	.0011	−.0026	.0107
Transportation & warehousing	.0004	.0102	.0025	−.0004	.0007	−.0014	.0103
Communication	.0001	.0112	.0039	.0184	.0018	.0065	.0218
Electric utilities	−.0009	.0198	.0022	.0142	.0008	.0035	.0147
Gas utilities	−.0025	.0311	.0015	.0060	.0007	.0011	.0020
Trade	.0003	.0111	.0025	.0049	.0016	.0046	.0104
Finance, insurance, & real estate	.0003	.0139	.0028	.0091	.0022	.0112	.0011
Other services	.0002	.0181	.0026	.0055	.0008	.0128	−.0013
Government enterprises	.0000	.0175	.0003	.0079	.0001	.0097	−.0025
Private households			.0121	.0373	−.0001	−.0005	
Government, excluding government enterprises					.0038	.0278	

production model by a general equilibrium model of production. Models of this type have been constructed for all U.S. industries by Berndt and Jorgenson (1973), Jorgenson and Fraumeni (1981), and Jorgenson (1984b).

The essential idea of the disaggregated approach is to model producer behavior through complete systems of demand functions for inputs into each industrial sector. This approach is a lineal descendant of the general equilibrium models of production introduced by Leontief (1951). By successive steps it is possible to relax the "fixed coefficients" assumption of input-output analysis by making the input-output coefficients functions of the input prices. This approach has the added advantage of relaxing the assumption of value added separability at the sectoral level. Finally, the approach makes it possible to endogenize the rate of productivity growth in each sector by making this growth rate a function of the input prices.

In section 3.6 I review the two modeling strategies outlined above and alternative strategies proposed in the econometric literature. The benefits of the radical simplifications that result from an aggregate production model must be weighed against the costs of departures from the highly restrictive assumptions that underly this model. The limitations of the aggregate production model can be illustrated by an analysis of the slowdown in U.S. economic growth since 1973. An econometric model of productivity growth for all U.S. industries is required for an explanation of the slowdown. In section 3.7 I conclude with a summary of the implications of recent studies of the sources of economic growth for future research on economic measurement.

3.2 Measuring Labor Input

The methodology for productivity measurement that underlies the data presented in tables 3.2 and 3.3 is based on a model of producer behavior. The point of departure for this model is a homogeneous production function $\{F^i\}$ for each of n industrial sectors:

$$Z_i = F^i(X_i, K_i, L_i, T), \quad (i = 1, 2, \ldots, n),$$

where T is time, $\{Z_i\}$ is output, and $\{X_i\}$, $\{K_i\}$, and $\{L_i\}$ are intermediate, capital, and labor inputs. We can define the shares of intermediate, capital, and labor inputs, say $\{v_X^i\}$, $\{v_K^k\}$, and $\{v_L^i\}$, in the value of output by:

$$v_X^i = \frac{P_X^i X_i}{q_i Z_i},$$

$$v_K^i = \frac{p_K^i K_i}{q_i Z_i},$$

$$v_L^i = \frac{p_L^i L_i}{q_i Z_i}, \quad (i = 1, 2, \ldots, n),$$

where $\{q_i\}$, $\{p_X^i\}$, $\{p_K^i\}$ and $\{p_L^i\}$ denote the prices of output and intermediate, capital, and labor inputs, respectively.

To analyze substitution among inputs I combine the production function for each sector with necessary conditions for producer equilibrium. These conditions are given by equalities between the shares of each input in the value of output and the elasticities of output with respect to that input:

$$\begin{aligned} v_X^i &= \frac{\partial \ln Z_i}{\partial \ln X_i}(X_i, K_i, L_i, T), \\ v_K^i &= \frac{\partial \ln Z_i}{\partial \ln K_i}(X_i, K_i, L_i, T), \\ v_L^i &= \frac{\partial \ln Z_i}{\partial \ln L_i}(X_i, K_i, L_i, T), \quad (i = 1, 2, \ldots, n). \end{aligned}$$

Under constant returns to scale, the elasticities and the value shares for all three inputs sum to unity, so that the value of output is equal to the value of the inputs.

Finally, we can define the rate of productivity growth, say $\{v_T^i\}$, for each sector, as the rate of growth of output with respect to time, holding intermediate, capital, and labor inputs constant:

$$v_T^i = \frac{\partial \ln Z_i}{\partial T}(X_i, K_i, L_i, T), \quad (i = 1, 2, \ldots, n).$$

It is important to note that this definition does not impose any restriction on substitution patterns among inputs. I employ the rate of productivity growth in analyzing changes in substitution possibilities over time.

3.2.1. Exact Index Numbers

The production function for each sector listed in tables 3.2 and 3.3 is defined in terms of output and intermediate, capital, and labor inputs. Each of the inputs is an aggregate that depends on the quantities of individual intermediate, capital, and labor inputs:

$$\begin{aligned} X_i &= X_i(X_{1i}, X_{2i} \ldots X_{ni}), \\ K_i &= K_i(K_{1i}, K_{2i} \ldots K_{pi}), \\ L_i &= L_i(L_{1i}, L_{2i} \ldots L_{qi}), \quad (i = 1, 2, \ldots, n), \end{aligned}$$

where $\{X_{ji}\}$ is the set of n intermediate inputs from the jth sector ($j = 1, 2, \ldots, n$), $\{K_{ki}\}$ the set of p capital inputs, and $\{L_{li}\}$ the set of q labor inputs. Here the production function is separable in intermediate, capital, and labor inputs.[4] If these inputs are each homogeneous in their components, we say that the production function is homothetically separable.[5] The aggregates for each sector are characterized by constant returns to scale.

The shares of the individual intermediate, capital, and labor inputs, say $\{v^i_{Xj}\}$, $\{v^i_{Kk}\}$, and $\{v^i_{Ll}\}$, can be defined in the values of the corresponding aggregates by:

$$v^i_{Xj} = \frac{p^i_{Xj} X_{ji}}{p^i_X X_i}, \quad (i, j = 1, 2, \ldots, n),$$

$$v^i_{Kk} = \frac{p^i_{Kk} K_{ki}}{p^i_K K_i}, \quad (i = 1, 2, \ldots, n;\ k = 1, 2, \ldots, p),$$

$$v^i_{Ll} = \frac{p^i_{Ll} L_{li}}{p^i_L L_i}, \quad (i = 1, 2, \ldots, n;\ l = 1, 2, \ldots, q),$$

where $\{p^i_{Xj}\}$, $\{p^i_{Kk}\}$, and $\{p^i_{Ll}\}$ are the prices of individual intermediate, capital, and labor inputs.

Necessary conditions for producer equilibrium are given by equalities between the shares of the individual inputs in the values of the corresponding aggregates and the elasticities of the aggregate with respect to the individual inputs:

$$v^i_{Xj} = \frac{\partial \ln X_i}{\partial \ln X_{ji}} (X_{1i}, X_{2i}, \ldots, X_{ni}),$$

$$v^i_{Kk} = \frac{\partial \ln K_i}{\partial \ln K_{ki}} (K_{1i}, K_{2i}, \ldots, K_{pi}),$$

$$v^i_{Ll} = \frac{\partial \ln L_i}{\partial \ln L_{li}} (L_{1i}, L_{2i}, \ldots, L_{qi}), \quad (i = 1, 2, \ldots, n).$$

Under constant returns to scale, the values of intermediate, capital, and labor inputs are equal to the sums of the values of their components.

The methodology that underlies the data presented in tables 3.2 and 3.3 is based on sectoral production functions of the translog form introduced by Christensen, Jorgenson, and Lau (1971, 1973).[6] Given translog production functions for all sectors, the corresponding price and quantity index numbers can be generated for all three inputs. The growth rate of each input between two periods is a weighted average of growth rates of its components. Weights are given by the average share of each component in the value of the input for the two periods. The corresponding price indexes are defined as ratios of the values of the inputs to the translog quantity indexes. Similarly, the translog index of productivity growth is the difference between the growth rate of output and a weighted average of growth rates of intermediate, capital, and labor inputs.[7]

The critical innovation in the methodology that underlies tables 3.2 and 3.3 is to distinguish among components of intermediate, capital, and labor inputs that differ in marginal productivity. For each sector intermediate input is represented as a function of deliveries from all other sectors. Capital input is broken down by class of asset and legal form of organization. Finally, labor input is broken down by characteristics of individual workers such as sex, age, education, and employment status.

3.2.2 Data Sources and Methods for Labor Input

A novel feature of the indexes of the quantity of labor input presented in tables 3.2 and 3.3 is that these indexes incorporate data from both establishment and household surveys. Estimates of employment, hours worked, and labor compensation for each industrial sector are controlled to totals based on establishment surveys that underlie the U.S. national income accounts. These totals are allocated among categories of the work force cross-classified by the characteristics of individual workers on the basis of household surveys. The resulting estimates of hours worked and average compensation per hour for each sector provide the basis for the indexes of labor input presented in table 3.2.

For each of the 37 sectors listed in table 3.2, prices and quantities of labor input are cross-classified by the two sexes, eight age groups, five educational groups, and two employment statuses—employee and self-employed. Annual data from 1947 to 1985 on hours worked and average labor compensation per hour are required for 160 components of the work force in each industry. For this purpose, employment, hours, weeks, and labor compensation within each sector are allocated on the basis of the available cross-classifications.[8] This methodology makes it possible to exploit all the published detail on labor input from the decennial Census of Population and the Current Population Survey.

The first step in developing sectoral measures of labor input is to construct employment matrices cross-classified by sex, age, education, and employment status for each year on the basis of household surveys from the Census of Population and the Current Population Survey. The resulting employment matrices are controlled to employment totals for each sector on the basis of establishment surveys from the U.S. national income and product accounts.[9] Hours worked by workers cross-classified by demographic characteristics are estimated on the basis of household surveys. The resulting estimates are controlled to totals for each industrial sector from the U.S. national accounts.[10] The third step in developing sectoral measures of labor input is to construct labor compensation matrices for each year on the basis of the Census of Population.[11] Control totals for annual labor compensation are taken from the U.S. national income accounts.

Average hourly compensation per person for employees is based on data on wage and salary income from the Census of Population. Differences in outlay on labor input per person reflect differences in marginal products among workers. However, the cost of labor input from the point of view of the producer also includes supplements. Differences in wage and salary income must be adjusted to incorporate employers' contributions to Social Security and unemployment compensation and other supplements to wages and salaries.

Earnings reported by the census for self-employed workers and income of unincorporated enterprises from the U.S. national income accounts include both labor and property income. Income from unincorporated enterprises can be divided between labor and property components, assuming that after tax rates of return are the same for corporate and noncorporate business. Labor compensation is distributed among the self-employed on the basis of wage differentials among employees in the corresponding industrial sector. To derive labor compensation per hour worked for each category of labor input, total labor compensation is divided by annual hours worked for each category.

The final step in constructing data on labor input for each of the 37 sectors is to combine price and quantity data, cross-classified by sex, age, education, and employment status, into price and quantity indexes of labor input. To construct an index of labor input for each sector, we express sectoral labor input, say $\{L_i\}$, as a translog function of its 160 individual components, say $\{L_{ji}\}$. The corresponding index of sectoral labor input is a translog quantity index of individual labor inputs:

$$\ln L_i(T) - \ln L_i(T-1) = \Sigma \bar{v}^i_{Ll} [\ln L_{li}(T) - \ln L_{li}(T-1)],$$

$$(i = 1, 2, \ldots, n),$$

where weights are given by average shares of each component in the value of sectoral labor compensation:

$$\bar{v}^i_{Ll} = \frac{1}{2}[v^i_{Ll}(T) + v^i_{Ll}(T-1)], \; (i = 1, 2, \ldots, n; \; l = 1, 2, \ldots, q),$$

and

$$v^i_{Ll} = \frac{p^i_{Ll} L_{li}}{\Sigma p^i_{Ll} L_{li}}, \quad (i = 1, 2, \ldots, n; \; l = 1, 2, \ldots, q).$$

The value shares are computed from data on hours worked $\{L_{li}\}$ and compensation per hour $\{p^i_{Ll}\}$ for each component of sectoral labor input, cross-classified by sex, age, education, and employment class of workers.

A measure of total hours worked for each sector can be derived by adding hours worked across all 160 categories of labor input within that sector. The quality of labor input is defined as the ratio of labor input to hours worked. Changes in the quality of hours worked represent the differences between changes in the translog quantity index of labor input and changes in an unweighted index of hours worked. Quantity indexes of labor input are presented in table 3.2 for 37 sectors. The corresponding indexes of labor input quality and hours worked are presented for each sector in table 3.3.

Translog index numbers for labor input were introduced for individual sectors of the U.S. economy by Gollop and Jorgenson (1980, 1983). The data on labor input that underly tables 3.2 and 3.3 are cross-classified by sex, age, education, employment status, and sector of employment for a total of 5,920 types of labor input. The growth of labor input can be decomposed to obtain the contributions to change in labor quality of all these characteristics.[12]

3.2.3 Alternative Sources and Methods

An overview of issues in the measurement of labor input is provided by the Rees Report (National Research Council 1979, esp. 122–28). Alternative quantity indexes of labor input and the corresponding price indexes are compared by Denison (1961), Kunze (1979), and Triplett (1983b). To provide additional perspective on the measurement of labor input, it is useful to compare the methodology and data sources that underly the indexes presented in tables 3.2 and 3.3, with those of the Bureau of Labor Statistics (BLS) (1983), Denison (1985), and Kendrick (1983a).[13] My comparative analysis covers both labor hours and compensation. I evaluate the alternative approaches in terms of the data sources and the requirements of the theory of producer behavior. Wherever possible, I test the assumptions implicit in the competing models.

My comparison begins with the measurement of hours. The BLS (1983, 66–68) measure of multifactor productivity employs the same data for hours as the traditional BLS (1971) measures of output per hour. About 85% of total hours are based on establishment surveys that collect information on hours paid rather than hours worked. Kendrick (1961a, 382, 496, 503, 515, 559; 1973, 156; 1983a, 56) and Kendrick and Grossman (1980, 25) present a strong case for an hours-worked series but use BLS (1971) establishment data on hours paid for some sectors. As evident from his earliest works, Denison (e.g., 1962b, 352) shares Kendrick's view that hours worked are more appropriate than hours paid.[14]

Both Denison and Kendrick attempt to measure hours worked on the basis of the hours-paid series published by BLS. The *BLS Handbook of Methods for Surveys and Studies* (1971) makes clear that separate hours estimates are developed for production and nonproduction workers only in the manufacturing sectors. According to the handbook (1971, 214–15), manufacturing production worker hours are taken directly from the data in the BLS area wage surveys and the study of *Employer Expenditures* (1963) published by BLS. For the nonmanufacturing industries the hours-paid series collected in the census employment survey program relate to nonsupervisory workers only. BLS assumes that these hours apply to all wage and salary workers. BLS does not provide estimates of hours paid for self-employed and unpaid family workers. For these groups, Denison and, for the most part, Kendrick use household survey data on hours worked.

There are important differences in the demographic mix of the supervisory and nonsupervisory occupations and in the average hours worked for different demographic groups. These differences make suspect the assumption that supervisory and nonsupervisory workers in each nonmanufacturing industry are paid for the same average number of hours per week. For example, according to the census (Bureau of the Census 1972, table 5), the 1970 female to male ratio was .87 in nonsupervisory occupations in the nonmanufacturing sector and only .22 in supervisory occupations. Furthermore, the census (1973a, table 45) data show that female nonsupervisory workers in 1970 worked 34.5 hours on average, while their male counterparts worked 41.5 hours.

Given that women work fewer weekly hours than men and are proportionately underrepresented in supervisory occupations, it is highly unlikely that supervisory laborers are paid for the same number of weekly hours as nonsupervisory laborers. A similar analysis could be based on age or education compositions; the evidence suggests that BLS estimates of annual hours paid are biased downward in the nonmanufacturing sectors. Shifts in the demographic composition of the supervisory and nonsupervisory occupational groups over time will bias estimates of productivity growth.

We next compare the Kendrick and Denison approaches to constructing indexes of labor input. Kendrick considers all workers within each industry to be homogeneous. He completely omits the influence of changing labor quality on his measure of each industry's labor input. Admittedly, Kendrick does distinguish between the hours worked by proprietors and unpaid family workers and those worked by wage and salary employees whenever the former group is a "significant fraction"; of the particular industry's labor force. Since Kendrick (1961a, 261; 1973, 12) decided not to weight labor hours from the two employment classes differently, he eliminates any potential effect of changing labor composition.

Kendrick does not attribute any significance to the differences among marginal products of various categories of workers. For Kendrick, the difference in the value of an hour's work by an electrical engineer and a truck driver should be attributed to differences in productivity rather than differences in labor input. Given Kendrick's definition, the appropriate index of labor input for each sector is an unweighted index of hours worked. By contrast, Denison posits that disaggregation by characteristics is essential in measuring labor input. In his view, however, any change in sector of employment does not reflect changes in labor input and should be captured by the measure of productivity growth.

Denison cross-classifies workers by demographic characteristics such as age, sex, and education in deriving indexes of labor input. He uses census data on earnings to construct weights for use in aggregating his education and sex-age hours series in his original *Sources of Economic Growth* (1962b) and his more recent work on productivity (1974, 1979, 1985). The principal problem with using census earnings data to measure marginal products is that reported earnings exclude all supplements to wages and salaries and include the return to capital invested by self-employed workers. Denison (e.g., 1979, 157–58) makes no adjustment to the census data to exclude returns to capital.

As Denison points out, earnings can be used in weighting the components of labor input only if the average earnings for workers cross-classified by education or by age and sex are proportional to the corresponding marginal products. Since supplements, particularly Social Security and unemployment insurance, are charged to employers, reported earnings do not reflect employers' relative labor outlays. If supplements are neglected, only those ratios of hourly earnings among groups of laborers with annual incomes below the lowest base for supplements will be unbiased estimates of relative wages as viewed by employers.

For example, if the average 35- to 64-year-old male has an annual income above the social security or unemployment insurance tax base, while the average 20- to 24-year-old female's earnings are below either base, then the relative valuation of an average hour's work by males and females based on earnings is clearly upward biased. Supplements add to the employers' outlay for both males and females but, in this example, supplements add proportionately more to the employers' outlay for females than for males. Based on 1969 earnings reported in the decennial *Census* (1973c, tables I and II), employed 35- to 64-year-old males had mean annual earnings ($10,008) well above either the Social Security ($7,800) or unemployment insurance ($3,000) tax bases in 1969. Females 18–24 years of age, however, had mean labor income of $2,960. Ratios of male (35–64 years old) to female (18–24 years old) hourly wage costs excluding supplements are upward biased estimates of relative labor costs incurred by employers.

The assumption of proportionality between earnings and labor outlay is valid only if the ratio of noncorporate property income to total earnings is constant across sex-age and education groups. If the representative 35- to 64-year-old male has a larger fraction of his earnings being generated from capital invested in noncorporate enterprises than does the representative 20- to 24-year-old female, then the earnings-based estimate for the relative valuation of an hour's work by males to an hour's work by females is upward biased. Data measuring the noncorporate property income of workers classified by demographic characteristics are unavailable. However, the reasonableness of Denison's assumption can be evaluated by comparing the distribution of employment in wage and salary versus self-employed activities across sex and age groups.

I refer to data published in the 1970 census to evaluate Denison's assumption. I construct ratios of self-employed persons to total employment in both wage and salary and self-employed activities. The ratios, reported in table 3.4, vary significantly across sex-age groups. For both males and females, the ratios generally increase with age; except for the two lowest age groups, the ratio for males is more than twice the ratio for females. The ratios for older males are considerably higher than the similar ratios for young females. The relevant ratio for 35- to 64-year-old males is .130; the corresponding ratio for 20- to 24-year-old females is .011. Compared to young females, older males

Table 3.4 Ratios of Self-employed Persons to Total Employment by Age and Sex, 1970[a]

Age	Male	Female
14–15 years	.044	.026
16–17 years	.016	.009
18–19 years	.014	.005
20–24 years	.029	.011
25–29 years	.052	.024
30–34 years	.078	.033
35–39 years	.101	.038
40–44 years	.114	.041
45–49 years	.124	.045
50–59 years	.154	.060
60–62 years	.166	.062
63–64 years	.183	.073
65–69 years	.243	.093
70–74 years	.300	.118
75 years and over	.336	.133

Source: Bureau of the Census (1973b), table 47.
[a]Total employed excludes unpaid family workers.

apparently allocate a greater proportion of their labor effort to self-employed activities.

We infer that earnings for a representative male include a higher percentage of returns to noncorporate capital than do the earnings for a representative female, even after controlling for age. In short, relative earnings are inadequate measures of relative marginal products. The wage and salary income of workers adjusted for supplements is a more appropriate starting point for a measure of labor compensation.

The final issue concerns changes in the pattern of hourly earnings and therefore weights for each labor category. Denison (1974, 1979, 1985) weights by sex-age and education categories but holds weights constant over various subperiods.[15] However, relative wages across industries and among demographic groups have shifted over time due to shifting demand conditions, altered production techniques, and the changing impact of constraints on labor supply. If relative hourly wages are the appropriate estimates of relative marginal products, the labor earnings weights must be allowed to change over time. If the weights are held constant, annual changes in marginal products are not reflected accurately. The resulting estimates of year-to-year productivity change are biased.

The discussion so far has focused on a comparison of data, assumptions, and measurement techniques. We close this section emphasizing an important conceptual difference distinguishing Kendrick's measures of sectoral labor input from the measures presented in tables 3.2 and 3.3. Kendrick (e.g., 1973, 146) purposefully defines any growth in sectoral output due to shifts in the demographic composition of the labor force as part of productivity change.

For Kendrick, any shift in labor's sex, age, and education mix that leads to greater levels of sectoral output reflects an advance in knowledge and is therefore part of productivity change. We evaluate Kendrick's definition of productivity change in terms of the theory of production in section 3.4.3, below.

The data on labor input presented in tables 3.2 and 3.3 incorporate changes in the composition of labor hours by sex, age, education, and employment status within each of the 37 sectors. The data on labor input in table 3.1 incorporate these shifts for the U.S. economy as a whole. Gollop and Jorgenson (1980) provide a detailed comparison between labor input indexes of this type and those of Kendrick for the period 1947–73. Quality change is an important component of the growth in labor input. This component accounts for much of the difference between Kendrick's measures of labor hours and the translog indexes of labor input given in tables 3.2 and 3.3.

3.3 Measuring Capital Input

The approach to the construction of the data on capital input presented in table 3.2 is strictly analogous to the approach outlined in section 3.2 for data on labor input. Capital services represent the quantity of capital input, just as labor services represent the quantity of labor input. Measures of capital services for depreciable assets are derived by representing capital stock at each point of time as a weighted sum of past investments. The weights correspond to the relative efficiencies of capital goods of different ages, so that the weighted components of capital stock have the same efficiency.

Rental rates for capital services provide the basis for property compensation, just as wage rates provide the basis for labor compensation. Information on rental transactions would be required in order to employ data sources for capital input that are analogous to those we have used for labor input. These data are not available in a readily accessible form, even for the substantial proportion of assets with active rental markets. However, rental values can be imputed on the basis of estimates of capital stocks and property compensation.

Data on rental prices for depreciable assets are generated by allocating property compensation for return to capital, depreciation, and taxes among assets. Depreciation is the decline in value of a capital good with age at a given point in time, so that estimates of depreciation depend on the relative efficiencies of capital goods of different ages. The estimates of capital input presented in table 3.1 incorporate the same data on relative efficiencies of capital goods into estimates of both capital stocks and rental prices.

3.3.1 Capital as a Factor of Production

The perpetual inventory method provides the theoretical framework for the measures of capital input presented in tables 3.1, 3.2, and 3.3.[16] The key innovation embodied in the quantity indexes of capital input presented in tables 3.1 and 3.2 is the rental price of capital input originated by Jorgenson (1963, 1965, 1967). This measure of the rental price was employed in the indexes of capital input introduced by Griliches and Jorgenson (1966) and Jorgenson and Griliches (1967).[17] The rental price concept was further developed by Hall and Jorgenson (1967, 1969, 1971). Their approach was employed by Christensen and Jorgenson (1969, 1970, 1973a, 1973b) to impute rental prices for capital goods that differ in depreciation pattern and tax treatment.[18]

We can refer to the capital goods acquired at different points of time as different vintages. Estimates of the relative efficiencies of capital goods of different ages are derived from a comprehensive study of acquisition prices of assets of different vintages by Hulten and Wykoff (1981a, 1981b, 1981c). We can outline the methodology employed by Hulten and Wykoff by first considering vintage price systems under geometric decline in efficiency with age. Under geometric decline in efficiency, both the rental price of capital services and the acquisition price of a capital asset decline geometrically with age. The rate of decline in efficiency can be estimated from a sample of prices of capital goods of different ages.

The econometric model for vintage price functions gives the price of acquisition of a capital good as a function of the age of the capital good and the time period of observation. This model can be generalized by introducing Box-Cox transformations of the prices of acquisition, the ages of capital goods, and the time period of observation.[19] A further generalization of the econometric model of vintage price functions has been proposed by Hall (1971). This generalization is appropriate for durable goods with a number of varieties that are perfect substitutes in production. Each variety is characterized by a number of attributes that affect relative efficiency. This "hedonic technique" for price measurement was originated by Court (1939) and Waugh (1929) and has been employed, for example, by Griliches (1961b) and studies in the volume edited by Griliches (1971b).[20]

As an illustration, Hall (1971) analyzes a sample of prices for half-ton pickup trucks with characteristics such as wheelbase, shipping weight, displacement, ratio of core to stroke, horsepower, torque, and tire width. Observations of these characteristics are analyzed for pickup trucks produced by Ford and Chevrolet in the United States for the period 1955–66. With perfect substitutability among pickup trucks of different ages, market equilibrium implies the existence of a vintage price function for trucks. This function gives the price of acquisition of a pickup truck as a function of age and the price of a new truck of the same type, expressed as a function of time. Hall estimates vintage price functions for each category of trucks from annual observations on the prices of used trucks.

Hulten and Wykoff (1981b) have implemented an econometric model of vintage price functions for eight categories of assets in the United States. In

1977, these categories included 55% of investment expenditures on producers' durable equipment and 42% of expenditures on nonresidential structures.[21] In the estimation of econometric models based on vintage price functions, the sample of used asset prices is "censored" by the retirement of assets from service. The price of acquisition for assets that have been retired from service is equal to zero. If only surviving assets are included in a sample of used asset prices, the sample is censored by excluding assets that have been retired. In order to correct the resulting bias in estimates of vintage price functions, Hulten and Wykoff (1981b) multiply the prices of surviving assets of each vintage by the probability of survival, expressed as a function of age.

Vintage price functions for commercial and industrial buildings are summarized in table 3.5. For each class of assets the rate of economic depreciation is tabulated as a function of the age of the asset. The natural logarithm of the price is regressed on age and time to obtain an average rate of depreciation, which Hulten and Wykoff refer to as the best geometric average (BGA). The square of the multiple correlation coefficient (R^2) is given as a measure of the goodness of fit of the geometric approximation to the fitted vintage price function for each asset. Vintage price functions are estimated with and without a correction for censored sample bias.

The first conclusion that emerges from the data presented in table 3.5 is that a correction for censored sample bias is extremely important in the estimation of vintage price functions. The Hulten-Wykoff study is the first to employ such a correction. The second conclusion reached by Hulten and Wykoff (1981b) is that "*a constant rate of depreciation can serve as a reasonable statistical approximation to the underlying Box-Cox rates even though the latter are not geometric*. This result, in turn, supports those who use the single

Table 3.5 **Rates of Economic Depreciation**

	With Censored Sample Correction		Without Censored Sample Correction	
Age	Commercial	Industrial	Commercial	Industrial
5	2.85	2.99	2.66	2.02
10	2.64	3.01	1.84	1.68
15	2.43	3.04	1.48	1.50
20	2.30	3.07	1.27	1.39
30	2.15	3.15	1.02	1.25
40	2.08	3.24	0.88	1.17
50	2.04	3.34	0.79	1.11
60	2.02	3.45	0.72	1.06
70	2.02	3.57	0.66	1.03
BGA	2.47	3.61	1.05	1.28
R^2	0.985	0.997	0.971	0.995

Source: Hulten and Wykoff (1981a), table 5, p. 387; commercial corresponds to office and industrial corresponds to factory.

parameter depreciation approach in calculating capital stocks using the perpetual inventory method" [italics in original.]. This finding has been corroborated by Hulten, Robertson, and Wykoff (1989).

Hulten, Robertson, and Wykoff (1989) have tested the stability of vintage price functions during the 1970s. After 1973 energy prices increased sharply and productivity growth rates declined dramatically at both aggregate and sectoral levels, as indicated by the data presented in table 3.1. Baily (1981) has attributed the slowdown in economic growth to the decline in relative efficiency of older capital goods, resulting from higher energy prices. Hulten, Robertson, and Wykoff (1989) find that the relative efficiency functions for nine types of producers' durable equipment were unaffected by higher energy prices: "While depreciation almost certainly varies from year to year in response to a variety of factors, we have found that a major event like the energy crises, which had the potential of significantly increasing the rate of obsolescence, did not in fact result in a systematic change in age-price profiles."[22]

In table 3.6 I present rates of economic depreciation derived by Jorgenson and Yun (1990) from the best geometric approximation approach of Hulten and Wykoff for all assets distinguished by the Bureau of Economic Analysis (BEA) in constructing the U.S. national income and product accounts. Hulten and Wykoff have compared the best geometric average rates with depreciation rates employed by BEA in constructing perpetual inventory estimates of capital stock. The Hulten-Wykoff rates for equipment average 0.133, while the BEA rates average 0.141, so that the two sets of rates are very similar. The Hulten-Wykoff rates for structures average 0.037, while the BEA rates average 0.060; these rates are substantially different.

Hulten and Wykoff (1981b) have summarized estimates of economic depreciation completed prior to their own study. The most common methodology for such studies is based on vintage price functions.[23] An alternative to the vintage price approach is to employ rental prices rather than asset prices in estimating patterns of decline in efficiency. This approach has been employed by Malpezzi, Ozanne, and Thibodeau (1987) to analyze rental price data on residential structures and Taubman and Rasche (1969) to study rental price data on commercial structures. While leases on residential property are frequently one year or less in duration, leases on commercial property are typically for much longer periods of time. Since the rental prices are constant over the period of the lease, estimates based on annual rental prices for commercial property are biased toward the "one-hoss shay" pattern found by Taubman and Rasche; Malpezzi, Ozanne, and Thibodeau find rental price profiles for residential property that decline with age.

A second alternative to the vintage price approach is to analyze investment for replacement purposes.[24] Coen (1980) compares the explanatory power of alternative patterns of decline in efficiency in a model of investment behavior that also includes the price of capital services. For equipment he finds that 11 of 21 two-digit manufacturing industries are characterized by geometric decline in efficiency, three by sum of the years' digits and seven by straight-

Table 3.6 Economic Depreciation Rates: Business Assets

Assets	Old Lifetime	Old Depreciation Rate	New Lifetime	New Depreciation Rate
1. Household furniture & fixtures	15	.1100	12	.1375
2. Other furniture	15	.1100	14	.1179
3. Fabricated metal products	18	.0917	18	.0917
4. Steam engines & turbines	21	.0786	32	.0516
5. Internal combustion engines	21	.0786	8	.2063
6. Farm tractors	8	.1633	9	.1452
7. Construction tractors	8	.1633	8	.1633
8. Agricultural machinery	17	.0971	14	.1179
9. Construction machinery	9	.1722	10	.1722
10. Mining & oilfield machinery	10	.1650	11	.1500
11. Metalworking machinery	16	.1225	16	.1225
12. Special industry machinery	16	.1031	16	.1031
13. General industrial	14	.1225	16	.1225
14. Office, computing	8	.2729	8	.2729
15. Service industry machinery	10	.1650	10	.1650
16. Communication equipment	14	.1179	15	.1100
17. Electrical transmission	14	.1179	33	.0500
18. Household appliances	14	.1179	10	.1651
19. Other electrical equipment	14	.1179	9	.1834
20. Trucks, buses, & truck trailers	9	.2537	9	.2537
21. Autos	10	.3333	10	.3333
22. Aircraft	16	.1833	16	.1833
23. Ships & boats	22	.0750	27	.0611
24. Railroad equipment	25	.0660	30	.0550
25. Scientific & engineering instruments	11	.1473	12	.1350
26. Photocopy & related equipment	11	.1473	9	.1800
27. Other nonresidential equipment	11	.1473	11	.1473
28. Industrial buildings	27	.0361	31	.0361
29. Mobile offices	36	.0247	16	.0556
30. Office buildings	36	.0247	36	.0247
31. Commercial warehouses	36	.0247	40	.0222
32. Other commercial buildings	36	.0247	34	.0262
33. Religious buildings	48	.0188	48	.0188
34. Educational buildings	48	.0188	48	.0188
35. Hospital & institutional buildings	48	.0233	48	.0233
36. Hotels & motels	40	.0247	32	.0247
37. Amusement & recreational	31	.0454	30	.0469
38. Other nonfarm buildings	31	.0454	38	.0370
39. Railroad structures	51	.0176	54	.0166
40. Telephone & telegraph structures	27	.0333	40	.0225
41. Electric light & power structures	30	.0300	40	.0225
42. Gas structures	30	.0300	40	.0225
43. Local transit	26	.0450	38	.0450
44. Petroleum pipelines	26	.0450	40	.0450
45. Farm structures	38	.0237	38	.0237
46. Petroleum & natural gas	16	.0563	16	.0563
47. Other mining exploration	16	.0563	16	.0563
48. Other nonresidential structures	31	.0290	40	.0225
49. Railroad replacement track	51	.0176	38	.0236
50. Nuclear fuel	—	—	6	.2500
51. Residential structures	—	.0130	—	.0130

Source: Jorgenson and Yun (1990), table 13B, p. 82.

line patterns. For structures he finds that 14 industries are characterized by geometric decline, five by straight-line, and two by one-hoss-shay patterns. Hulten and Wykoff (1981b) conclude that: "The weight of Coen's study is evidently on the side of the geometric and near-geometric forms of depreciation."

3.3.2 Data Sources and Methods for Capital Input

Data on capital input are unavailable for the government sector, excluding government enterprises, listed in table 3.2. For each of the 35 private industrial sectors listed in this table, prices and quantities of capital input are cross-classified by four asset classes—producers' durable equipment, nonresidential structures, inventories, and land—and three legal forms of organization—corporate and noncorporate business and nonprofit enterprises.

Data on producers' durable equipment can be further subdivided among the 27 categories listed in table 3.6, while data on nonresidential structures can be subdivided among 23 categories listed there. For the 35 private industrial sectors listed in table 3.2 annual data from 1947 to 1985 on capital stock and its rental price are required for an average of as many as 156 components of the capital stock. Households and institutions are treated as a separate sector with prices and quantities of capital input cross-classified by producers' and consumers' durable equipment, residential and nonresidential structures, and land.

The first step in developing sectoral measures of capital input is to construct estimates of capital stock by industry for each year from 1947 to 1985. Investment data from the Bureau of Economic Analysis (1987a) for producers' durable equipment and structures are distributed among industries on an establishment basis. Estimates of investment for all sectors are controlled to totals from the U.S. national product accounts. For residential structures investment data are taken directly from the U.S. national product accounts.[25] Investment goods prices from the U.S. national product accounts are employed to obtain estimates of investment in equipment and structures in constant prices.

Estimates of stocks of land by industry begin with estimates of the stock of land for the economy as a whole. Balance sheet data are employed to allocate land among industrial sectors and between corporate and noncorporate business within each sector with the exception of private households and nonprofit institutions. BEA has constructed estimates of inventory stocks in current and constant prices for all sectors. These estimates are consistent with data on inventory investment for the U.S. economy as a whole from the national product accounts. The data are broken down by legal form of organization within each industry.

The second step in developing sectoral measures of capital input is to construct estimates of prices of capital services from data on property compensation. For each asset the price of investment goods is a weighted sum of future rental prices, discounted by a factor that incorporates future rates of return. Weights are given by the relative efficiencies of capital goods of different ages. The same weights are used in constructing estimates of rental prices and capital stocks. For depreciable assets the weights decline with age; for nondepreciable assets the weights are constant.

Differences in the tax treatment of property compensation among legal forms of organization result in differences in rental prices of capital services. Estimates of the rental prices of capital services in the corporate sector include data on the corporate income tax. Data on property taxes for corporate business are also included. Property compensation for corporate business within each industrial sector must be allocated among equipment, structures, land, and inventories. Corporate property compensation is the sum of rental payments for capital services for all four classes of assets.

Similarly, data on property taxes for noncorporate business are included in estimates of the rental prices of capital services in the noncorporate sector. The noncorporate rate of return is set equal to the corporate rate of return after corporate taxes. This assumption makes it possible to allocate noncorporate income between labor and property compensation. Noncorporate property compensation is the sum of rental payments for capital services for all four classes of assets.

To derive prices of capital services for private households and nonprofit institutions, the rate of return on owner-occupied housing must be estimated. The rate of return for private households and nonprofit institutions is set equal to the corporate rate of return after corporate and personal taxes. Data on property taxes for private households are incorporated into estimates of the rental prices of capital services used in this sector. Property compensation for households and institutions is the sum of rental payments for all classes of assets.

The final step in constructing data on capital input for each of the 35 private industrial sectors is to combine price and quantity data, cross-classified by class of asset and legal form of organization, into price and quantity indexes of capital input. To construct an index of capital input for each industrial sector, I express sectoral capital input, say $\{K_i\}$, as a translog function of its 156 individual components, say $\{K_{ki}\}$. The corresponding index of sectoral capital input is a translog quantity index of individual capital inputs:

$$\ln K_i(T) - \ln K_i(T-1) = \Sigma \bar{v}^i_{Kk} [\ln K_{ki}(T) - \ln K_{ki}(T-1)],$$
$$(i = 1, 2, \ldots, n),$$

where weights are given by average shares of each component in the value of sectoral property compensation:

$$\bar{v}^i_{Kk} = \frac{1}{2} [v^i_{Kk}(T) + v^i_{Kk}(T-1),$$
$$(i = 1, 2, \ldots, n; k = 1, 2, \ldots, p),$$

and

$$v^i_{Kk} = \frac{p^i_{Kk} K_{ki}}{\Sigma p^i_{Kk} K_{ki}}, \quad (i = 1, 2, \ldots, n; k = 1, 2, \ldots, p).$$

The value shares are computed from data on capital services $\{K_{ki}\}$ and the rental price of capital services $\{p^i_{Kk}\}$, cross-classified by asset class and legal form of organization. An analogous approach is applied to data for private households and institutions.

A measure of capital stock for each sector can be derived by adding capital stocks across all categories of capital input within that sector. The quality of capital stock is defined as the ratio of capital input to capital stock. Changes in the quality of capital stock represent differences between changes in the translog quantity index of capital input and changes in an unweighted index of capital stock. Indexes of the quantity of capital input are presented in table 3.2 for 36 sectors. The corresponding indexes of capital quality and capital stock are presented in table 3.3.

The rental prices introduced by Christensen and Jorgenson (1969, 1970, 1973a, 1973b) were extended to the level of individual industrial sectors by Fraumeni and Jorgenson (1980) and Gollop and Jorgenson (1980). Fraumeni and Jorgenson (1986) have incorporated patterns of relative efficiencies based on the best geometric average (BGA) rates fitted by Hulten and Wykoff. The data on capital input that underly tables 3.2 and 3.3 incorporate differences in depreciation patterns by types of producers' durable equipment and nonresidential structures, differences in tax treatment by corporate and noncorporate business and nonprofit forms of organization, and differences in efficiency by age for an average of as many as 156 types of capital input for each of the 35 private industrial sectors. Additional types of capital input are distinguished for consumers' durable equipment and residential structures utilized by private households and institutions.

3.3.3 Alternative Sources and Methods

An overview of issues in the measurement of capital input is provided by the Rees Report National Research Council (1979, esp. 128–40). The treatment of capital as a factor of production became the central issue in an extended debate among Denison (1957, 1966, 1969, 1972), Griliches (1961a), Griliches and Jorgenson (1966), Hulten (chap. 4, in this volume), Jorgenson (1968, 1973a, 1980, 1989), Jorgenson and Griliches (1967, 1972a, 1972b), and Kendrick (1961b, 1968, 1973). The debate has been summarized and evaluated by Diewert (1980, 480), Katz (1988), Mohr (1988b, 1988c), and Norsworthy (1984a, 1984b). To provide additional perspective on the measurement of capital input I find it useful to compare the methodology and data sources that underly the indexes presented in tables 3.2 and 3.3 with those of BLS, Denison, and Kendrick.

Internal consistency of a measure of capital input requires that the same pattern of relative efficiency is employed in measuring both capital stock and the rental price of capital services. The decline in efficiency affects both the level of capital stock and the corresponding rental price. The estimates of capital stocks and rental prices that underly the data presented in tables 3.2 and 3.3 are based on geometrically declining relative efficiencies with the rates of decline presented in table 3.6. The same patterns of decline in efficiency are used for both capital stock and the rental price of each asset, so that the requirement for internal consistency of measures of capital input is met.

I next describe the methods and data sources employed by BLS, Denison, and Kendrick for estimating capital stocks. I then present their methods and sources for estimating rental prices of capital services and attempt to determine whether the resulting measures of capital input are internally consistent. Denison and Kendrick employ estimates of capital stock for equipment and structures from the BEA capital stock study. The methodology employed by BEA in constructing estimates of capital stock is described by the BEA (1987a), Gorman, Musgrave, Silverstein, and Comins (1985), Musgrave (1986), and Young and Musgrave (1980). These estimates are derived by the perpetual inventory method using investment data based on the U.S. national product accounts. BLS also utilizes the perpetual inventory method to derive estimates of capital stock for equipment and structures from investment data based on the U.S. national product accounts.

The perpetual inventory method for measuring capital input is employed in all four studies that we consider. In this method the sequence of relative efficiencies of capital goods of different ages $\{d(\tau)\}$ enables us to characterize capital stock at the end of each period, say $A(T)$, as a weighted sum of past investments:

$$A(T) = \sum_{\tau=0}^{\infty} d(\tau) I(T-\tau),$$

where $I(T - \tau)$ is investment in period $T - \tau$ and the weights are given by the sequence of relative efficiencies.

For each asset, the sequence of relative efficiencies of capital goods of different ages enables us to characterize the price of investment goods in each period, say $P_I(T)$, as a weighted sum of future rentals:

$$p_I(T) = \sum_{\tau=0}^{\infty} d(\tau) \prod_{S=1}^{\tau+1} \frac{1}{1 + r(T+S)} p_K(T+\tau+1),$$

where $p_K(T+\tau+1)$ is the rental price in period $T+\tau+1$ and the weights are given by the sequence of relative efficiencies $\{d(\tau)\}$. In this expression $r(T)$ is the rate of return on capital in period T and $\Pi_{S=1}^{\tau+1} 1/[1 + r(T+S)]$ is the discount factor in period T for future prices in period $T+\tau+1$.

Capital goods decline in efficiency at each point of time, generating needs for replacement of productive capacity. The proportion of an investment to be replaced at age τ, say $m(\tau)$, is equal to the decline in efficiency from age $\tau - 1$ to age τ:

$$m(\tau) = -[d(\tau) - d(\tau - 1)], \quad (\tau = 1, 2, \ldots, T).$$

I refer to these proportions as *mortality rates* for capital goods of different ages.

I define deprecation as the value that must be recovered in every period to keep wealth intact. Taking first differences of the expression for the price of investment goods in terms of future rental prices, we can express the depreciation on a capital good in period T, say $p_D(T)$, in terms of future rental prices and the mortality distribution $\{m(\tau)\}$:

$$p_D(T) = \sum_{\tau=1}^{\infty} m(\tau) \prod_{S=1}^{\tau} \frac{1}{1 + r(T+S)} p_K(T+\tau).$$

We begin our comparison of alternative measures of rental prices of capital services with a characterization of the rental price concept. In the absence of taxation the rental price of capital services at time T takes the form:

$$p_K(T) = p_I(T - 1)r(T) + p_D(T) - [p_I(T) - p_I(T - 1)],$$

where depreciation, $p_D(T)$, depends on the pattern of relative efficiencies. The value of the services of capital stock is the product of the rental price and the quantity of capital stock:

$$p_K(T)A(T - 1) = \{p_I(T - 1)r(T) + p_D(T) - [p_I(T) - p_I(T - 1)\} \cdot A(T - 1).$$

Finally, the value of capital services is equal to property compensation, so that we can solve for the rate of return, given data on property compensation:

$$r(T) = \frac{\text{Property compensation} - \{p_D(T) - [p_I(T) - p_I(T - 1)]\} \cdot A(T - 1)}{p_I(T - 1) \cdot A(T - 1)}.$$

The first and most important criterion for internal consistency of a measure of capital input is that the same patterns of relative efficiency must underlie both the estimates of capital stock $A(T)$ and the estimates of rental price $p_K(T)$ for each class of assets. Hulten and Wykoff (1981b) have shown that the BGA rates of depreciation provide an accurate description of the decline in the price of acquisition of capital goods with age. The Hulten-Wykoff geometric rates are utilized in compiling estimates of both capital stocks and rental prices for the indexes of capital input presented in tables 3.1 and 3.2.

BLS (1983, 57–59) also employs relative efficiency functions estimated by Hulten and Wykoff. However, BLS does not utilize the geometric relative efficiency functions fitted by Hulten and Wykoff. Instead, BLS has fitted a set of hyperbolic functions to the relative efficiency functions estimated by Hulten and Wykoff. Consistency is preserved between the resulting estimates of capital stocks and rental prices by implementing a system of vintage accounts for each class of assets. Implicitly, this set of accounts includes asset prices and quantities of investment goods of all ages at each point of time. BLS (1983, 57–59) shows that measures of capital input based on hyperbolic and geometric relative efficiency functions are very similar.

For each class of assets Denison's estimates of capital stock are based on a linearly declining pattern of relative efficiency. To derive the method of depreciation appropriate for linearly declining relative efficiencies, we first express depreciation for an asset of age V at time T, say $p_D(T, V)$, in the form:

$$\begin{aligned} p_D(T, V) &= \sum_{\tau=1}^{\infty} m(\tau+V) \prod_{S=1}^{\tau} \frac{1}{1 + r(T + S)} p_K(T+\tau), \\ &= \frac{1}{\theta L} \sum_{\tau=1}^{L-V-1} \prod_{S=1}^{\tau} \frac{1}{1 + r(T+S)} p_K(T+\tau) \\ &\quad + [1 - \frac{1}{\theta}(1 - \frac{1}{L})] \prod_{S=1}^{L-V} p_K(T+L-V). \end{aligned}$$

Assuming that the rates of return $\{r(T + S)\}$ and the prices of capital services $\{p_K(T+\tau)\}$ are constant, we obtain the following expression for depreciation on an asset of age V:

$$p_D(V) = \frac{1}{r\theta L} - \left[\frac{1}{r\theta L} - 1 + \frac{1}{\theta}\right]\left(\frac{1}{1+r}\right)^{L-V} p_K, \ (V = 0, 1, \ldots, L-1).$$

Similarly, the value of a new asset is equal to the sum of depreciation over all ages:

$$\begin{aligned} p_I &= \sum_{V=0}^{L-1} p_D(V), \\ &= \frac{1}{r}\left(\frac{1}{\theta} - \left[\frac{1}{r\theta L} - 1 + \frac{1}{\theta}\right]\left[1 - \left(\frac{1}{1+r}\right)^{L}\right]\right)p_K, \end{aligned}$$

so that depreciation allowances appropriate for a linearly declining pattern of relative efficiency are given for each age by the formula:

$$\frac{p_D(V)}{p_I} = \frac{\frac{1}{\theta L} - r\left[\frac{1}{r\theta L} - 1 + \frac{1}{\theta}\right]\left(\frac{1}{1+r}\right)^{L-V}}{\frac{1}{\theta} - \left[\frac{1}{r\theta L} - 1 + \frac{1}{\theta}\right]\left[1 - \left(\frac{1}{1+r}\right)^{L}\right]}, \quad (V = 0, 1, \ldots, L-1).$$

The value of depreciation at time T for a linearly declining pattern of relative efficiency is the sum over assets of all ages:

$$\sum_{V=0}^{L-1} p_D(T, V)I(T-V-1) =$$
$$p_I(T) \sum_{V=0}^{L-1} \frac{\frac{1}{\theta L} - r\left[\frac{1}{r\theta L} - 1 + \frac{1}{\theta}\right]\left(\frac{1}{1+r}\right)^{L-V}}{\frac{1}{\theta} - \left[\frac{1}{r\theta L} - 1 + \frac{1}{\theta}\right]\left[1 - \left(\frac{1}{1+r}\right)^{L}\right]} I(T - V - 1).$$

Denison employs linearly declining relative efficiency in measuring capital stock; in fact, he employs three different weighted averages of the straight-line and "one-hoss shay" patterns.[26] For all three weighted averages Denison employs the straight-line method of depreciation. For linearly declining patterns of relative efficiency, depreciation allowances are increasing, constant, or decreasing with age for values of the parameter θ greater than, equal to, or less than $1 + (1/rL)$, respectively. For the straight-line pattern depreciation allowances are decreasing with age; for the one-hoss shay pattern depreciation allowances are increasing with age. Denison's assumption that depreciation allowances are constant is not appropriate for any of his methods of measuring capital stock, so that all three of the resulting measures of capital input are internally inconsistent.

Kendrick (1973, 27–29) employs capital stock estimates based on linearly declining relative efficiencies in allocating property compensation among assets on the basis of "net earnings." Kendrick's measure of net earnings is based on capital consumption allowances from the U.S. national income accounts as an estimate of depreciation. These estimates are based in turn on depreciation allowances for tax purposes and do not reflect a consistent valuation of assets over time or a consistent method of depreciation.

The method of depreciation appropriate for Kendrick's estimates of capital stock based on linearly declining relative efficiencies is the same as that we have given above for Denison with the parameter θ equal to unity:

$$\frac{p_D(V)}{p_I} = \frac{\frac{1}{L}\left[1 - \left(\frac{1}{1+r}\right)^{L-V}\right]}{1 - \frac{1}{rL}\left[1 - \left(\frac{1}{1+r}\right)^{L}\right]}, \quad (V = 0, 1, \ldots, L-1).$$

The value of depreciation at time T for linearly declining relative efficiencies is the sum over assets of all ages:

$$\sum_{V=0}^{L-1} p_D(T, V)I(T-V-1) = p_I(T) \sum_{V=0}^{L-1} \frac{\frac{1}{L}\left[1 - \left(\frac{1}{1+r}\right)^{L-V}\right]}{1 - \frac{1}{rL}\left[1 - \left(\frac{1}{1+r}\right)^{L}\right]} I(T - V - 1).$$

Kendrick (1973) also employs alternative capital stock estimates based on constant relative efficiencies in allocating property compensation among assets on the basis of "gross earnings." Constant relative efficiencies are also utilized by Kendrick and Grossman (1980, 26) and Kendrick (1983a, 56–57). The declining balance pattern of relative efficiencies employed by Kendrick is inappropriate for constant relative efficiencies. The correct method is given by the limit of the formula described above with θ going to positive infinity:

$$\frac{P_D(V)}{p_I} = \frac{r\left(\frac{1}{1+r}\right)^{L-V}}{1 - \left(\frac{1}{1+r}\right)^{L}}, \quad (V = 0, 1, \ldots, L-1).$$

The value of depreciation at time T for constant relative efficiencies is the sum:

$$\sum_{V=0}^{L-1} p_D(T, V)I(T - V - 1) = p_I(T) \sum_{V=0}^{L-1} \frac{r\left(\frac{1}{1+r}\right)^{L-V}}{1 - \left(\frac{1}{1+r}\right)^{L}} I(T - V - 1).$$

My conclusion is that neither of Kendrick's two measures of capital input is based on an internally consistent treatment of capital stocks and rental prices of capital services. In estimating capital stocks Kendrick uses straight-line and one-hoss shay patterns of relative efficiency. His weights based on gross earnings ignore differences among assets in rates of depreciation; his weights based on net earnings employ depreciation as calculated for tax purposes, so that neither the depreciation method nor the valuation of assets is consistent over time.

The estimates of capital service prices that underly the capital input indexes presented in table 3.2 incorporate differences in property tax rates among types of assets, differences in the tax treatment of corporate and noncorporate income due to the corporate income tax, and differences between equipment and structures due to variations in the tax formulas for depreciation and the investment tax credit for equipment. BLS (1983, 50) employs data on tax depreciation and the investment tax credit and differences in property tax rates among types of assets. However, corporate and noncorporate assets are assumed to have the same capital service prices, so that the effect of the corporate income tax is ignored. Denison and Kendrick ignore differences in property tax rates among types of assets, the effect of the corporate income tax, the tax treatment of depreciation, and the investment tax credit in allocating property compensation among assets.[27]

We have focused the discussion of capital input on the internal consistency of estimates of capital stocks and the corresponding rental prices. However, it is important to emphasize an important conceptual difference between Kendrick's measures of sectoral capital input and the measures we have presented in tables 3.2 and 3.3. Kendrick (e.g., 1973, 146) purposefully defines any growth in sectoral output due to shifts in the composition of the capital stock by class of asset or legal form of organization as part of productivity change. For Kendrick, any shift in the mix of capital by depreciation pattern or tax treatment that leads to greater levels of sectoral output reflects an advance in knowledge and is therefore part of productivity change. I evaluate Kendrick's definition of productivity change in section 3.4.3 below.

The data on capital input presented in tables 3.2 and 3.3 incorporate shifts in the composition of the capital stock by class of asset and legal form of organization within an industrial sector. The data on capital input in table 3.1 incorporate these shifts for the U.S. economy as a whole. Gollop and Jorgenson (1980) provide a detailed comparison between capital input indexes of this type and those of Kendrick for the period 1947–73. Quality change is an important component of the growth in capital input. This component accounts for much of the difference between Kendrick's estimates of capital stock and the translog indexes of capital input given in tables 3.2 and 3.3.

3.4 Measuring Output, Intermediate Input, and Productivity

An important innovation embodied in the data on productivity presented in table 3.2 is that intermediate, capital, and labor inputs are treated symmetrically at the sectoral level. The value of output at the sectoral level includes the value of intermediate input as well as the values of capital and labor inputs. All three inputs are employed in analyzing the sources of growth in sectoral output. The industry definitions employed in the U.S. national income accounts are used in measuring output. These definitions are based on establishments within each industry.

A more restrictive methodology for sectoral productivity measurement is based on the concept of value added. Output is represented as a function of intermediate input and value added; value added is represented in turn as a function of capital input, labor input, and time. In the value added approach intermediate input is not treated symmetrically with capital and labor inputs. The existence of the value added aggregate requires that time and capital and labor inputs are separable from intermediate input. Given the quantities of intermediate input and value added, output is independent of changes in technology.

The methodology for productivity measurement outlined in previous sections treats all three inputs symmetrically. The sectoral models of production do not require the existence of a value added aggregate in constructing an index of productivity growth. The value-added approach is based on more restrictive assumptions but requires precisely the same data. Both the restricted and unrestricted methodologies require prices and quantities of output and intermediate, capital, and labor inputs for full implementation.

3.4.1 Sectoral Output, Intermediate Input, and Productivity

I have employed a model of production based on a production function $\{F^i\}$ for each of the n sectors. The production function gives output $\{Z_i\}$ as a function of intermediate input $\{X_i\}$, capital input $\{K_i\}$, labor input $\{L_i\}$, and time T. We can specialize this model by introducing a value-added function $\{G^i\}$ for each sector, giving the quantity of value added, say $\{V_i\}$, as a function of capital input, labor input, and time:[28]

$$V_i = G^i(K_i, L_i, T), \quad (i = 1, 2, \ldots, n),$$

where

$$\begin{aligned} Z_i &= F^i(X_i, V_i), \\ &= F^i[X_i, G^i(K_i, L_i, T)], \quad (i = 1, 2, \ldots, n). \end{aligned}$$

I say that the production function is neutral with respect to intermediate input, since the substitution of intermediate input for value added is unaffected by changes in technology. If the value-added function is homogeneous of degree one in capital and labor inputs, we say that the production function is homothetically neutral. Homogeneity implies that proportional changes in capital and labor inputs result in proportional changes in value added, so that the value-added function is characterized by constant returns to scale. If the production function is homogeneous of degree one in intermediate, capital, and labor inputs, neutrality of the production function implies homothetic neutrality.

Denoting the price of value added by $\{p_V^i\}$, we can define the share of value added, say $\{v_V^i\}$, in the value of output by

$$v_V^i = \frac{p_V^i V_i}{q_i Z_i}, \quad (i = 1, 2, \ldots, n).$$

Necessary conditions for producer equilibrium include equalities between the share of value added and the elasticity of output with respect to value added:

$$v_V^i = \frac{\partial \ln Z_i}{\partial \ln V_i}(X_i, V_i), \quad (i = 1, 2, \ldots, n).$$

Under constant returns to scale the elasticities and the value shares for intermediate input and value added sum to unity, so that the value of output is equal to the sum of the values of intermediate input and value added. Necessary conditions for producer equilibrium also include equalities between the shares of capital and labor inputs in value added and the elasticities of the quantity of value added with respect to those inputs. Conditions for producer equilibrium imply that value added is equal to the sum of the values of capital and labor inputs.

In defining output Kendrick (1973, 17) considers whether or not to exclude the value of depreciation from the value of output. At the sectoral level, depreciation could be excluded along with the value of intermediate goods in the measurement of value added. Kendrick considers two measures of productivity, one based on value-added gross of depreciation and the other based on value-added net of depreciation. He associates the gross measure with gross capital stock as a measure of capital input and the net measure with net capital stock as a measure of capital input.

In section 3.3.3, above, I have shown that the selection of an appropriate concept of capital input depends on the relative efficiencies of capital goods of different vintages. Associated with each measure of capital input $A(T-1)$, there is a corresponding measure of depreciation $p_D(T)$. Gross capital stock, as defined by Kendrick, corresponds to the one-hoss shay pattern of decline in efficiency. I have given the corresponding measure of depreciation in section 3.3.3. There is no connection between gross capital stock as a measure of capital input and value added gross of depreciation as a measure of output. Similarly, there is no connection between net capital stock as a measure of capital input and value-added net of depreciation as a measure of output. For any pattern of decline in efficiency there are corresponding measures of depreciation and capital input. For any measure of depreciation, there are measures of value added both gross and net of depreciation.

Kendrick (1973, 18) indicates that he would have preferred to use a measure of output net of depreciation. Kendrick is able to implement an approach based on value-added net of depreciation only at the economy-wide level, where he uses net national product in place of gross national product as a measure of value added. To evaluate Kendrick's approach to the measurement of value-added net of depreciation we can decompose the value of capital input into the value of return to capital, evaluated at the own rate of return, and the value of depreciation:

$$p_K(T)A(T-1) = p_I(T-1)\left[r(T) - \frac{p_I(T) - p_I(T-1)}{p_I(T-1)}\right] A(T-1) + p_D(T)A(T-1).$$

As before, I have simplified this expression by ignoring the impact of taxation.

Value added $p_V(T)V(T)$ is the sum of the value of capital input

$p_K(T)A(T-1)$ and the value of labor input $p_L(T)L(T)$. Value-added net of depreciation is defined as the difference between value added and the value of depreciation:

$$p_V(T)V(T) - p_D(T)A(T-1) = p_I(T-1)\left[r(T) - \frac{p_I(T) - p_I(T-1)}{p_I(T-1)}\right] A(T-1) + p_L(T)L(T).$$

Capital stock $A(T-1)$ appears on both the left-hand side, where it is associated with depreciation, and on the right-hand side, where it is associated with the own rate of return on capital or, using Kendrick's terminology, the net earnings of capital.

Gross value added $\{V^i\}$ can be rationalized as a measure of output by imposing a separability assumption on the production function $\{F^i\}$ for each sector. This is done by introducing the value-added function $\{G^i\}$ for the sector. Intermediate input is separated from capital and labor inputs and changes in technology by the value added function. Gross value added is represented as a function of capital input, labor input, and time. If we were to attempt to represent net value added as a function of capital input, labor input, and time, net value added and the list of inputs would both involve the quantity of capital input.

By contrast with net value added, gross value added can be defined, implicitly, as a function of output and intermediate input. The corresponding definition of net value added would involve output, intermediate input, and capital input. I conclude that the quantity of net value added is not an appropriate point of departure for modeling producer behavior. At the economywide level only Kendrick's measure of productivity based on gross value added avoids including capital input in the definition of both output and input. Fortunately, only gross value added is used for Kendrick's sectoral aggregates of individual industries, so that his sectoral measures of productivity are free from this defect.

Kendrick and Grossman (1980, 22–25) and Kendrick (1983a, 56) have employed measures of output at the level of individual industries based on data from the BEA on gross product originating in each industrial sector. Both studies have dropped the concept of value added net of depreciation employed by Kendrick (1973). This important change in methodology has the advantage over the methodology employed in Kendrick's (1973) study that the problem of including capital input in both net value added and the list of inputs is entirely avoided.[29]

3.4.2 Data Sources and Methods for Output and Intermediate Input

Data on output in current and constant prices are available from the Office of Economic Growth of the Bureau of Labor Statistics (1987). In order to evaluate output from the point of view of the producing sector, excise and sales taxes must be subtracted and subsidies must be added to the value of output. The resulting price of output from the producers' point of view is equal to the ratio of the value of output in current prices to the value of output in constant prices.

Data on interindustry transactions published by BEA (1984 and various years) must be employed to disaggregate intermediate input by sector of origin. These data are based on industry definitions employed in the U.S. interindustry accounts. In order to bring measures of intermediate input into conformity with industry definitions from the U.S. national income accounts, interindustry transactions must be reallocated among sectors. This reallocation must take into account the reclassifications, redefinitions, and transfers employed in constructing the U.S. interindustry accounts, as discussed by Walderhaug (1973). To construct prices and quantities of intermediate input by sector of origin the value of intermediate input originating in each sector must be deflated by an index of purchasers' prices for the output of that sector. The indexes of producers' prices for the output of each sector are transformed to purchasers' prices by adding sales and excise taxes and subtracting subsidies.

The final step in constructing data on intermediate input for each of the 35 industrial sectors is to combine price and quantity data, classified by sector of origin, into price and quantity indexes of intermediate input. To construct an index of intermediate input for each industrial sector, I express sectoral intermediate input, say $\{X_i\}$, as a translog function of its n individual components, say $\{X_{ji}\}$. The corresponding index of sectoral intermediate input is a translog quantity index of individual intermediate inputs:

$$\ln X_i(T) - \ln X_i(T-1) = \Sigma \bar{v}_{Xj} [\ln X_{ji}(T) - \ln X_{ji}(T-1)],$$
$$(i = 1, 2, \ldots, n),$$

where weights are given by average shares of each component in the value of sectoral intermediate outlay:

$$\bar{v}^i_{Xj} = \frac{1}{2} [v^i_{Xj}(T) + v^i_{Xj}(T-1)], \quad (i, j = 1, 2, \ldots, n),$$

and

$$v^i_{Xj} = \frac{p^i_{Xj} X_{ji}}{\sum_j p^i_{Xj} X_{ji}}, \quad (i, j = 1, 2 \ldots n).$$

The value shares are computed from data on intermediate input $\{X_{ji}\}$ and the corresponding prices paid by the receiving sectors $\{p^i_{Xj}\}$ for each component of sectoral intermediate input.

An unweighted index of intermediate input for each sector is derived by adding across the intermediate inputs from all originating sectors. The quality of intermediate input is defined as the ratio of the translog quantity index to an unweighted index for each sector. Changes in the quality of intermediate input represent differences between changes in the translog quantity index and changes in the unweighted index. Indexes of the quantity of output and intermediate input are presented in table 3.2 for 35 sectors. The corresponding index of intermediate input quality and an unweighted index of intermediate input are presented in table 3.3 for each sector.

To allocate the growth of sectoral output among the contributions of intermediate, capital, and labor inputs and changes in productivity, I construct data on the rate of productivity growth. To construct on index of productivity for each industrial sector, I express sectoral output $\{X_i\}$ as a translog function of sectoral intermediate input $\{X_i\}$, capital input $\{K_i\}$, labor input $\{L_i\}$, and time T. The corresponding index of productivity is the translog index of the rate of productivity growth $\{\bar{v}_T^i\}$:

$$\bar{v}_T^i = [\ln Z_i(T) - \ln Z_i(T-1)] - \bar{v}_X^i [\ln X_i(T) - \ln X_i(T-1)] - \bar{v}_K^i [\ln K_i(T) - \ln K_i(T-1)] - \bar{v}_L^i [\ln L_i(T) - \ln L_i(T-1)], \quad (i = 1, 2 \ldots n),$$

where weights are given by average shares of sectoral intermediate, capital, and labor inputs in the value of sectoral output:

$$\bar{v}_T^i = \frac{1}{2} [v_T^i(T) + v_T^i(T-1)],$$

$$\bar{v}_X^i = \frac{1}{2} [v_X^i(T) + v_X^i(T-1)],$$

$$\bar{v}_K^i = \frac{1}{2} [v_K^i(T) + v_K^i(T-1)],$$

$$\bar{v}_L^i = \frac{1}{2} [v_L^i(T) + v_L^i(T-1)], \quad (i = 1, 2, \ldots, n),$$

and

$$v_X^i = \frac{p_X^i X_i}{q_i X_i},$$

$$v_K^i = \frac{p_K^i K_i}{q_i Z_i},$$

$$v_L^i = \frac{p_L^i L_i}{q_i Z_i}, \quad (i = 1, 2, \ldots, n).$$

The starting point for the construction of data on sectoral productivity growth is a sectoral production account in current prices. The fundamental accounting identity is that the value of output is equal to the value of input. The value of output excludes all sales and excise taxes and includes subsidies paid to producers. The value of input includes all taxes and supplements paid made by producers, as well as the compensation received by the suppliers of each input. Valuation from the producers' point of view is essential for the integration of data on output and input into measures of productivity growth at the sectoral level.

The concept of valuation from the point of view of the producer is used in the sectoral production accounts that underlie tables 3.2 and 3.3. This concept is intermediate between the national accounting concepts of valuation at market prices and valuation at factor cost. The value of output at market prices includes taxes paid by producers and excludes subsidies received by producers. The value of output at factor cost excludes these taxes and includes subsidies. Control totals for the values of output and intermediate, capital, and labor inputs are based on the U.S. national income accounts.

For the government sector, excluding government enterprises, output in tables 3.2 and 3.3 is defined as labor input; for private households, output is set equal to an index of capital and labor input. For these sectors productivity growth is zero by definition. Rates of productivity growth for the remaining 35 sectors are presented on an annual basis for the period 1947–85 in table 3.2.

3.4.3 Alternative Sources and Methods

An overview of issues in the measurement of intermediate input is provided by the Rees Report (National Research Council 1979, esp. 140–44). To provide additional perspective on the measurement of output, intermediate input, and productivity we find it useful to compare the methodology and data sources that underly the data presented in tables 3.2 and 3.3 with those of Kendrick and Leontief, who provide alternative estimates of sectoral productivity.[30] In table 3.2 intermediate input is treated symmetrically with capital input and labor input in measuring productivity growth at the sectoral level. The resulting measure of productivity is an index number constructed from data on prices and quantities of output, intermediate input, capital input, and labor input.

The first study of productivity for individual industrial sectors including intermediate input was that of Leontief (1953b). He compared interindustry transactions among 14 industries for the United States for 1919, 1929, and 1939 in constant prices of 1939. For each industry he tabulated relative changes in the ratios of intermediate inputs and labor input to output; the ratio of capital input to output was simply ignored. Relative changes between 1919 and 1929 and between 1929 and 1939 were weighted by averages of the quantities of inputs for each pair of years to obtain an index of productivity change for each sector. The weights were summed to the average value of input into each sector in constant prices of 1939, excluding capital input. If Leontief's weights had been applied to relative changes in the ratios of individual inputs to output, including capital input, he would have obtained the negative of the translog index of productivity growth presented in table 3.2.

Kendrick (1956, 1961a, 1973) advocates an approach to sectoral productivity measurement based on value added, where value added is defined as the sum of the value of capital input and the value of labor input. Kendrick's approach to productivity measurement is based on the model I have presented in section 3.4.1 above, with output represented as a function of intermediate input and the quantity of value added. The price and quantity of value added are index numbers constructed from data on prices and quantities of output and intermediate input. Value added is represented as a function of capital input, labor input, and time. The corresponding measure of productivity is an index number constructed from data on prices and quantities of value added, capital input, and labor input.

Kendrick combines value added functions for each sector with necessary conditions for producer equilibrium. The rate of productivity growth for value added is an appropriate measure of productivity, provided that output can be represented as a function of intermediate input and value added. In fact, Kendrick (1973, 17) does not use value added as a measure of output at the level of individual industries included in his study. He employs output in measuring productivity at the level of individual industries and simply ignores the growth of intermediate input. The resulting rates of productivity growth are measures of the rate of productivity growth for value added only if rates of growth of output and intermediate goods are identical.

To provide further perspective on Kendrick's approach, I represent the accounting identity between the value of output, say $\{q_i Z_i\}$, and the sum of the values of intermediate input $\{p_X^i X_i\}$, capital input $\{p_K^i K_i\}$, and labor input $\{p_L^i L_i\}$ in the form:

$$q_i X_i = p_X^i X_i + p_K^i K_i + p_L^i L_i, \quad (i = 1, 2, \ldots, n).$$

Value added, say $p_V^i V_i$, is defined as the difference between the value of output and the value of intermediate input:

$$\begin{aligned} p_V^i V_i &= q_i Z_i - p_X^i X_i, \\ &= p_K^i K_i + p^i L_i, \quad (i = 1, 2, \ldots, n), \end{aligned}$$

so that value added is equal to the sum of the values of capital and labor inputs. By employing output $\{q_i Z_i\}$ in place of value added $\{p_V^i V_i\}$ and setting the value of input equal to the sum of the values of capital and labor inputs, Kendrick has omitted on average more than half of the value of sectoral inputs.

The same problem arises in Kendrick's analysis of aggregates over individual industries. For these aggregates Kendrick (1973, 22) employs data from the Bureau of Economic Analysis on gross product originating. For approximately 50% of the business economy the data are based on output rather than value added, so that Kendrick's measures of productivity for aggregates over individual industries ignore the growth of intermediate input for half of the industries. The condition required for validity of his measures of productivity growth for aggregates is precisely the same as the condition we have given for individual industries: Rates of growth of output and intermediate inputs must be identical for all sectors.

We can test Kendrick's assumption directly, using the output and intermediate input data presented in tables 3.2 and 3.3. Table 3.7 presents the average annual rates of growth of output and intermediate input in each of 35 sectors over the 1947–69 period, the period analyzed by Kendrick (1973). The ratio

Table 3.7 Sectoral Intermediate Input and Output: Rates of Growth, 1947–69

Industry	Average Annual Rates of Growth: Intermediate Input	Average Annual Rates of Growth: Output	Ratio of Growth of Intermediate Input to Growth of Output
Agriculture, forestry & fisheries	.0174	.0173	1.0023
Metal mining	.0419	.0153	2.7407
Coal mining	−.0113	−.0081	1.3881
Crude petroleum & natural gas	.0453	.0381	1.1885
Nonmetallic mineral mining	.0515	.0478	1.0775
Construction	.0383	.0422	.9084
Food & kindred products	.0214	.0253	.8482
Tobacco manufactures	.0042	.0075	.5567
Textile mill products	.0266	.0293	.9060
Apparel & other textile products	.0296	.0336	.8818
Lumber & wood products	.0242	.0191	1.2706
Furniture & fixtures	.0320	.0342	.9350
Paper & allied products	.0401	.0417	.9627
Printing & publishing	.0386	.0330	1.1691
Chemicals & allied products	.0461	.0625	.7382
Petroleum refining	.0314	.0406	.7722
Rubber & plastic products	.0538	.0549	.9804
Leather & leather products	−.0081	.0000	.0000
Stone, clay, & glass products	.0453	.0390	1.1598
Primary metals	.0305	.0218	1.3937
Fabricated metal products	.0332	.0337	.9866
Machinery, except electrical	.0418	.0359	1.1647
Electrical machinery	.0512	.0620	.8254
Motor vehicles	.0398	.0434	.9165
Other transportation equipment	.0837	.0765	1.0931
Instruments	.0398	.0506	.7864
Miscellaneous manufacturing	.0338	.0371	.9112
Transportation & warehousing	.0326	.0251	1.2998
Communication	.0560	.0701	.7984
Electric utilities	.0465	.0647	.7194
Gas utilities	.0964	.0787	1.2245
Trade	.0361	.0368	.9794
Finance, insurance, & real estate	.0553	.0471	1.1751
Other services	.0527	.0386	1.3663
Government enterprises	.0573	.0344	1.6663

of the average annual rate of growth of intermediate input to the corresponding growth rate of output is reported for each sector in the last column of table 3.7. Ratios greater than unity in table 3.7 suggest that Kendrick's measures of productivity growth are upward biased, while ratios less than unity imply downward biased measures. The data in table 3.7 illustrate that Kendrick's assumption is inappropriate and, more important, a significant source of bias. Even if one chooses to restrict the sectoral model of production by postulating the existence of a value-added aggregate, the growth rate of the quantity of value added cannot be measured by the growth rate of output alone.[31]

I have emphasized that Kendrick defines growth in sectoral output due to shifts in the demographic composition of the labor force and shifts in the composition of the capital stock by class of asset or legal form of organization as part of productivity change. However, Kendrick treats growth in sectoral output due to shifts in the composition of input between capital and labor inputs as growth in input rather than productivity change. To eliminate these shifts he weights capital and labor inputs by their marginal products, following the methodology originated by Tinbergen (1942).

It is inconsistent to weight capital and labor inputs by their marginal products without weighting the components of each input by the appropriate marginal products. The theory of production includes both the production function and the necessary conditions for producer equilibrium. These conditions involve the marginal products of capital and labor inputs. They also involve the marginal products of the components of each input. The inconsistency between Kendrick's aggregation of capital and labor inputs and his aggregation within each of these inputs gives rise to substantial biases.

To eliminate biases due to the effects of shifts in the composition of input among intermediate, capital, and labor inputs, these inputs must be weighted by their marginal products, as outlined in section 3.4.2 above. Finally, the components of intermediate input, like the components of capital and labor inputs, must be weighted by the corresponding marginal products. Intermediate inputs account for more than half of the value of inputs at the sectoral level. Omission of intermediate input is a very significant source of bias in Kendrick's measures of productivity growth, as demonstrated by the evidence presented in table 3.7.

In order to assess the biases that arise from using unweighted measures of intermediate, capital, and labor inputs, I have compiled measures of each input with appropriate weights for all components in table 3.2. In Table 3.3 I have compiled the corresponding unweighted measures together with ratios between the weighted and unweighted measures that we identify as indicators of input quality. Measures of input quality should be equal to unity for all sectors in all time periods in order to validate Kendrick's definition of productivity change. The data presented in table 3.3 show that Kendrick's definition is inappropriate and the source of very substantial bias in the measurement of productivity.

In section 3.1.2 I have pointed out that intermediate input is the most important source of growth in output at the sectoral level. In effect, Kendrick has set aside the task of measuring this source of sectoral growth by introducing the assumption that intermediate input and output grow at the same rate. This assumption is contradicted by the evidence presented in table 3.7. Similarly, Kendrick has assumed that capital and labor inputs do not change in quality at the sectoral level, setting aside the task of disaggregating these inputs by marginal productivity. This assumption is contradicted by the evidence presented in table 3.3. In this table capital input is disaggregated by an average of as many as 156 individual components in each sector, while labor input is disaggregated by 160 individual components in each sector.

The data on intermediate input, output, and productivity presented in tables 3.2 and 3.3 incorporate changes in the quality of intermediate, capital, and labor inputs. The data on capital and labor inputs in table 3.1 incorporate these changes for the U.S. economy as a whole. Gollop and Jorgenson (1980) provide a detailed comparison between productivity indexes of this type and those of Kendrick for the period 1947–73. Kendrick's indexes greatly exaggerate the role of productivity change as a source of growth at the sectoral level. Quality change is an important component of the growth of capital and labor inputs at both sectoral and aggregate levels. This component accounts for a substantial portion of the differences between Kendrick's estimates of productivity change and the translog indexes of productivity change given in tables 3.2 and 3.3. However, a sizable portion of these differences can be attributed to Kendrick's omission of intermediate input as a source of growth at the sectoral level.

3.5 Measuring Aggregate Output and Productivity

Following Solow (1957) and Tinbergen (1942), my aggregate model of production is based on a production function, say F, characterized by constant returns to scale:

$$V = F(K, L, T),$$

where T is time, V is value added, and K and L are capital and labor inputs. We can define the shares of capital and labor inputs, say v_K and v_L, in value added by:

$$v_K = \frac{p_K K}{p_V V},$$

$$v_L = \frac{p_L L}{p_V V},$$

where p_V, p_K, and p_L denote the prices of value added, capital input, and labor input, respectively.

Necessary conditions for producer equilibrium are given by equalities between the value shares of each input and the elasticity of output with respect to that input:

$$v_K = \frac{\partial \ln V}{\partial \ln K} (K, L, T),$$
$$v_L = \frac{\partial \ln V}{\partial \ln L} (K, L, T).$$

Under constant returns to scale, value added is equal to the value of capital and labor inputs. Finally, we can define the rate of productivity growth for the economy as a whole, say v_T, as the growth rate of value added with respect to time, holding capital input and labor input constant:

$$v_T = \frac{\partial \ln V}{\partial T} (K, L. T).$$

The aggregate production function is defined in terms of value added, capital input, and labor input. The quantities of capital and labor inputs are functions of the quantities of their components:

$$K = K(K_1, K_2, \ldots, K_p),$$
$$L = L(L_1, L_2, \ldots, L_q).$$

We can define the shares of the components of capital and labor inputs, say $\{v_{Kk}\}$ and $\{v_{Ll}\}$, in the value of the corresponding aggregate by:

$$v_{Kk} = \frac{p_{Kk} K_k}{\Sigma\, p_{Kk} K_k}, \quad (k = 1, 2, \ldots, p),$$
$$v_{Ll} = \frac{p_{Ll} L_l}{\Sigma\, p_{Ll} L_l}, \quad (l = 1, 2, \ldots, q).$$

Necessary conditions for producer equilibrium are given by equalities between the value share of each component and the elasticity of the aggregate with respect to that component:

$$v_{Kk} = \frac{\partial \ln K}{\partial \ln K_k} (K_1, K_2 \ldots K_p), \quad (k = 1, 2, \ldots, p),$$
$$v_{Ll} = \frac{\partial \ln L}{\partial \ln L_l} (L_1, L_2 \ldots L_q), \quad (l = 1, 2, \ldots, q).$$

Under constant returns to scale, the value of each input is equal to the value of its components.

3.5.1. Aggregation over Sectors

We can also formulate a model of production for the economy as a whole by aggregating over models of production for individual industrial sectors.

The purpose of such a model is to integrate the analysis of sources of economic growth for individual industrial sectors presented in tables 3.2 and 3.3 with the analysis for the economy as a whole presented in table 3.1. For this purpose I adopt the restrictive assumption that a value-added function like that defined in section 3.4 above exists for all sectors. It is important to emphasized that this assumption is not used in constructing the data presented for individual industries in tables 3.2 and 3.3 However, this assumption is implicit in the analysis of sources of economic growth for the economy as a whole presented in table 3.1 and all studies at the aggregate level, beginning with Tinbergen (1942).

We can combine sectoral value added functions for all industrial sectors with market equilibrium conditions for each factor of production to obtain an aggregate model of production. Using this model of production, I allocate the growth of output among contributions of primary factor inputs and the rate of productivity growth in table 3.1. By combining sectoral and aggregate production models we can express the rate of aggregate productivity growth in terms of the rates of sectoral productivity growth and reallocations of value added, capital input, and labor input among sectors.

Aggregate value added V is the sum of quantities of value added $\{V_i\}$ in all industrial sectors. The aggregate model of production includes market equilibrium conditions that take the form of equalities between the supplies of each type of labor $\{L_l\}$ and the sums of demands for that type of labor by all sectors. Similarly, market equilibrium implies equalities between the supplies of each type of capital $\{K_k\}$ and the sums of demands for that type of capital by all sectors.[32] It is possible to distinguish among capital and labor inputs that differ in marginal productivity at the aggregate level as well as at the sectoral level. Deliveries to intermediate demand by all sectors are precisely offset by receipts of intermediate inputs, so that transactions in intermediate goods do not appear at the aggregate level.

The existence of an aggregate production function imposes very stringent requirements on the underlying sectoral models of production.[33] All sectoral value-added functions must be identical to the aggregate production function.[34] In addition, the functions giving capital and labor inputs for each sector in terms of their components must be identical to the corresponding functions at the aggregate level. In essence, the value-added function and the capital and labor input functions for each sector must be replicas of the aggregate functions. The reallocations of value added, capital input, and labor input among sectors presented in table 3.1 provide measures of departures from these assumptions.

Reallocations of value added incorporate differences in value-added functions among industries as well as departures from the separability assumptions required for the existence of a value-added function for each industrial sector. Similarly, reallocations of capital and labor inputs incorporate differences in these aggregates among sectors as well as departures from the separability assumptions required for the existence of the aggregates. If value added and all components of capital and labor inputs were to grow at the same rate for all industries, there would be no reallocations.

The methodology I have outlined for the economy as a whole can be implemented by considering specific forms for the aggregate production function and for capital and labor inputs as functions of their components. I take these functions to be translog in form, so that we can generate a translog index of the rate of productivity growth. The average rate of productivity growth is the difference between the growth rate of value added and a weighted average of growth rates of capital and labor inputs. Similarly, we can generate translog indexes of capital and labor inputs, giving the growth rate of each input as a weighted average of growth rates of its components.

The measures of aggregate output, input, and productivity presented in table 3.1 are derived by explicit aggregation over the industrial sectors listed in tables 3.2 and 3.3. The measure of aggregate productivity growth depends on sectoral productivity growth rates and on terms that reflect reallocations of value added, capital input, and labor input among sectors.[35] Sectoral productivity growth rates are weighted by ratios of the value of output in the corresponding sector to the sum of value added in all sectors.[36] This formula was originally proposed by Domar (1961) for a model with two producing sectors. Each sector is characterized by a Cobb-Douglas production function with output as a function of intermediate input from the other sector, capital input, labor input, and time as an indicator of the level of technology. A closely related approach to aggregate productivity measurement uses sectoral productivity growth rates based on value added rather than output.[37]

Domar's (1961) approach to aggregation over sectors has been extended by Hulten (1978) and Jorgenson (1980) to an arbitrary number of producing sectors without using the assumption that the sectoral production functions are linear logarithmic. Both Domar and Hulten assume that prices of intermediate inputs are the same for producing and receiving sectors and prices of capital and labor inputs are the same for all sectors. Jorgenson allows for differences in prices received and paid among sectors. Under the assumptions of Domar and Hulten the rate of productivity growth for the economy as a whole does not depend on the reallocations of value added, capital input, and labor input among sectors presented in the second panel of table 3.1.[38]

3.5.2. Data Sources and Methods for Aggregate Output and Productivity

The starting point for the measurement of aggregate productivity is a production account for the U.S. economy in current prices. The fundamental identity for the production account is that the value of output is equal to the value of input. The value of output and input is defined from the point of view of the producer. Revenue is measured as proceeds to the producing sector of the economy and outlay as expenditures of the sector. The role of an aggregate production account in a complete accounting system for the U.S. economy is discussed by Christensen and Jorgenson (1969, 1970, 1973a, 1973b) and Jorgenson (1980).[39]

The value of output for the U.S. economy as a whole is equal to the value of deliveries to final demand—personal consumption expenditures, gross private domestic investment, government purchases, and net exports—excluding indirect business taxes on output, excise and sales taxes, and including subsidies paid to producers. The value of input includes the value of primary factors of production—capital and labor inputs—including indirect business taxes on input, property taxes, and other taxes on property compensation.

The definition of aggregate output outlined above is intermediate between output at market prices and output at factor cost, as these terms are conventionally defined. The production account for the U.S. economy as a whole includes value added in the 37 sectors listed in table 3.2. These sectors include 35 industrial sectors, government, except for government enterprises, and private households and institutions.

As an accounting identity, the value of output is equal to the value of input from the point of view of the producing sector. The value of input includes income originating in business, households and institutions, and government, as defined in the U.S. national income and product accounts. The value of input also includes capital consumption allowances, business transfer payments, the statistical discrepancy, and certain indirect business taxes on property and property compensation. Finally, the value of input includes the imputed value of services of consumers' durables and durables held by institutions and net rent on institutional real estate.

The quantity of value added for each sector is derived by combining price and quantity data on output and intermediate input into price and quantity indexes of value added. To construct an index of value added for each industrial sector, I express sectoral output, say $\{Z_i\}$, as a translog function of sectoral intermediate input $\{X_i\}$ and sectoral value added $\{V_i\}$. The corresponding index of sectoral value added can be written in implicit form:

$$\begin{aligned} \ln Z_i(T) - \ln Z_i(T-1) = {} & \bar{v}_X^i[\ln X_i(T) - \ln X_i(T-1)] \\ & + \bar{v}_V^i[\ln V_i(T) - \ln V_i(T-1)], \\ & (i = 1, 2, \ldots, n), \end{aligned}$$

where the weights are given by the average value shares:

$$\begin{aligned} \bar{v}_X^i &= \frac{1}{2}[v_X^i(T) + v_X^i(T-1)], \\ \bar{v}_V^i &= \frac{1}{2}[v_V^i(T) + v_V^i(T-1)], \quad (i = 1, 2, \ldots, n). \end{aligned}$$

and

$$v_X^i = \frac{p_X^i X_i}{q_i Z_i},$$

$$v_V^i = \frac{p_V^i V_i}{q_i X_i}, \quad (i = 1, 2, \ldots, n).$$

The growth rate of value added can be expressed in terms of growth rates of intermediate input and output and the average value shares:

$$\ln V_i(T) - \ln V_i(T-1) = \frac{1}{\bar{v}_V^i}[\ln Z_i(T) - \ln Z_i(T-1)] - \frac{\bar{v}_X^i}{\bar{v}_V^i}[\ln X_i(T) - \ln X_i(T-1)],$$

$$(i = 1, 2, \ldots, n).$$

The quantity of aggregate value added is the sum of quantities of value added in all industries. Finally, the price of aggregate value added is the ratio of value added to the quantity of value added for the economy as a whole.[40]

In section 3.2 I have described data on annual hours worked and labor compensation per hour, cross-classified by sex, age, education, and employment class of workers. The aggregate model of production includes equilibrium conditions between the supply of each type of labor and the sum of demands for that type of labor by all sectors. The value of each of the 160 labor inputs for the economy as a whole is equal to the sum of the values over all sectors. Labor compensation for the economy as a whole is controlled to labor compensation from the U.S. national income accounts.

Aggregate data on prices and quantities of labor input, cross-classified by sex, age, education, and employment class, but not by industry, underlie the indexes of labor input presented in table 3.1. For the economy as a whole, hours worked and labor compensation for each of 160 categories of the work force are added over all industries. Labor compensation is divided by annual hours worked to derive labor compensation per hour worked for each category. Finally, price and quantity data are combined into price and quantity indexes of aggregate labor input.

To construct an index of labor input for the economy as a whole, I express aggregate labor input L as a translog function of its 160 individual components $\{L_l\}$. The corresponding index of labor input takes the form

$$\ln L(T) - \ln L(T-1) = \Sigma \bar{v}_{Ll}[\ln L_l(T) - \ln L_l(T-1)],$$

where weights are given by the average shares of the individual components in the value of labor compensation:

$$\bar{v}_{Ll} = \frac{1}{2}[v_{Ll}(T) + v_{Ll}(T-1)], \quad (l = 1, 2, \ldots, q),$$

$$v_{Ll} = \frac{p_{Ll}L_l}{\Sigma p\mathrm{L}_{Ll}L_l}, \quad (l = 1, 2, \ldots, \mathrm{q}).$$

The value shares are computed from data on hours worked $\{L_l\}$ and compensation per hour $\{p_{Ll}\}$ for all components of labor input, cross-classified by sex, age, education, and employment class of workers. A measure of total hours worked for the economy as a whole can be obtained by adding hours worked across all categories of labor input. The quality of aggregate hours worked is defined, as before, as the ratio of labor input to hours worked. Indexes of the quantity of labor input and labor quality are presented for the economy as a whole in table 3.1.

In section 3.3 I have described data on capital stocks and rental prices, cross-classified by asset class and legal form of organization. The aggregate model of production includes market equilibrium conditions between the supply of each type of capital and the sum of demands for that type of capital by all sectors. The value of each of the capital inputs for the economy as a whole is equal to the sum of values over all sectors. Consistent with the treatment of labor compensation, property compensation for the economy as a whole is controlled to property compensation from the U.S. national income accounts.

Aggregate data on prices and quantities of capital input, cross-classified by asset class and legal form of organization, but not by industry, underlie the indexes of capital input presented in table 3.1. For the economy as a whole, capital stock and property compensation for each category are added over all industries. Property compensation is divided by capital stock to derive property compensation per unit of capital stock for each category. Finally, price and quantity data are combined into price and quantity indexes of aggregate capital input.

To construct an index of capital input for the economy as a whole, I express aggregate capital input K as a translog function of its individual components $\{K_k\}$. The corresponding index of capital input takes the form

$$\ln K(T) - \ln K(T-1) = \Sigma \bar{v}_{Kk} [\ln K_k(T) - \ln K_k(T-1)],$$

where weights are given by the average shares of individual components in the value of property compensation:

$$\bar{v}_{Kk} = \frac{1}{2} [v_{Kk}(T) + v_{Kk}(T-1)], \quad (k = 1, 2, \ldots, p),$$

and

$$v_{Kk} = \frac{p_{Kk}K_k}{\Sigma p_{Kk}K_k}, \quad (k = 1, 2, \ldots, p).$$

The value shares are computed from data on capital stocks $\{K_k\}$ and rental prices $\{p_{Kk}\}$ for all components of capital input, cross-classified by asset class and legal form of organization. A measure of capital stock for the economy as a whole can be obtained by adding capital stock across all categories of capital input. The quality of aggregate capital stock is defined, as before, as the ratio of capital input to capital stock. Indexes of the quantity of capital input and capital quality are presented for the economy as a whole in table 3.1.

3.5.3 Alternative Sources and Methods

To provide additional perspective on U.S. economic growth it is useful to compare the sources and methods that underly the analysis given in table 3.1 with those of other studies.[41] For the U.S. economy as a whole Christensen and Jorgenson (1969, 1970, 1973a, 1973b) have presented an analysis of sources of U.S. economic growth similar to that presented in the first panel of table 3.1. Their study covers the period 1929–69 for the private sector of the U.S. economy.

Christensen, Cummings, and Jorgenson (1978, 1980) have extended the estimates of Christensen and Jorgenson through 1973. Aggregate value added is defined from the producers' point of view, including the value of sales and excise taxes and including the value of subsidies; however, the quantity of value added is measured as an index of deliveries to final demand rather than the sum of quantities of value added over industrial sectors. The quantity of labor input is divided among categories of the labor force broken down by educational attainment, but not by sex, age, employment class, or occupation.

The empirical results of Christensen, Cummings, and Jorgenson (1980) for the period 1947–73 are very similar to those given in table 3.1. For this period their estimate of the average growth rate of value added for the private domestic sector of the U.S. economy is 4.00% per year; by comparison the estimate of the rate of growth for the U.S. economy given in table 3.1 is 3.79% per year. The two estimates are not precisely comparable since Christensen, Cummings, and Jorgenson do not include government sectors in their measure of aggregate output.

Christensen, Cummings, and Jorgenson estimate the average growth rate of capital input at 4.26% per year for the period 1947–73; the estimate for this period given in table 3.1 is 4.16% per year. These estimates are closely comparable, except that the estimates in table 3.1 include capital input for government enterprises. Christensen, Cummings, and Jorgenson estimate the average growth rate of labor input at 1.62% per year, while the estimate presented in table 3.1 is 1.80% per year. Finally their estimate of the rate of productivity growth is 1.34% per year, while the estimate given in table 3.1 is 1.11% per year. Again, the two estimates for labor input and the rate of productivity growth are not precisely comparable since the estimates given in table 3.1 include labor input for the government sectors.

Christensen, Cummings, and Jorgenson (1980) have presented estimates of aggregate productivity growth for Canada, France, Germany, Italy, Japan, Korea, the Netherlands, and the United Kingdom as well as for the United States. Their estimates cover various periods beginning after 1947 and ending in 1973; the estimates cover the period 1960–73 for all countries. Conrad and Jorgenson (1975) have developed data for Germany for the period 1950–73, Ezaki and Jorgenson (1973) have presented estimates for Japan for the period 1951–68 and Jorgenson and Nishimizu (1978) have given estimates for Japan for the period 1952–74. Christensen and Cummings (1981) have provided estimates for Korea for the period 1960–73.

Elias (1978) has developed data on a basis that is comparable with Christensen, Cummings, and Jorgenson (1980) for Argentina, Brazil, Chile, Columbia, Mexico, Peru, and Venezuela for the period 1940–74. Groes and Bjerregaard (1978) have developed comparable estimates for Denmark for the period 1950–72. On the basis of the close correspondence between the results for the U.S. economy as a whole given in table 3.1 and those of Christensen, Cummings, and Jorgenson, I conclude that it is appropriate to compare the aggregate results in the first panel of table 3.1 with those for the countries presented in their study and the other studies I have listed.[42]

BLS (1983) has employed private business product as a measure of value added in the U.S. economy as a whole. This measure is obtained from the gross national product by excluding output originating in general government, government enterprises, owner-occupied housing, rest of the world, households and institutions, and the statistical discrepancy. The resulting measure of value added is gross of depreciation. This has the important advantage of avoiding the confounding of measures of output and capital input that I have analyzed in section 3.4.1, above. I have summarized the differences between my methodology for measuring labor and capital inputs and that of BLS in sections 3.2.3 and 3.3.3.

Denison (1985) employs an approach to production based on value added at the economywide level. He uses national income as a measure of value added. This measure excludes capital consumption allowances and indirect business taxes. His measure of capital input is based on the net earnings of capital, also excluding business taxes. The prices and quantities of inputs and outputs employed in Denison's measure of productivity satisfy the accounting identity between the value of output and the value of input. However, the corresponding model of aggregate production involves net value added, so that output and inputs are confounded by including capital input in both categories, as I pointed out in section 3.4.1. I conclude that the quantity of net value added employed by Denison is not an appropriate starting point for modeling producer behavior at the aggregate level.[43]

The problem with net value added as a measure of output for the economy as a whole can be traced to the definition of capital consumption allowances introduced by Denison (1957, 238–55). This concept of depreciation is defined by Young and Musgrave (1980, 32), as follows: "Depreciation is the cost of the asset allocated over its service life in proportion to its estimated service at each date." Denison (1972, 104–5) refers to this method of allocation as the "capital input method." Within the framework for measuring capital input presented in section 3.3.1, above, Denison's concept of capital consumption allowances is based on allocating the cost of an asset over its lifetime in proportion to the relative efficiencies $\{d(\tau)\}$ of capital goods of different ages rather than in proportion to depreciation $p_D(T)$.

Young and Musgrave (1980, 33–37) contrast the Denison definition with the "discounted value definition" of depreciation $p_D(T)$ employed in the model of capital as a factor of production presented in section 3.3.1. Among the advantages for the "capital input method" claimed by Denison (1957, 240) and Young and Musgrave (1980, 33) is that this definition avoids discounting of future capital services. In fact, discounting can be avoided in the measurement of depreciation if and only if the decline in the efficiency of capital goods is geometric. In this case the relative efficiencies $\{d(\tau)\}$ decline with the age of an asset at a constant rate. Capital service prices $p_K(T)$ and investment goods prices $p_I(T)$ decline with age at the same rate, and depreciation $p_D(T)$ is proportional to the price of an investment good.

As I have pointed out in section 3.3.3, above, Denison's assumptions about the relative efficiencies of capital goods of different ages require discounting of future capital services to obtain an appropriate measure of depreciation. Denison's attempt to avoid discounting leads him to confuse the relative efficiencies $\{d(\tau)\}$ with decline in the value of an asset as a basis for measure depreciation $p_D(T)$. This leads, in turn, to an inconsistency between the assumptions about relative efficiencies utilized in measuring capital input $A(T-1)$ and the assumptions employed in measuring the rental price of capital input $p_K(T)$. This chain of inconsistencies and contradictions can be broken only by replacing the "capital input method" of measuring depreciation introduced by Denison (1957) with the "discounted value definition" presented in section 3.3.3. The "discounted value definition" is employed, for example, by Christensen, Cummings, and Jorgenson (1980) and BLS (1983).

Denison's (1974, 9) "capital input method" of depreciation leads him to draw an analogy between the consumption of intermediate goods and capital consumption allowances. Since the consumption of intermediate goods is eliminated in the course of aggregating over sectors, but capital consumption allowances are not eliminated by aggregation, this analogy is inappropriate and misleading. The price and quantity of capital input are index numbers obtained by weighting each component of capital input by its rental price. Rental prices depend on differences in depreciation among assets and differences in the tax treatment of the resulting property compensation. By suppressing these differences Denison greatly underestimates the contribution of capital input to economic growth. A comparison of the capital input measures of Denison (1967) with those of Christensen and Jorgenson (1969, 1970, 1973a, 1973b) is given by Jorgenson and Griliches (1972a). Jorgenson (1989) provides a detailed discussion of Denison's treatment of capital consumption allowances.

Maddison (1987) has recently constructed aggregate growth accounts for the period 1870–1984 for France, Germany, Japan, the Netherlands, the United Kingdom, and the United States. He has divided this period into the subperiod 1870–1913, almost the same as that considered by Tinbergen (1942), and the subperiods 1913–50, 1950–73, and 1973–84. For the period 1913–84 Maddison gives an analysis of the sources of growth in gross domestic product for all six countries, including hours worked, changes in labor quality, capital stock, and changes in capital quality. His analysis of the sources of growth for the period 1870–1913 includes only hours worked and capital stock, omitting changes in input quality.

Maddison draws on the work of Carré, Dubois, and Malinvaud (1975) for France. This study covers 1913 and the period 1949–66 on an annual basis and presents an analysis of sources of growth of gross domestic product that includes hours worked, quality of labor input, and capital stock. Maddison utilizes results from the study of Ohkawa and Rosovsky (1973) for Japan, which covers the period 1908–64 and analyzes the growth of gross domestic product. This analysis incorporates employment, quality of labor input, and capital stock. For the United Kingdom, Maddison employs the work of Matthews, Feinstein, and Odling-Smee (1982). This study covers the period 1856–1973 and gives an analysis of the sources of growth of gross domestic product, including hours worked, quality of labor input, and capital stock. For the United States, Maddison utilizes the work of Kendrick (1961a, 1973).

Although Maddison considers the measurement of the quality of capital input by introducing rental prices for individual capital inputs, he rejects this approach and assumes that the rate of growth of capital quality is 1.5% per year for the period 1913–84 for all six countries included in his study. This assumption is not based on empirical data, but Maddison modifies the assumption for the subperiods 1950–73 and 1973–84 by an adjustment for changes in the average age of capital goods that incorporates investment data. A more satisfactory approach to the long-term analysis of sources of U.S. economic growth has been presented by Abramovitz and David (1973a, 1973b) for the period 1800–1967. This analysis incorporates the results of Christensen and Jorgenson (1970) for the period 1929–67 and includes hours worked, quality of labor input, capital stock, and quality of capital input. For the period 1800–1927 the analysis is limited to hours worked and capital stock as sources of growth.

For the U.S. economy as a whole Kendrick (1961a, 1973), Kendrick and Sato (1963), Kendrick and Grossman (1980), and Kendrick (1983a) have employed an approach to the measurement of value added through summation over the growth rates of quantities of value added in all sectors with weights that change periodically. The corresponding estimates of the growth rates of capital and labor inputs are constructed by summing the corresponding quantities over all sectors with weights that depend on property and labor compensation by sector.[44]

Kendrick employs unweighted sums of capital stock and hours worked as measures of capital and labor inputs at the sectoral level. At the aggregate level he employs unweighted sums as a variant of his principal estimates. The differences between the weighted and unweighted measures of capital and labor inputs at the aggregate level are associated with differences in the prices of capital and labor inputs among industries. Since Kendrick's measures of capital and labor inputs at the sectoral level do not incorporate changes in the quality of these inputs, a substantial portion of the differences between his weighted and unweighted measures at the aggregate level is due to unmeasured differences in input quality at the sectoral level.

The measures of value added, capital input, and labor input presented in the first panel of table 3.1 are constructed from unweighted sums of value added, individual components of capital input, and individual components of labor input over all industries. An alternative measure of aggregate value added can be constructed by weighting value added in each industry by the price of value added in that industry. Similarly, alternative measures of aggregate capital and labor inputs can be constructed by weighting individual components of these inputs in each industry by the prices of these components in that industry.

Differences between growth rates of measures of output and input that reflect differences in prices of output and inputs among industries and measures that do not reflect these differences are presented in the second panel of table 3.1. These differences are the measures of reallocations of value added, capital input, and labor input among sectors. The rate of aggregate productivity growth can be represented as a weighted sum of sectoral productivity growth rates and the contributions of the reallocations. If the prices of value added, capital input, and labor input were the same for all industries, the contributions of reallocations to aggregate productivity growth would vanish.

I conclude that capital and labor inputs can be usefully classified by industry in decomposing the rate of aggregate productivity growth between reallocations of value added, capital input, and labor input among sectors and rates of productivity growth at the sectoral level.[45] For this decomposition measures of output and inputs with and without industry as a classification are required. It is important to note that this argument cannot be extended to other characteristics of labor input such as sex, age, education, and employment status. If there are differences in rates of remuneration of individual components of labor input differing in these characteristics, labor input must be broken down by characteristics at both aggregate and sectoral levels. Similarly, capital input must be broken down by type of asset and legal form of organization at both levels.

I have focused attention on the integration of sectoral measures of output, input, and productivity growth with the corresponding aggregate measures. To avoid including capital input in the measure of aggregate output and the aggregate inputs, as implied by Denison's (1962a, 1962b, 1967, 1974, 1979, 1985) measure of output, I present data in table 3.1 that utilize gross value added at the aggregate level. BLS (1983), Christensen, Cummings, and Jorgenson (1980), Kendrick (1984), and the studies utilized by Maddison (1987) also employ gross value added.[46] However, output in these studies is derived from aggregate production data rather than explicit aggregation over industrial sectors. The resulting measures of aggregate productivity growth are not integrated with corresponding sectoral measures, as in the second panel of table 3.1.

The existence of an aggregate production function implies that all sectoral value added functions are identical. If all sectors pay the same prices for primary factor inputs, the reallocations of value added, capital input, and labor input among sectors have no effect on aggregate output. The contributions of these reallocations can be regarded as measures of departures from the assumptions that underly the aggregate model of production. The data presented in table 3.1 make it possible to assess the significance of these departures. Over the period 1947–85 the reallocations are very small relative to the growth of capital and labor inputs and productivity growth. Over shorter periods, such as 1953–57 and 1973–79, these reallocations are large relative to aggregate productivity growth.[47]

The assumptions required to validate an aggregate model of production are obviously highly restrictive. The evidence presented in table 3.1 suggests that these assumptions are not seriously misleading over a time span as long as the period 1947–85 that we have considered. Similar evidence for other time periods is lacking. However, it seems plausible that an aggregate production model is an appropriate point of departure for studies of long-term growth like those of Abramovitz and David (1973a, 1973b) for the period 1800–1967, Christensen and Jorgenson (1973a) for the period 1929–69, Maddison (1987) for the period 1913–84, and Tinbergen (1942) for the period 1870–1914. For shorter periods an aggregate production model can be seriously misleading.

3.6 Econometric Modeling of Production

A key innovation in the methodology that underlies the indexes presented in tables 3.2 and 3.3 is the symmetric treatment of intermediate, capital, and labor inputs. Output can be represented as a function of all three inputs and time. Substitution possibilities among intermediate inputs and primary factor inputs can be incorporated explicitly. I have contrasted this approach with a more restrictive model based on the existence of a value-added aggregate within each sector. In this alternative approach output is represented as a function of intermediate input and the quantity of value added. Value added in turn is represented as a function of capital and labor inputs and time.

In section 3.5.1, above, I have pointed out that the existence of an aggregate production function requires the existence of sectoral value added functions. Furthermore, these value-added functions must be identical for all sectors. These highly restrictive assumptions are appropriate for studies of long-term growth, but can be seriously misleading for shorter periods. To explain important changes in rates of economic growth, such as the recent growth slowdown in industrialized countries, a disaggregated approach is required. It is important to emphasize that a disaggregated approach, based on models of production for individual industrial sectors, is far more costly than aggregate production modeling. However, such an approach is essential in overcoming the limitations of aggregate models of production.

An econometric model based on the symmetric treatment of intermediate, capital, and labor inputs makes it possible to dispense with the value-added approach employed by Kendrick and tested in table 3.7, above. The rate of sectoral productivity growth can be expressed as functions of the prices of all inputs and the level of technology. Models of production for all industrial sectors can be combined to form a general equilibrium model of production. Symmetric treatment of intermediate, capital, and labor inputs makes it possible to integrate the analysis of sources of economic growth with general equilibrium modeling.

3.6.1. Sectoral Production Modeling

General equilibrium modeling of production originated with the seminal work of Leontief (1951), beginning with the implementation of the static input-output model. Leontief (1953a) gave a further impetus to the development of general equilibrium modeling by introducing a dynamic input-output model. Empirical work associated with input-output analysis is based on estimating the unknown parameters of an interindustry model from a single interindustry transactions table. These estimates are based on a "fixed coefficients" assumption in modeling demands for all inputs. Under this assumption all inputs are proportional to output.

The first successful implementation of a general equilibrium model without the fixed coefficients assumptions of input-output analysis is due to Johansen (1976). Johansen retained the fixed coefficients assumption in modeling demands for intermediate goods. This form of the fixed coefficients assumption is tested in table 3.7, above. Johansen employed linear logarithmic or Cobb-Douglas production functions in modeling productivity growth and the substitution between capital and labor inputs within a value-added aggregate. Linear logarithmic production functions imply that relative shares of inputs in the value of output are fixed, so that the unknown parameters characterizing substitution between capital and labor inputs can be estimated from a single data point.

In modeling producer behavior Johansen employed econometric methods only in estimating constant rates of productivity growth. The essential features of Johansen's approach have been preserved in the general equilibrium models surveyed by Bergman (1990), Robinson (1989) and Shoven and Whalley (1984). The unknown parameters describing technology in these models are determined by "calibration" to a single data point. Data from a single interindustry transactions table are supplemented by a small number of parameters estimated econometrically. The obvious disadvantage of this approach is that arbitrary constraints on patterns of substitution are required in order to make calibration possible.

An alternative approach to modeling producer behavior for general equilibrium models is through complete systems of demand functions for inputs in each industrial sector. Each system gives quantities demanded as functions of prices of inputs and output. This approach to the modeling of producer behavior was originated by Berndt and Jorgenson (1973).[48] As in the descriptions of technology by Leontief and Johansen, production is characterized by constant returns to scale in each sector. Output is represented as a function of capital, labor, energy, and materials inputs and time as an indicator of the level of technology.[49]

Under constant returns to scale commodity prices can be expressed as functions of factor prices, utilizing the nonsubstitution theorem of Samuelson (1951). This greatly facilitates the solution of the econometric general equilibrium models constructed by Hudson and Jorgenson (1974) and Jorgenson and Wilcoxen (1990). The nonsubstitution theorem permits a substantial reduction in dimensionality of the space of prices to be determined by the model. The coefficients of the general equilibrium model can be determined endogenously, taking into account prices of primary factor inputs and levels of productivity.

The implementation of econometric models of producer behavior for general equilibrium analysis is very demanding in terms of data requirements. These models require the construction of a consistent time series of interindustry transactions tables. By comparison, the noneconometric approaches of Leontief and Johansen require only a single interindustry transactions table. Second, the implementation of systems of input demand functions requires econometric methods for the estimation of parameters in systems of nonlinear simultaneous equations.

Translog index numbers for intermediate, capital, and labor inputs and rates of productivity growth are employed in the analysis of sources of economic growth presented in tables 3.2 and 3.3. Translog production functions can be used in specifying econometric models for determining the distribution of the value of output among the productive inputs and the rate of productivity growth. In estimating the parameters of these models the quantity indexes of inputs, the corresponding price indexes, and indexes of productivity growth can be employed as data.

Jorgenson and Fraumeni (1981) and Jorgenson (1984b) have constructed econometric models of producer behavior based on the translog functional form for the 35 industrial sectors of the U.S. economy included in tables 3.2 and 3.3. Similar models for Japan have been constructed by Kuroda, Yoshioka, and Jorgenson (1984). Production models for all industrial sectors have been incorporated into an econometric general equilibrium model of the United States by Jorgenson and Wilcoxen (1990).[50] The econometric methodology for construction of sectoral models of production is discussed in detail by Jorgenson (1986a).

3.6.2. Aggregate Production Modeling

The traditional approach to modeling producer behavior at the aggregate level begins with the assumption that the production function is characterized by constant returns to scale. In addition, the production function is assumed to be additive in capital and labor inputs. Under these restrictions demand and supply functions can be derived explicitly from the production function and the necessary conditions for producer equilibrium. However, this approach has the disadvantage of imposing constraints on patterns of substitution—thereby frustrating the objective of determining these patterns empirically.

The traditional approach was originated by Cobb and Douglas (1928) and employed in empirical research by Douglas and his associates for almost two decades. These studies are summarized by Douglas (1948, 1967, 1976). The principal methodology employed in Douglas's research is based on the analysis of cross section data for manufacturing industries, treating individual industries rather than plants or firms as observations. The measure of output employed in these studies is based on the value-added model outlined in section 3.4.1 above.

The use of individual industries as observations requires the assumption that the value-added functions for all industries are identical, which is precisely the assumption required for the existence of an aggregate production function. Tinbergen (1942) was the first to formulate the aggregate production function with time as an indicator of the level of technology. This is the form of the production function employed in the analysis of sources of economic growth at the aggregate level.[51]

The limitations of the traditional approach were made strikingly apparent by Arrow, Chenery, Minhas, and Solow (1961; henceforward ACMS), who pointed out that the Cobb-Douglas production function imposes a priori restrictions on patterns of substitution among inputs. In particular, elasticities of substitution among all inputs must be equal to unity. The constant elasticity of substitution (CES) production function introduced by ACMS adds flexibility to the traditional approach by treating the elasticity of substitution between capital and labor as an unknown parameter to be estimated by econometric methods. However, the CES production function retains the assumptions of additivity and homogeneity and imposes very stringent limitations on patterns of substitution. McFadden (1963) and Uzawa (1962) have shown, essentially, that elasticities of substitution among all inputs must be the same.[52]

The translog index numbers for capital and labor inputs and the rate of productivity growth for the economy as a whole are employed in the analysis of the sources of economic growth presented in table 3.1. The translog production function can also be used in specifying an econometric model for determining the rate of productivity growth and the distribution of value added between the primary factor inputs. The quantity indexes of inputs, the corresponding price indexes, and the index of productivity growth can be employed as data in estimating the parameters of this econometric model.[53]

The benefits of an aggregate production model must be weighed against the costs of departures from the highly restrictive assumptions that underly the existence of an aggregate production function. Where these assumptions are inappropriate, the econometric approach to general equilibrium analysis outlined above can be employed in analyzing patterns of production for the economy as a whole. This approach is based on sectoral models of production rather than an aggregate production model. Sectoral models are also useful in decomposing aggregate economic growth into sectoral components.[54]

The results presented in table 3.1 show that an aggregate production model is appropriate for studies of long-term U.S. economic growth. However, an aggregate model can be misleading for relatively short time periods, such as the individual business cycles 1953–57 and 1973–79. For the period 1947–85 as a whole the rate of aggregate productivity growth is 0.71% per year, while the weighted sum of sectoral productivity growth rates of 0.88% per year. The difference between aggregate productivity growth and sectoral productivity growth provides a measure of departures from the stringent assumptions that underly the aggregate production model. This difference is not negligible, even for the period 1947–85.

Considering the second panel of table 3.1, we can decompose the decline in the aggregate productivity growth rate into the sum of sectoral productivity growth rates and the reallocations of value added, capital input, and labor input. The decline in sectoral productivity growth between the period 1947–85 and the subperiod 1973–79 was 1.00% per year. This decline is almost sufficient to account for the slowdown in U.S. economic growth. The precipitous fall in sectoral productivity growth was augmented at the aggregate level by a fall in the reallocation of value added of 0.34 percent. I conclude that the assumptions that underly the aggregate model of production failed to hold during the period 1973–79.

The decline in productivity growth at the level of individual industries can be identified as the main culprit in the slowdown of U.S. economic growth since 1973. To provide an explanation of this decline we must go behind the measurement of sectoral productivity growth rates to identify the determinants of productivity growth at the sectoral level. To illustrate the econometric approach to productivity growth we present a summary of the results of fitting an econometric model to detailed data on sectoral output and capital, labor, energy, and materials inputs for 35 industrial sectors of the U.S. economy.

Our econometric study is based on sectoral models of production for each 35 individual industries. Although production functions contain all the available information about producer behavior for each sector, we find it useful to express the sectoral models of production in an alternative and equivalent form. Under constant returns to scale we can introduce price functions for each industry.[55] The price function gives the price of output as a function of the prices of capital, labor, energy, and materials inputs and time, representing the level of technology. Price functions summarize the information about producer behavior contained in the production functions in a more convenient form.

Given the price function for each industry, we can express the shares of each of the four inputs in the industry—capital, labor, energy, and materials inputs—in the value of output as functions of the prices of inputs and the level of technology. We can add to the four equations for the value shares an equation that completes the model. This equation gives the sectoral rate of productivity growth as a function of the prices of the inputs and the level of technology. The equation determining the productivity growth rate is our econometric model of sectoral productivity growth.

Like any econometric model, the relationships determining the value shares of capital, labor, energy, and materials inputs and the rate of productivity growth involve unknown parameters that must be estimated. Included among these parameters are biases of productivity growth. For example, the bias of productivity growth for capital input gives the change in the share of capital input in the value of output in response to changes in technology.[56] It is said that productivity growth is capital using if the bias for capital input is positive. Similarly, it is said that productivity growth is capital saving if the bias for capital input is negative. The sum of the biases for all four inputs must be precisely zero since the changes in all four shares must sum to zero.

The biases of productivity growth appear as coefficients of time, representing the level of technology, in the four equations for the value shares of the four inputs. Our econometric model for each industrial sector of the U.S. economy also includes an equation that determines the rate of productivity growth. The biases appear with an opposite sign as coefficients of the prices in the equation for sectoral productivity growth. This feature of the econometric model makes it possible to use information about both changes in the value shares with the level of technology and changes in the rate of productivity growth with prices in estimating the biases of productivity growth.[57]

Capital-using productivity growth, associated with a positive bias of productivity growth for capital input, implies that an increase in the price of capital input diminishes the rate of productivity growth. Similarly, capital-saving productivity growth implies that productivity growth increases with the price of capital input. Ho and Jorgenson (1990) have fitted econometric models based on translog price functions to data for all 35 industrial sectors. Since our primary concern is with the determinants of sectoral productivity growth, I present a classification of industries by biases of productivity growth in table 3.8.

The pattern of productivity growth that occurs most frequently in table 3.8 is capital-using, labor-saving, energy-using, and materials-using productivity growth. This pattern occurs for 11 of the 35 industries. For this pattern the

Table 3.8 Classification of Industries by Biases of Productivity Growth

Pattern of Biases	Industries
Capital using, labor using, energy using, materials saving	textile mills; apparel; lumber & wood
Capital using, labor saving, energy using, materials using	agriculture; construction; food & kindred products; furniture & fixtures; paper & allied; printing & publishing; stone, clay, & glass; electrical machinery; miscellaneous manufacturing; transportation services; wholesale & retail trade
Capital using, labor saving, energy using, materials saving	nonmetallic mining; tobacco; leather; fabricated metal; machinery, except electrical; instruments; communications; services; government enterprises
Capital using, labor saving, energy saving, materials using	coal mining; petroleum & coal products
Capital saving, labor using, energy using, materials using	finance, insurance, & real estate
Capital saving, labor using, energy using, materials saving	motor vehicles
Capital saving, labor using, energy saving, materials using	metal mining
Capital saving, labor saving, energy using, materials using	oil & gas extraction; chemicals; rubber & miscellaneous plastics; transportation equipment & ordnance; electric utilities
Capital saving, labor saving, energy using, materials saving	primary metals; gas utilities

biases of productivity growth for capital, energy, and materials inputs are positive and the bias of productivity growth for labor input is negative. This pattern implies that increases in the prices of capital, energy, and materials inputs diminish the rate of productivity growth, while an increase in the price of labor input enhances productivity growth.

The most striking change in the relative prices of capital, labor, energy, and materials inputs that has taken place since 1973 is the substantial increase in the price of energy. Reversing historical trends toward lower real prices of energy in the U.S., the Arab oil embargo of late 1973 and early 1974 resulted in a dramatic increase in oil import prices. Real energy prices to final users increased by 23% in the U.S. during the period 1973–75, despite price controls on domestic petroleum and natural gas. In 1978 the Iranian revolution sent a second wave of oil import price increases through the U.S. economy. Real energy prices climbed by 34% over the following two-year period.[58]

I have now provided part of the solution of the problem of disappointing

U.S. economic growth since 1973. Higher energy prices are associated with a decline in sectoral productivity growth for 32 of the 35 industries included in table 3.8. The slowdown in sectoral productivity growth is more than sufficient to explain the decline in U.S. economic growth. It is important to emphasize that an econometric model of sectoral productivity growth is essential to solving the problem of the slowdown in U.S. economic growth since 1973. An aggregate model of production excludes energy and materials inputs by definition since deliveries to intermediate demand are offset by receipts of intermediate inputs.

Denison (1979, 1983, 1984, 1985) has attempted to analyze the slowdown in U.S. economic growth using an aggregate model of production and has pronounced the slowdown a "mystery." The results presented in the first panel of table 3.1 appear to bear out this conclusion. The decline in the rate of aggregate productivity growth is more than sufficient to account for the decline in the rate of growth of value added. However, the decline in economic growth is left unexplained in the absence of an econometric model to determine the rate of productivity growth. A model based on an aggregate production function would fail to establish the critical role of the increase in energy prices after 1973, since energy is excluded as an input at the aggregate level by assumption.

In section 3.5.1. above, I have pointed out that the existence of an aggregate production function requires sectoral value added functions that are the same for all sectors. In section 3.4.1 we have observed that the existence of a sectoral value-added function requires separability between the level of technology and intermediate input. Changes in technology have an impact on sectoral productivity growth only through their impact on value added. An econometric model of productivity growth based on a value-added function for each industry would also eliminate the role of energy prices by assumption. I conclude that the link between energy prices and productivity growth requires a sectoral model of production that treats inputs of energy and materials symmetrically with inputs of capital and labor.

The steps I have outlined—disaggregating the sources of economic growth to the sectoral level, decomposing sectoral output growth between productivity growth and the growth of capital, labor, energy, and materials inputs, and modeling the rate of growth of sectoral productivity growth rate econometrically—have been taken only recently. The results of Ho and Jorgenson (1990) have corroborated those of Jorgenson and Fraumeni (1981) and Jorgenson (1984b). Jorgenson (1984b) has further disaggregated energy between electricity and nonelectrical energy. Similar results have been obtained for the Japanese economy, which suffered a far more severe slowdown than the U.S. economy, by Kuroda, Yoshioka, and Jorgenson (1984).[59] Much additional research will be required to provide an exhaustive explanation of the slowdown of U.S. economic growth and the implications for the future growth of the economy.

3.6.3. Alternative Production Models

While the rate of productivity growth is endogenous in the econometric models I have outlined, these models must be carefully distinguished from models of induced technical change, such as those analyzed by Hicks (1963), Kennedy (1964), Samuelson (1965), von Weizsacker (1962), and many others. In those models the biases of productivity growth are endogenous and depend on relative prices. In the model that underlies the results presented in table 3.8 the biases are constant parameters that can be estimated econometrically. As Samuelson (1965) has pointed out, models of induced technical change require intertemporal optimization since technical change at any point of time affects future production possibilities.[60]

The simplest intertemporal model of production is based on capital as a factor of production. In the model presented in section 3.3, myopic decision rules can be derived by treating the price of capital input as a rental price of capital services. The rate of productivity growth at any point of time is a function of relative prices but does not affect future production possibilities. This greatly simplifies the intertemporal modeling of producer behavior and facilitates the construction of an econometric model. Given myopic decision rules for producers in each industrial sector, all of the implications of the economic theory of production can be described in terms of the sectoral production function or the sectoral price function.

A less restrictive intertemporal model of production generates costs of adjustment from changes in the level of capital input through investment. As the level of investment increases, the amount of marketable output produced from given input levels decreases. Marketable output and investment can be treated as joint outputs that are produced from capital and other inputs.[61] Models of producer behavior based on costs of adjustment can be implemented on the basis of myopic decision rules, provided that accumulated costs of adjustment can be observed. One approach to measuring these costs is to set them equal to the difference between the market value of the producing unit and the market value of its capital stock.[62]

As an alternative to myopic decision rules, expectations can be incorporated explicitly into dynamic models of producer behavior based on costs of adjustment. An objection to dynamic models of production based on static expectations is that current prices change from period to period, but expectations are based on unchanging future prices.[63] An alternative approach is to base the dynamic optimization on forecasts of future prices. Since these forecasts are subject to random errors, it is natural to require that the optimization process takes into account the uncertainty that accompanies forecasts of future prices.

Two alternative approaches to optimization under uncertainty have been proposed. Provided that the objective function for producers is quadratic and constraints are linear, optimization under uncertainty can be replaced by a corresponding optimization problem under certainty.[64] An alternative approach to optimization under uncertainty is to employ the information about expectations of future prices contained in current input levels. This approach has the advantage that it is not limited to quadratic objective functions and linear constraints.[65]

I have considered econometric models of production based on disembodied technical change. Changes in technology affect old and new vintages of capital goods symmetrically. An alternative approach is to embody changes in technology in new vintages of capital goods. The embodiment of technical change was originated by Solow (1957, 316–17).[66] The index numbers for productivity growth described in sections 3.4 and 3.5 are based on the residual between the growth of output and the growth of inputs. This residual can be interpreted as a measure of the rate of disembodied technical change. Measures of the rate of embodied technical change can also be constructed from data on the residual.[67]

Hall (1971) and Jorgenson and Griliches (1967) have identified embodied technical change with changes in the quality of capital goods. The line of research suggested by Solow's (1960) concept of embodied technical change involves substituting quality-corrected price indexes for existing price indexes of capital goods.[68] Changes in quality can be incorporated into price indexes for capital goods by means of the "hedonic technique" employed by Griliches (1961b) and studies in the volume edited by Griliches (1971b). For example, Cole, Chen, Barquin-Stolleman, Dulberger, Helvacian, and Hodge (1986) have recently developed quality corrections for computer price indexes employed in the U.S. national product accounts.[69]

At both sectoral and aggregate levels we have considered producer behavior under constant returns to scale. This methodology makes it possible to unify data generation, analysis of the sources of economic growth, and econometric modeling of production. The analysis of economic growth and the econometric modeling can be carried out independently. Both employ index numbers of output, inputs, and productivity. Under increasing returns to scale and competitive markets for output and all inputs, producer equilibrium is not defined by profit maximization, since no maximum of profits exists. The analysis of sources of economic growth and the modeling of producer behavior under increasing returns to scale cannot be carried out independently. The implementation of a model of producer behavior under increasing returns to scale requires an econometric approach.[70]

In regulated industries the price of output is set by regulatory authority. Given demand for output as a function of the regulated price, the level of output is exogenous to the producing unit. With output fixed from the point of view of the producer, necessary conditions for equilibrium can be derived from cost minimization. To illustrate the econometric modeling of economies of scale, we can briefly consider examples from the extensive literature on the U.S. electric power industry and the communications industry. An econometric model of electric power generation in the United States has been implemented by Christensen and Greene (1976). This model is based on translog cost functions for cross sections of individual electric utilities in 1955 and 1970. A key feature of the electric power industry in the United States is that individual firms are subject to price regulation. The regulatory authority sets the price for electric power. Electric utilities are required to supply the electric power that is demanded at the regulated price.

Christensen and Greene have employed translog cost functions fitted to data on individual utilities to characterize scale economies for individual firms. For both 1955 and 1970 the cost functions are U shaped with a minimum point occurring at very large levels of output. The cost function for 1970 is considerably below that for 1955, reflecting changes in technology.[71] Gollop and Roberts (1981) have employed translog cost functions for individual firms in analyzing annual data on eleven electric utilities in the United States for the period 1958–75. They use the results to decompose the growth of productivity between economies of scale and technical change. For the period as a whole economies of scale account for an average of 40% of productivity growth, while technical change accounts for the remaining 60%. Gollop and Roberts have provided a prototype for the analysis of sources of sectoral output growth in the electric generating industry.

A model with increasing returns to scale has been implemented for time-series data on Bell Canada, a regulated firm accounting for more than half of the output of the Canadian telecommunications industry, by Denny, Fuss, and Waverman (1981a). This model is based on cost minimization subject to regulatory pricing constraints. Bell Canada has multiple outputs consisting of different types of telecommunications services. Prices for these outputs are not proportional to marginal costs. Denny, Fuss, and Waverman provide an analysis of sources of growth of productivity for Bell Canada over the period 1952–76. Economies of scale account for 64% of productivity growth, technical change accounts for 20%, and nonmarginal cost pricing accounts for the remaining 16%.

Given the importance of economies of scale in the electric generating and communications industries, it is interesting to consider the implementation of a model for a whole industry, incorporating economies of scale. Such a model would require an econometric model for each firm, incorporating a panel of annual observations for all firms in the industry, similar to the panel constructed by Gollop and Roberts (1981) for 11 electric utilities.[72] To provide a decomposition of productivity growth for the industry between economies of scale and technical change the model would require an allocation of the growth of industry output among firms.

An important frontier in the econometric modeling of production lies in the disaggregation of sectoral production models to the level of the individual producing unit. For industries with significant economies of scale at this level, it is possible to supplement sectoral models of production with models based on panel data for individual firms and plants. This is already feasible for industries with well-documented production patterns at the level of the individual unit. At present, the required data are available only for regulated industries, such as electricity generation, communications, and transportation. However, the LRD project of the Bureau of the Census will provide a data source that may make it feasible to model production patterns for U.S. industry at the firm or plant level on a broader scale.[73]

The model of "learning by doing" proposed by Arrow (1962) provides an approach to modeling producer behavior with features similar in some respects to increasing returns to scale. This model has been employed in analyzing production from batch-type production processes, for example, in studies of the airframe industry summarized by Alchian (1963). Solow (1967) compares this model to models characterized by increasing returns to scale and provides additional references. Another alternative to the Christensen-Greene model for electric utilities has been developed by Fuss (1977, 1978). In Fuss's model the cost function is permitted to differ ex ante, before a plant is constructed, and ex post, after the plant is in place.[74] Fuss employs a generalized Leontief cost function introduced by Diewert (1971, 1973) with four input prices—structures, equipment, fuel, and labor. He models substitution among inputs and economies of scale for 79 steam generation plants for the period 1948–61.

It is worthwhile to consider the data requirements for development of a model of an industry incorporating differences between ex ante and ex post substitution possibilities. To simplify the discussion we can consider the special case of putty-clay technology with ex post "fixed coefficients." Such a model requires a panel of annual observations on individual establishments within an industry. The modeling of substitution possibilities at the establishment level requires estimates of lifetime costs for alternative technologies at the time of construction of each plant. The modeling of subsequent decisions about whether or not to retire the plant requires comparisons of the price of output and variable costs for each plant at every point of time.

We conclude that a wide variety of alternative production models are available for both aggregate and sectoral production modeling. The aggregate production model introduced by Cobb and Douglas (1928) and developed in Tinbergen (1942) in the form used in the studies of sources of economic growth cited in section 3.5, above, retains its usefulness in modeling long-term growth trends. However, the critical empirical evidence provided by the energy crisis of the 1970s has exposed important limitations of aggregate production modeling. These limitations cannot be overcome by introducing additional complexity at the aggregate level.

Sectoral production models are required to explain the slowdown in economic growth in the United States and other industrialized countries that took place after 1973. These models must incorporate inputs of energy and materials along with inputs of capital and labor. The "fixed coefficients" assumptions employed by Leontief and Johansen have been supplanted by econometric modeling of production at the sectoral level. This assumption is also implicit in the value-added models of production employed, for example, by Kendrick (1961a, 1973) and tested in table 3.7 above. The value-added model has also been supplanted at the sectoral level by a model that treats intermediate, capital, and labor inputs symmetrically.

The costs of assembling consistent time series of interindustry transactions tables and disaggregating measures of capital and labor inputs at the sectoral level are very substantial. These costs will continue to be a formidable obstacle to implementing econometric general equilibrium models of production. In addition, a great deal of further testing will be needed to establish the most appropriate specification for such models. However, this work will be essential in assimilating the important new evidence on patterns of production made available by the energy crisis of the 1970s and its aftermath. The new econometric tools that have been developed for modeling production will help to sustain the momentum in empirical research that has characterized the study of sources of economic growth ever since Tinbergen (1942).[75]

The analysis of sources of economic growth is an essential component of any study of economic growth. However, a theory of growth must also include an explanation of the growth in supplies of capital and labor inputs. In the neoclassical model of economic growth presented by Tinbergen (1942), saving generates growth in capital input and population growth generates growth in labor input. These features of the theory of economic growth have been retained in the neo-classical growth models developed by Solow (1956, 1970, 1988).

The theoretical underpinnings of an analysis of growth in factor supplies are to be found in the theory of consumer behavior. For example, the study of saving requires modeling saving-consumption decisions. Similarly, the analysis of labor supplies requires modeling demographic behavior and labor-leisure choices. A theory of economic growth must incorporate the sources of economic growth and the modeling of producer behavior. The analysis of growth of factor supplies and the modeling of consumer behavior are required to complete the theory.

Recent research on economic growth has given considerable emphasis to the analysis of sources of economic growth and the modeling of producer behavior. This has proved to be very fruitful, as suggested by the research I have summarized in this paper. However, the future agenda could usefully give greater attention to growth of factor supplies and the modeling of consumer behavior. This focus characterized the classic studies of economic growth by Goldsmith (1955, 1962), Kuznets (1961, 1971), Machlup (1962), and Schultz (1961).

3.7 Conclusion

In this paper I have used the sources of economic growth to illustrate the critical importance of interrelationships between national accounting and economic theory. The link between the two is the econometric modeling of production. The national accountant uses economic theories of production to generate systems of accounts and corresponding systems of price and quantity index numbers. Theories of production are used in determining what the accounts should include and exclude. The econometrician uses theories of production to generate systems of behavioral equations and the statistical methods employed in estimating the parameters of these equations.

The research activities I have mentioned can be carried out in isolation. Accounting systems and the associated systems of index numbers can be developed with no attempt to derive them from an underlying model of producer or consumer behavior. A purely statistical approach of this type can be compared, unfavorably in my view, with the economic approach pioneered by Simon Kuznets and embodied in modern systems of national accounts, like the U.S. NIPA or the United Nations system of national accounts.

Similarly, econometric studies can be conducted with no attention to accounting methods used in generating the underlying data. However, many of the most interesting problems in econometrics involve the characterization of higher order properties of technology and preferences. As examples, biases of technical change and elasticities of substitution are second-order properties of technology, since they depend on second-order derivatives of price and production functions. The lesson of decades of experience in modeling technology, dating back at least to Arrow, Chenery, Minhas, and Solow (1961), is that econometric estimates of these parameters are highly sensitive to methods of measurement. The best resolution of this problem is to generate accounting systems and econometric models within the same framework. This approach is articulated most fully in Diewert's elegant theory of exact index numbers.

Finally, theories of production can be generated in a form that abstracts from applications. For example, we can contrast the relatively general form of the theory of production presented in Hicks's (1946) *Value and Capital* with the more specific form of the theory presented by Hicks (1963) in *The Theory of Wages*. The concepts of the elasticity of substitution and the bias of technical change, introduced by Hicks (1963), have inspired a whole generation of econometric modelers of production. In section 3.6 I have shown that the bias of technical change is the key to understanding the slowdown in economic growth in industrialized countries since 1973. Clearly, the more specific form of the theory has proved to be better suited to applications.

My conclusion is that the most fruitful approach to research in economic measurement is one that combines national accounting, econometrics, and economic theory. This approach has emerged gradually in the successive volumes that report the proceedings of the Conference on Research in Income and Wealth. In the early days of the conference, econometrics was almost entirely absent, but economic theory and national accounting were by represented in the persons of Simon Kuznets and the other founders of the conference. This is not to say that every researcher has to play the role of national accountant, statistician, and economic theorist. Very few of us can combine such diverse talents in the way that Kuznets and many of the founders of the conference did.

We do not have to go all the way back to Adam Smith to appreciate the benefits of a division of labor. Accountants can design systems that are adapted to modeling, econometricians can develop models based on consistent systems of accounts and sound conceptualization, and theorists can choose a level of abstraction appropriate to applications in accounting and econometric modeling. It seems to me that these are the lessons that we, the current generation of participants in the Conference on Research in Income and Wealth, can derive from the experiences of our predecessors of the past half century.

In concluding this paper I would like to emphasize that our final objective remains economic measurement itself. I have used the sources of economic growth to illustrate how our measurements have become more precise and more comprehensive. The view of economic growth that is now coming into focus is very different from the picture based on Douglas's fateful abstraction of the aggregate production function. While this new perspective represents important scientific progress, additional challenges are constantly emerging, even in this much studied area. The research opportunities that have been created are more than sufficient to utilize the combined talents of a legion of national accountants, econometricians, and economic theorists for the next half century and beyond.

Notes

1. The first English-language reference to Tinbergen's article was by Valavanis-Vail (1955); an English translation appeared in Tinbergen's *Selected Papers* (1959). The article was also cited by Solow (1963a).

2. The initial version of the estimates of labor input presented in table 3.1 were published in Studies in Income and Wealth by Gollop and Jorgenson (1980, 1983). Denison (1985) has continued to publish more highly aggregated estimates of labor input growth. The Bureau of Labor Statistics has initiated a project to develop measures of labor input adjusted for changes in labor quality; see Waldorf, Kunze, Rosenblum, and Tannen (1986).

3. This approach can be contrasted with a more restrictive approach based on the existence of a value-added aggregate within each sector. The value-added approach is utilized by Kendrick (1956, 1961a, 1973, 1983a) and Kendrick and Grossman (1980).

These studies exclude intermediate input from consideration. The earlier study by Leontief (1953b) excluded capital input.

4. The concept of separability was introduced by Leontief (1947a, 1947b) and Sono (1961).

5. The concept of homothetic separability was originated by Shephard (1953, 1970). Lau (1969, 1978) has demonstrated that if the production function is homogeneous, separability implies homothetic separability.

6. The translog production function was first applied at the sectoral level by Berndt and Christensen (1973, 1974), using a value-added aggregate. The translog cost function incorporating intermediate input was applied at the sectoral level by Berndt and Jorgenson (1973) and Berndt and Wood (1975). Detailed references to sectoral production studies incorporating intermediate input are given by Jorgenson (1986a).

7. Translog quantity indexes were introduced by Irving Fisher (1922) and have been discussed by Christensen and Jorgenson (1969), Kloek (1966), Theil (1965), and Törnqvist (1936). These indexes were first derived from the translog production function by Diewert (1976). The corresponding index of productivity growth was introduced by Christensen and Jorgenson (1970). This index of productivity growth was first derived from the translog production function by Jorgenson and Nishimizu (1978). Earlier, Diewert (1976) had interpreted the ratio of translog indexes of output and input as an index of productivity. Samuelson and Swamy (1974) have provided a comprehensive survey of the economic theory of index numbers.

8. The allocations are based on the method of iterative proportional fitting discussed by Bishop, Fienberg, and Holland (1975, esp. 83–102, 188–91).

9. Establishment surveys count only persons actually at work during the survey week. By using establishment-based estimates of the number of jobs in each sector and assigning to absent workers the average annual hours worked by individuals with comparable characteristics, hours worked for each type of worker can be estimated on an annual basis.

10. Hours worked by workers cross-classified by demographic characteristics are estimated on the basis of household surveys. The resulting estimates are controlled to totals for each sector from the U.S. national accounts. Hours worked for each category of labor input is the product of employment, hours worked per week, and the number of weeks in the calendar year, 52. The concepts employed in these estimates of labor input reflect the conventions used in the Census of Population and the Current Population Survey.

11. These data provide estimates of average compensation per person rather than average compensation per job. To combine the data with estimates based on jobs from establishment surveys average compensation per person must be converted to average compensation per job. Matrices of weeks paid per year for each category of workers are required for this purpose. Labor compensation is the product of average compensation per person, the number of jobs per person, and the number of jobs. Estimates of average compensation per person and the number of weeks paid per year are based on household surveys, while estimates of the number of jobs are based on establishment surveys.

12. Chinloy (1980, 1981) provides such a decomposition for the U.S. economy as a whole, excluding sector of employment. Jorgenson, Gollop, and Fraumeni (1987) present a decomposition for all characteristics of individual workers, including sector of employment.

13. Domar (1962, 1963) has provided reviews of Kendrick (1961a); Abramovitz (1962) has reviewed Denison (1962b) and given a comparison with Kendrick (1961a).

14. In his subsequent works, Denison (1967, 1974, 1979, 1985) begins from an hours-paid series when constructing his hours estimates for wage and salary workers. He converts the average hours paid per job to average hours worked per job, using

unpublished BLS ratios of "hours at work" to "hours paid." These ratios, extrapolated from data for the year 1966, were developed by BLS for the 1952–74 period. Based on the trends in the 1952–74 series, Denison (1979, 155; 1985, 64) further extrapolates his hours-worked series back to 1947 and forward to 1982.

15. Denison (1974, 187) assumes that the sex-age earnings weights he creates for males and females from 1966 and 1967 data, respectively, and the education weights from 1959 data are constant over and thus representative of all postwar years. Denison (1979, 44–45, 158, 1985) constructs two sets of weights for both sex-age and education cohorts.

16. The model of capital input employed underlying the measures presented in table 3.1 was originated by Walras ([1877] 1954). The relationship between capital stock and rental prices was first analyzed by Hotelling (1925) and Haavelmo (1960) and has been further developed by Arrow (1964) and Hall (1968). Models of capital as a factor of production are discussed by Diewert (1980), Hulten (chap. 4, in this volume), and Jorgenson (1973a, 1989). Price and quantity indexes associated with capital as a factor of production are special cases of the index numbers proposed by Hicks (1946). Expositions of Hicks aggregation and references to the literature are given by Bruno (1978) and Diewert (1978, 1980, esp. 434–38).

17. These indexes of capital input have been discussed by Denison (1966, 1969).

18. The resulting indexes of capital input have been discussed by Denison (1972), Harper, Berndt, and Wood (1989), Jorgenson (1980), Jorgenson and Griliches (1972a, 1972b), Katz (1988), Mohr (1986, 1988b, 1988c), and Norsworthy (1984a, 1984b).

19. Hulten and Wykoff (1981b) employ Box-Cox transformations of all three variables and estimate separate parameters for each variable from a sample of capital goods prices.

20. The hedonic technique has been analyzed by Muellbauer (1975) and Rosen (1974). Surveys of the literature have been given by Deaton and Muellbauer (1980), Griliches (1971a, 1988a), and Triplett (1975, 1987).

21. Hulten and Wykoff have estimated vintage price functions for structures from a sample of 8,066 observations on market transactions in used structures. These data were collected by the Office of Industrial Economics of the U.S. Department of the Treasury in 1972 and published in *Business Building Statistics* (Office of Industrial Economics 1975). Hulten and Wykoff have estimated vintage price functions for equipment from prices of machine tools collected by Beidleman (1976) and prices of other types of equipment collected from used equipment dealers and auction reports of the U.S. General Services Administration.

22. The Baily hypothesis has also been discussed by Berndt, Mori, Sawa, and Wood (1990).

23. This methodology was first employed by Terborgh (1954). Detailed references to the literature are given by Hulten and Wykoff (1981b), Jorgenson (1989), and Mohr (1988a). Recent applications are presented by Hulten, Robertson, and Wykoff (1989) and Wykoff (1989).

24. This approach was originated by Meyer and Kuh (1957) and has been employed by Coen (1975, 1980), Eisner (1972), and Feldstein and Foot (1974).

25. Tenant-occupied housing is assigned to the finance, insurance, and real estate sector, while owner-occupied housing is assigned to the private household sector.

26. In *Sources of Economic Growth* (1962b, 97–98), Denison employs a measure of capital input for equipment and structures with relative efficiencies constant over the lifetime of the capital good, the one-hoss shay pattern of relative efficiency. In *Why Growth Rates Differ* (1967, 140–41), Denison uses a measure of capital input with relative efficiencies given by an unweighted average of the one-hoss shay and straight-line patterns:

$$d(\tau) = \begin{cases} 1 - \dfrac{\tau}{2L}, & (\tau = 0, 1 \ldots L-1), \\ 0, & (\tau = L, L+1 \ldots). \end{cases}$$

In *Accounting for United States Economic Growth, 1929 to 1969* (1974, 54–55) Denison introduces yet another relative efficiency pattern, based on a weight of one-fourth for straight-line patterns and three-fourths for one-hoss shay patterns:

$$d(\tau) = \begin{cases} 1 - \dfrac{\tau}{4L}, & (\tau = 0, 1 \ldots L-1), \\ 0, & (\tau = L, L+1 \ldots). \end{cases}$$

The corresponding measure of capital input is employed by Denison in *Accounting for Slower Economic Growth* (1979, 50–52) and *Trends in American Economic Growth, 1929–1982* (1985, 65).

For a linearly declining pattern of relative efficiency the mortality distribution can be represented in the form:

$$m(\tau) = \begin{cases} \dfrac{1}{\theta}L & (\tau = 1, 2 \ldots L-1), \\ 1 - \dfrac{1}{\theta}\left(1 - \dfrac{1}{L}\right) & (\tau = L), \\ 0 & (\tau = L+1, L+2 \ldots), \end{cases}$$

where θ is unity for straight-line replacement, positive infinity for one-hoss shay replacement, and two and four, respectively, for Denison's two averages of straight-line and one-hoss shay.

27. In *Sources of Economic Growth* (1962b) and *Why Growth Rates Differ* (1967, p. 10), Denison ignores differences in the tax treatment of corporate and noncorporate income. In *Accounting for United States Economic Growth, 1929 to 1969* (1974, 267–271) Denison employs separate estimates of corporate and noncorporate capital stock for the nonfarm business sector. He derives weights for these assets from data on corporate and noncorporate income by allocating noncorporate income between labor compensation of the self-employed and property compensation; however, his procedures ignore the effect of the corporate income tax. These procedures are also utilized in *Accounting for Slower Economic Growth* (1979, 171) and *Trends in American Economic Growth, 1929 to 1982* (1985, 56).

Kendrick (1973, 30) allocates noncorporate income between property compensation and the labor compensation of the self-employed. He assumes that the self-employed within each sector receive the same hourly compensation as employees. Kendrick does not separate corporate and noncorporate assets in measuring capital input. This approach is also employed by Kendrick and Grossman (1980, 26) and Kendrick (1983a, 56).

28. The model of production based on value added has been discussed by Arrow (1974), Bruno (1978), Diewert (1978, 1980), Sato (1976), and Sims (1969, 1977). Sato provides references to the literature.

29. de Leeuw (1989) and Denison (1989) have discussed the BEA (1987b) gross product originating data. Denison has proposed an alternative breakdown of aggregate productivity measures by end product.

30. Sectoral models of production have been implemented for the United States by Baily (1982), Fraumeni and Jorgenson (1980, 1986), Gollop and Jorgenson (1980, 1983), Gullickson and Harper (1987), Hall (1986, 1987, 1988), Kendrick (1956, 1961a, 1973, 1983a), Kendrick and Grossman (1980), Leontief (1953b), Massell

(1961), Star (1974), Thor, Sadler, and Grossman (1984), and Wolff (1985a). Sectoral models have been implemented for Germany by Conrad (1985), Conrad and Jorgenson (1985), and Frohn, Krengel, Kuhbier, Oppenlander, and Uhlmann (1973); for Japan by Ezaki (1978, 1985), Jorgenson, Kuroda, and Nishimizu (1987), Nishimizu and Hulten (1978), and Watanabe (1971); for Japan, Korea, Turkey, and Yugoslavia by Nishimizu and Robinson (1986); and for the United Kingdom by Armstrong (1974).

The studies of sectoral productivity for Germany by Conrad and Conrad and Jorgenson, for Japan by Jorgenson, Kuroda, and Nishimizu and for Japan, Korea, Turkey, and Yugoslavia by Nishimizu and Robinson are closely comparable in methodology to the study for the United States summarized in tables 3.2 and 3.3. Conrad and Jorgenson provide international comparisons among Germany, Japan, and the United States, including relative levels of productivity by sector in the three countries.

Thor, Sadler, and Grossman (1984) and Jorgenson, Kuroda, and Nishimizu (1987) provide international comparisons between Japan and the United States. The methodology of Thor, Sadler and Grossman is based on that of Kendrick and Grossman. Domar, Eddie, Herrick, Hohenberg, Intriligator, and Miyamoto (1964) provide international comparisons among Canada, Germany, Japan, the United Kingdom, and the United States for the period 1948–60 with separate estimates for as many as 11 sectors within each country. The methodology employed in this study is closely comparable to that of Kendrick (1956, 1961a). Englander and Mittelstadt (1988) have presented international comparisons among 20 OECD countries for the period 1960–86 for as many as 15 industrial sectors in each country. Their methodology is similar to that of Kendrick.

31. The data in table 3.7 also provide a test of Leontief's (1951, 1953a) "fixed coefficients" assumption in interindustry analysis. Under this assumption, all intermediate inputs are proportional to output, so that Leontief's (1936) approach to aggregation implies the existence of an intermediate input aggregate. The fixed coefficients assumption implies that ratios of growth of intermediate input to growth of output in table 3.7 must be equal to unity.

32. The derivation of a production possibility frontier from a multisectoral model of production was originated by Debreu (1951, 285) and has been discussed by Bergson (1961, 1975), Diewert (1980), Fisher (1982), Fisher and Shell (1972), Moorsteen (1961), and Weitzman (1983). Debreu's (1954, 52–54) definition of aggregate productivity growth has been discussed by Diewert (1976, 1980), Hulten (1973), Jorgenson and Griliches (1967), and Richter (1966).

33. The implications of aggregation over industrial sectors for the existence of an aggregate production function was a central issue in the "reswitching controversy" initiated by Samuelson (1962). This controversy has been summarized by Brown (1980) and Burmeister (1980a, 1980b), who provide extensive references to the literature.

34. This condition for the existence of an aggregate production function is due to Hall (1973) and has been discussed by Denny and Pinto (1978) and Lau (1978).

35. The relationship of aggregate and sectoral indexes of productivity growth was first discussed by Debreu (1954) and Leontief (1953b) under the assumption that prices paid for primary factors of production are the same for all sectors. The relationship between aggregate and sectoral productivity indexes under the assumption that prices of primary factors of production differ among sectors was first discussed by Kendrick (1956, 1961a) and Massell (1961).

36. This generalizes a formula originally proposed by Domar (1961), correcting the procedure introduced by Leontief (1953b). Domar's approach, like Leontief's, is based on the assumption that prices paid for primary factors of production are the same for all sectors. Leontief averages weighted relative changes in ratios of intermediate and

labor inputs to output over all sectors. Domar points out that the appropriate measure of aggregate productivity growth is a weighted sum rather than a weighted average. Leontief's approach fails to eliminate deliveries to intermediate demand in the process of aggregating over sectors.

Domar's approach has been discussed by Baumol and Wolff (1984), Diewert (1980), Gollop (1979, 1983), Hulten (1978), and Jorgenson (1980) and has been employed by Fraumeni and Jorgenson (1980, 1986), Nishimizu and Hulten (1978), and Wolff (1985a). One of the curiosities of the literature on productivity measurement is that Leontief's approach has been reintroduced by the Statistical Office of the United Nations (1968), Watanabe (1971), Star (1974), and Ezaki (1978, 1985). Watanabe advocates weights for sectoral productivity growth rates based on the ratio of the value of output in each sector to the sum of the values of outputs in all sectors. Ezaki and Star advocate the use of this same weighting system.

37. This approach was introduced by Kendrick (1956) and has been discussed by Bergson (1961, 1975), Domar (1961), Fisher (1982), Fisher and Shell (1972), Kendrick (1961a), Massell (1961), Moorsteen (1961), the Statistical Office of the United Nations (1968, 69, "Value Added and Primary Inputs: The Net System of Productivity Measurement"), and Weitzman (1983). This approach has been employed by Armstrong (1974), Frohn, Krengel, Kuhbier, Oppenlander, and Uhlmann (9173), Kendrick (1956, 1961a, 1973, 1983a), Kendrick and Grossman (1980), and Massell (1961).

38. Hulten's approach has been implemented for 10 sectors of the Japanese economy for the period 1955–71 by Nishimizu and Hulten (1978).

39. The data that underly tables 3.1 and 3.2 comprise a complete set of U.S. national production accounts for inputs as well as outputs at sectoral and aggregate levels. This system of accounts complements the existing U.S. national accounts for outputs presented by BEA (1986). These accounts can be integrated with the system of national accounts for income and expenditure, capital formation, and wealth outlined by Jorgenson (1980) and implemented by Fraumeni and Jorgenson (1980). The production accounts that underly tables 3.1 and 3.2 can also be combined with systems of national accounts such as those proposed by Eisner (1978, 1985, 1989), Kendrick (1976, 1979), and Ruggles and Ruggles (1970, 1973). Campbell and Peskin (1979) and Eisner (1988) have provided a useful summary and comparison among these accounting systems and give detailed references to the literature. Kendrick's accounting system has been discussed by Engerman and Rosen (1980). Finally, the production accounts can be combined with the system of accounts for the United States proposed by Ruggles and Ruggles (1982). This system integrates income and product accounts, flow of funds accounts, and balance sheets for assets and liabilities.

40. The existence of a value-added aggregate equal to the sum of the quantities of value added in all sectors is an implication of Hicks (1946) aggregation. Further details on Hicks aggregation are given by Bruno (1978) and Diewert (1978, 1980).

41. Models of aggregate production have been implemented for the United States by Abramovitz (1956), Abramovitz and David (1973a, 1973b), Baily (1981), BLS (1983), Christensen and Jorgenson (1969, 1970, 1973a, 1973b), Christensen, Cummings, and Jorgenson (1978, 1980, 1981), Denison (1962a, 1962b, 1967, 1974, 1979, 1985), Fabricant (1959), Jorgenson and Griliches (1967, 1972a, 1972b), Kendrick (1956, 1961a, 1973, 1983a), Kendrick and Grossman (1980), Knowles (1954, 1960), Mills (1952), Norsworthy and Harper (1981), Norsworthy, Harper, and Kunze (1979), Schmookler (1952), Solow (1957, 1960, 1962, 1963a), and Valavanis-Vail (1955).

42. Jorgenson and Nishimizu (1978) have developed methodology for measuring relative productivity levels between countries and have applied this methodology to bilateral comparisons between Japan and the United States during the period 1952–74. Caves, Christensen, and Diewert (1982a, 1982b) have developed methodology for

multilateral productivity comparisons. Denny and Fuss (1983) have presented an alternative approach. Christensen, Cummings, and Jorgenson (1981) have applied the methodology of Caves, Christensen, and Diewert in deriving estimates of relative levels of productivity for the nine countries analyzed by Christensen, Cummings, and Jorgenson (1978, 1980).

43. Denison (1985) has provided estimates of aggregate productivity for the U.S. economy covering the period 1929–82. Earlier, Denison (1967) presented comparable estimates at the aggregate level for Belgium, Denmark, France, Germany, the Netherlands, Norway, the United Kingdom, and the United States for the period 1950–62.

Correa (1970) has given estimates for Argentina, Brazil, Chile, Columbia, Ecuador, Honduras, Mexico, Peru, and Venezuela for the period 1950–62. Walters (1968, 1970) has provided estimates for Canada for the period 1950–67; Dholakis (1974) has presented estimates for India for the period 1948–69; for Japan Kanamori (1972) has given estimates for the period 1955–68 and Denison and Chung (1976) have given estimates for the period 1952–71; finally, Kim and Park (1985) have presented estimates for Korea for the period 1963–82. Bergson (1978) has provided estimates of aggregate productivity for the Soviet Union, France, Germany, Italy, and Japan for the period 1955–70. All of these estimates are closely comparable in methodology to Denison's estimates for the United States. Bergson (1987) has given estimates of relative productivity levels for Hungary, Poland, the Soviet Union, Yugoslavia, and France, Germany, Italy, Japan, Spain, the United Kingdom, and the United States for the year 1975, extending his earlier study of productivity trends.

Kuznets (1971) has compared Denison's productivity estimates with estimates derived from an analysis of long-term growth trends for Canada, France, Norway, the United Kingdom, and the United States.

44. Beckmann and Sato (1969) and Sato and Beckmann (1968) have compared aggregate productivity estimates for Germany, Japan, and the United States. These estimates are based on the methodology of Kendrick and Sato (1963) for the United States. Balassa and Bertrand (1970) have compared sources of economic growth for countries of Western and Eastern Europe, using methods similar to those of Kendrick. Kendrick (1983b) has provided aggregate productivity estimates for Canada, France, Germany, Italy, Japan, Sweden, the United Kingdom, and the United States for the period 1960–78. Kendrick (1984) has updated these estimates to 1979 and added Belgium to the list of countries.

45. The contribution of changes in the distribution of capital and labor inputs among sectors to productivity growth for the U.S. economy as a whole has been measured by Kendrick (1973) for 34 industry groups for the period 1948–66. The contribution of these changes to the rate of productivity growth for the U.S. manufacturing sector has been measured by Massell (1961) for 17 industry groups for the period 1946–57. Denison (1985) has measured the contribution of changes in the distribution of capital and labor inputs between farm and nonfarm sectors of the U.S. economy for the period 1929–82 and of labor input between self-employment and other employment within the nonfarm sector for the same period.

46. Norsworthy (1984b) compares the methodologies employed by Christensen, Cummings, and Jorgenson, Denison, and Kendrick. A detailed comparison of the empirical results of Christensen, Cummings, and Jorgenson (1980) with those of BLS, Denison, and Kendrick is presented by BLS (1983). As we have already pointed out, the concept of net value added used at the aggregate level in Kendrick's (1956, 1961a, 1973) early studies was abandoned by Kendrick and Grossman (1980) and Kendrick (1983a). Norsworthy concludes that Denison's (1985) concept of value added net of depreciation has been superseded by value added gross of depreciation as a starting point for studies of productivity at the aggregate level.

47. Gollop (1985) has surveyed the literature on the role of intersectoral shifts.

48. Bergman (1985), Johansen (1976), and Taylor (1975) provide detailed references to the literature on the approach to general equilibrium modeling originated by Johansen. The econometric approach to general equilibrium modeling, introduced by Hudson and Jorgenson (1974), is further discussed by Bergman (1990), Jorgenson (1982, 1984a, 1986a), and Jorgenson and Wilcoxen (1990).

49. An important issue in the modeling of producer behavior at the sectoral level is the existence of aggregate inputs, such as the capital, labor, energy, and materials inputs. The production function is required to be homothetically separable in the components of each of these aggregates in the approach of Berndt and Jorgenson. The methodology for testing homothetic separability was originated by Jorgenson and Lau (1975). This methodology has been discussed by Blackorby, Primont, and Russell (1977) and Denny and Fuss (1977). An alternative approach has been developed by Woodland (1978).

Berndt and Christensen (1973) and Norsworthy and Harper (1981) have tested the existence of aggregate capital input. Berndt and Christensen (1974) have tested the existence of aggregate labor input. Woodland (1978) has tested the existence of both capital and labor inputs. Berndt and Wood (1975) have tested the existence of the value-added aggregate discussed in section 3.4. The results of these tests are favorable to the existence of aggregates for capital input, but highly unfavorable to the existence of an aggregate for labor or an aggregate for value added like that employed in Kendrick's (1956, 1961a) studies of sectoral productivity growth.

50. Friede (1979) and Nakamura (1984) have constructed models of this type for Germany, while Longva and Olsen (1983) have constructed such a model for Norway.

51. Early studies of aggregate producer behavior, including those based on the Cobb-Douglas production function, have been surveyed by Heady and Dillon (1961) and Walters (1963). Samuelson (1979) discusses the impact of Douglas's research.

52. The implications of the results of McFadden and Uzawa have been discussed by Solow (1967). Econometric studies based on the CES production function have been surveyed by Griliches (1967), Jorgenson (1974), Kennedy and Thirlwall (1972), Nadiri (1970), and Nerlove (1967).

53. Aggregate models of producer behavior based on the translog functional form have been constructed for the United States by Christensen, Jorgenson, and Lau (1971, 1973) and Jorgenson and Yun (1986). Aggregate models for the United States have also been developed by Hall (1973), Burgess (1974), and Kohli (1981, 1983). Denny and Pinto (1978) have constructed an aggregate model of production for Canada. Conrad and Jorgenson (1977, 1978) have developed aggregate models for Germany.

54. Illustrations of this type of application are provided by the analysis of the impact of alternative energy policies on U.S. economic growth by Hudson and Jorgenson (1974) and the effects of environmental regulation on U.S. economic growth by Jorgenson and Wilcoxen (1990).

55. The price function was introduced by Samuelson (1953).

56. This definition of the bias of productivity growth is due to Hicks (1963). Alternative definitions of biases of productivity growth are compared by Binswanger (1978).

57. Further details on econometric modeling of sectoral productivity growth are given by Jorgenson (1986a).

58. Trends in energy prices since 1973 are discussed in greater detail by Jorgenson (1986b). Bruno (1984) has discussed the impact of higher raw materials prices after 1973. The bias of productivity growth for materials is positive for twenty of the 35 industries listed in table 3.8. For these industries an increase in the price of materials is associated with lower productivity growth.

59. Baily (1986), Baily and Chakrabarti (1988), Denison (1983), Griliches (1988b), Jorgenson (1988b), and Romer (1987) have discussed the slowdown in economic growth in the United States. A comparison of the slowdowns in Japan and the United States is presented by Jorgenson (1988a), Giersch and Wolter (1983) and Lindbeck (1983) have analyzed the slowdown in industrialized countries. Baily and Gordon (1988), Englander and Mittelstadt (1988), Maddison (1987), and Wolff (1985b) have provided surveys of the literature on the slowdown in productivity growth in industrialized countries.

60. Surveys of the literature on induced technical change are given by Binswanger (1978), Solow (1967), and Thirtle and Ruttan (1987).

61. Dynamic models of production based on costs of adjustment have been analyzed, e.g., by Lucas (1967) and Uzawa (1969).

62. This approach has been employed in models of investment behavior based on Tobin's (1969) *q* theory, such as those constructed by Hayashi (1982) and Summers (1981). The literature on econometric models of investment behavior based on Tobin's *q* theory has been surveyed by Chirinko (1988). Jorgenson (1973b) has discussed models of investment behavior based on costs of adjustment.

63. Dynamic models with static expectations have been employed by Denny, Fuss, and Waverman (1981b), Epstein and Denny (1980), and Morrison and Berndt (1981). Berndt and Fuss (1986) have surveyed the literature on dynamic models of production.

64. This approach has been developed in considerable detail by Hansen and Sargent (1980, 1981) and has been employed in modeling producer behavior by Epstein and Yatchew (1985), Meese (1980), and Sargent (1978).

65. Pindyck and Rotemberg (1983a, 1983b) have utilized this approach.

66. Models of producer behavior with embodied technical change were developed by Solow (1960, 1962, 1963a, 1964). Solow (1963a) provides a comparison of rates of embodied technical change between Germany and the United States and gives references to the literature. Barger (1969) presents estimates of rates of embodied and disembodied technical change for Denmark, France, Germany, Italy, the Netherlands, Norway, Sweden, the United Kingdom, and the United States for the period 1950–64.

67. Solow (1960, 1962) has pointed out that separate rates of embodied and disembodied technical change cannot be identified from the residual alone. This point has been elaborated by Denison (1964a, 1964b), Green (1966), Hall (1968), and Jorgenson (1966).

68. An overview of issues in the measurement of aggregate output, including the adjustment of price indexes for quality change, is presented in the Rees Report (National Research Council 1979, esp. 88–121). Highly preliminary estimates of the impact of these corrections on measures of productivity were presented by Jorgenson and Griliches (1967). Gordon (1990) has provided comprehensive quality corrections for price indexes of producers' durable equipment. Gordon's results have been discussed by Engerman and Rosen (1980).

69. Dulberger (1989) has presented econometric models of computer prices that underly the computer price indexes employed in the U.S. national accounts. Alternative models of computer prices are provided by Gordon (1989). Baily and Gordon (1988) and Triplett (1989) have surveyed the literature on computer price models. Denison (1989) has presented objections to the use of quality-corrected price indexes in the national accounts. Triplett (1990) and Young (1989) have discussed these objections in detail.

70. Econometric studies of economies of scale in the electric generating sector have been surveyed by Cowing and Smith (1978). A review of studies of economies of scale in transportation industries has been presented by Winston (1985). A review of such

studies in communications industries has been given by Fuss (1983). Econometric modeling of economies of scale in all three regulated industries has been surveyed by Jorgenson (1986a). Diewert (1981) reviews methods for measuring productivity in regulated industries. Studies of productivity in regulated industries are presented in the volume edited by Cowing and Stevenson (1981).

71. More recently, the Christensen-Greene data base has been extended by Greene (1983) to incorporate cross sections of individual electric utilities for 1955, 1960, 1965, 1970, and 1975. Greene is able to characterize economies of scale and technical change simultaneously.

72. Panel data sets have been constructed for the airline industry by Caves, Christensen, and Trethaway (1984) for the period 1970–81 and for the railroad industry by Caves, Christensen, Trethaway, and Windle (1985) for the period 1951–75. In these studies a distinction between economies of scale and economies of density is introduced. Economies of density are defined in terms of the elasticity of total cost with respect to output, holding points served, and other characteristics of output fixed. Economies of scale are defined as the elasticity of total cost with respect to output and points served. Economies of density are important in both airlines and railroads, but neither industry is characterized by economies of scale.

73. A description of the LRD program is provided by McGuckin and Pascoe (1988). Other data bases at the firm level are described by Griliches (1984).

74. A model of production with differences between ex ante and ex post substitution possibilities was introduced by Houthakker (1955–56). This model has been further developed by Johansen (1972) and Sato (1975) and has been discussed by Hildenbrand (1981) and Koopmans (1977). Recent applications are given by Bentzel (1978), Forsund and Hjalmarsson (1979, 1983, 1987) and Forsund and Jansen (1983). Fisher (1971), Fisher, Solow, and Kearl (1977), Liviatan (1966), and Solow (1963b) have analyzed the results of fitting "smooth" production functions to data generated from ex post fixed coefficients or putty-clay technology. A survey of the literature on putty-clay models and other alternatives to models based on production and cost functions is given by Solow (1967).

75. A detailed survey of econometric methods for modeling producer behavior is presented by Jorgenson (1986a).

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