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

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	

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

Industry	Average Annual Rates of Growth						
	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	

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.

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

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.

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:

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

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:

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

rate 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

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:

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

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 $\{\bar{v}^i_T\}$:

$$\begin{aligned} \bar{v}^i_T = {} & [\ln Z_i(T) - \ln Z_i(T-1)] - \bar{v}^i_X [\ln X_i(T) - \ln X_i(T-1)] \\ & - \bar{v}^i_K [\ln K_i(T) - \ln K_i(T-1)] - \bar{v}^i_L [\ln L_i(T) - \ln L_i(T-1)], \\ & (i = 1, 2 \ldots n), \end{aligned}$$

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

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

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

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

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

and

$$v^i_X = \frac{p^i_X X_i}{q_i X_i},$$

$$v^i_K = \frac{p^i_K K_i}{q_i Z_i},$$

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

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

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.

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 $\{L_i\}$ 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

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

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

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 Jor-

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

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.

ric 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

umes 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

(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

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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