FEDERAL RESERVE BANK OF SAN FRANCISCO

WORKING PAPER SERIES

# Dale W. Jorgenson: An Intellectual Biography

John Fernald
INSEAD
Federal Reserve Bank of San Francisco

March 2022

Working Paper 2022-08

https://www.frbsf.org/economic-research/publications/working-papers/2022/08/

**Suggested citation:**

Fernald, John. 2022 "Dale W. Jorgenson: An Intellectual Biography," Federal Reserve Bank of San Francisco Working Paper 2022-08. https://doi.org/10.24148/wp2022-08

**Dale W. Jorgenson: An intellectual biography**[1]

John Fernald[2]
Federal Reserve Bank of San Francisco and INSEAD
March 30, 2022

**Abstract**

Dale W. Jorgenson has been a central contributor to a wide range of economic and policy issues over a long and productive career. His research is characterized by a tight integration of economic theory, appropriate data that matches the theory, and sound econometrics. His groundbreaking work on the theory and empirics of investment established the research path for the economics profession. He is a founder of modern growth accounting: Official statistics in many countries, including the United States, implement Jorgenson's methods. Relatedly, without Jorgenson's unflagging efforts, consistent industry KLEMS datasets for many countries—which have been widely used in recent decades for growth accounting, econometrics, and other applications—would not exist. Jorgenson is also a pioneer in econometric modeling of producer and consumer behavior and of econometrically estimated, intertemporal general equilibrium modeling for policy analysis.

Keywords: Dale Jorgenson, Investment, Growth Accounting
JEL Codes: B21, B31, D20, O40

---

[1] Prepared for a Palgrave volume on Harvard University economics and economists. I thank Dale Jorgenson for helpful conversations in preparing this article. I am grateful for helpful conversations and/or correspondence with Susanto Basu, Ben Bernanke, Barbara Fraumeni, Robert Hall, Mun Ho, Charles Hulten, Robert Inklaar, Dale Jorgenson, Linda Jorgenson, Lawrence Lau, Trina Ott, and Jon Samuels.
[2] Email: john.fernald@insead.edu

## 1. Introduction

Dale W. Jorgenson has been a central contributor to a wide range of economic and policy issues over a long, productive, and influential career. As of 2022, he has written well over 300 articles and authored or edited some 37 books, with more than 70 coauthors. He has advised more than 70 Ph.D. theses. Even in his late 80s, Dale's research productivity has barely slowed.[3]

As a newly minted Harvard Ph.D., Dale started as an assistant professor at Berkeley in 1959. He returned to Harvard aas a full professor a decade later, in 1969. He remained an active full professor for the next 52 years. In fall 2021, at the age of 88, he became a research professor, which offers most of the perks of professorship but without the teaching. Even in his final year as part of the teaching faculty, he introduced a timely new undergraduate course on "The Economics of the Coronavirus"—taught remotely from his home office.

Jorgenson is perhaps best known for his research on investment, growth accounting, and the econometric modeling of producer and consumer behavior. For many years, he was the foremost authority in the theory and empirics of investment. Even today, academic theories of investment have their roots in Jorgenson (1963), which viewed demand for investment as a derived demand from the value of capital as a factor of production. The cost of capital, or the implicit rental rate per real dollar of capital stock, plays a key role in many macroeconomic models.

---

[3] Throughout this essay, I use the more formal 'Jorgenson' and the less formal 'Dale', depending on what seems most appropriate in context.

Jorgenson is a founder of modern growth accounting. Official statistics in many countries, including the United States, implement Jorgenson's growth-accounting approach. Jorgenson pioneered industry productivity datasets for several countries that look at gross output and separate measurement of inputs of capital (K), labor (L), energy (E), materials (M) and services (S) (KLEMS). Beyond his own research, his efforts and inspiration drove the creation of many internationally comparable and consistent KLEMS datasets, which have found a large number of research and policy applications. Without Jorgenson, these datasets would almost surely not exist. In some countries, these datasets are now produced by official statistical agencies.[4]

Jorgenson was also a pioneer in econometric modeling of producer and consumer behavior. This modeling is important on its own, and as part of econometrically estimated intertemporal and multi-sectoral general equilibrium models. He was an early developer of these types of models, which offer a complete and coherent perspective on the economy and economic policy. By moving beyond the assumption of a representative consumer, he showed how to do policy analysis in these models in ways that explicitly captured considerations of both efficiency and equity.

Jorgenson's contributions go well beyond these three areas of investment, growth accounting, and econometric modeling. This essay will touch on some of these other contributions, largely in the context of these three areas. His large body of work shows a tremendous consistency of research style. The hallmarks are a tight integration of economic

[4] The collection of essays in Fraumeni (2020), which were inspired by Jorgenson's pathbreaking work, demonstrate the wide application of KLEMS models around the world.

theory, appropriate data that matches the theory, and sound econometrics. His research has consistently addressed pressing academic and policy issues.

Various threads connect the different strands of research. One thread is investment and the cost of capital. Dale's research has consistently emphasized the role of investment in tangible and human capital, and it has consistently emphasized how the user cost—that is, the implicit rental cost of the accumulated capital—yields a service flow that we can measure. Another thread is intertemporal and multi-sectoral general equilibrium modeling: Much of his research provides key building blocks for econometric estimation of those models, and for interpreting the welfare implications of the models. A final thread is that Jorgenson consistently uses economic theory to inform data collection and measurement.

This essay begins with a short personal note in Section 2 that illustrates aspects of Dale's personality. Section 3 provides some background on Dale's life. Section 4 reviews some of his key intellectual contributions. That section focuses in detail on investment; growth accounting; and econometric modeling and general equilibrium. I connect other research contributions to these three themes. Section 5 discusses Dale's substantial influence on data collection—specifically, on official statistical measures of the economy. Section 6 concludes.

## 2. A Personal Note

I first met Dale in 1988 when he taught my Harvard Ph.D. econometrics course. My classmates and I found Dale an intimidating, formal figure with enormous presence.[5] He was

[5] One of Dale's coauthors noted, "Dale is never informal."

always impeccably dressed in a jacket and tie. He spoke crisply and authoritatively as neat rows of matrix algebra sprouted on the chalk board behind him—much faster than I could scribble down.

Behind his serious demeanor was a dry wit. On the first day of class, he reminded us that we needed to receive at least a B+ in the course in order to continue in the PhD program. "Last year," he said with a straight face, "a student tried very hard not to achieve that mark. However, at the last minute, the student failed in his attempt. He received a grade of B+."

It was several years before I talked with Dale again. I had begun a project looking at the productivity of infrastructure. But I had reached a point where I felt overwhelmed and adrift. Since this project was at the intersection of macroeconomics and productivity, I made an appointment to meet with Dale.

I met Dale in his Belfer Center office, in the Kennedy School of Government building**.** Dale had a suite of offices there for his students, collaborators, and international visitors. He held office hours there rather than in his spacious Littauer (economics department) office.

I was nervous—intimidated by Dale's authority and keenly aware of all I did not know. Dale listened attentively as I described what I had done so far. He nodded along and asked clarifying questions. He made helpful suggestions. He then concluded with something that I remember to this day: "You're making great progress. Keep up the good work."

Those words of support were exactly what I needed to hear. I felt relief, gratitude, and excitement. Dale's inspiration propelled me forward. Some three decades later, I will always appreciate what I experienced that day and have seen many times since: Dale's attentiveness, support, warmth, and kindness.

I am hardly alone in seeing this supportive side of Dale. Dale was Ben Bernanke's undergraduate thesis advisor. Ben is, of course, the former chair of the Federal Reserve Board of Governors, as well as being an enormously influential academic economist. Ben was a Harvard undergraduate, class of 1975. He describes Dale as "an extraordinarily kind and effective mentor." Dale hired Ben as a research assistant the summer after his junior year, and again after his senior year. Dale advised his senior thesis on the economic effects of natural gas price caps. The thesis won the prize for the best thesis in the economics department and was the basis of Ben's first professional publication, joint with Dale (Bernanke and Jorgenson, 1975). Ben told me that "Dale has been supportive of me throughout my whole career."[6]

The support and mentorship that Dale showed so many throughout their careers has endeared him to generations of students.

## 3. Jorgenson's life

Dale was born in Bozeman, Montana on May 7, 1933. He was an only child. His parents had grown up and met in Minnesota. After marrying, they drove west, intending to go to California. They arrived in Bozeman during a nice time of year and stayed. Three years after Dale was born, the family moved to Helena, Montana, which is where Dale grew up. "Montana was a pleasant place," he told me, "especially if you like winters." He paused. "I don't."

After high school, Dale had hoped to attend the U.S. Naval Academy, but his eyesight wasn't good enough. Instead, he enrolled at Reed College in Oregon. Reed was a formative

---

[6] This paragraph is based on email from Ben Bernanke to the author, September 1, 2021.

experience, with a high-level academic program. Initially, Dale thought he would be a physics major. But he found physics boring. Economics was more exciting than, and as quantitative as, the physical sciences.

One Reed professor was particularly influential. Carl M. Stevens had earned his economics PhD at Harvard (1951) and, after three years at Yale, joined the Reed faculty in 1954. Stevens was Jorgenson's undergraduate thesis adviser. After graduating from Reed in 1955, Stevens encouraged Dale to go to Harvard for his Ph.D.

Dale found Harvard to be a multi-cultural and diverse place, even in the 1950s. He made lifelong friends from around the world. He was in a hurry to get on with his life and career and finished his Ph.D. in 3½ years under Wassily Leontief's supervision. His thesis, entitled "Duality and Stability in Dynamic Input-Output Analysis," analyzed and extended aspects of Leontief's (1953) dynamic input-output model.

After receiving his Ph.D. in 1959, Dale started at U.C. Berkeley as an assistant professor. His rise in the profession was swift. He was tenured in 1961 and promoted to full professor in 1963, at age 30. He visited the University of Chicago for a year in 1962-3, where he began an important if short collaboration with Zvi Griliches, highlighted by Jorgenson and Griliches (1967). We discuss that seminal paper in the next section.

In 1969, Harvard persuaded Dale to leave Berkeley and return to Harvard. He arrived the same year as Zvi Griliches and a year after Kenneth Arrow. Dale thought Harvard could be better than it was, and Dick Caves, the chair of the economics department, told Dale that this was his chance to help rebuild the department. Caves wanted to modernize (and mathematicise) the department—with a goal of helping it to compete with MIT's economics department downriver. Dale and Zvi were two of the brightest young empirical economists in the country.[7]

In 2002, Dale was named a University Professor, Harvard's highest honor. Among other things, that gave Dale the right to teach whatever he wanted. Following the financial crisis, Dale began teaching two new undergraduate courses. In his initial offerings, "Growth and Crisis in the World Economy" and "The Rise of Asia and the World Economy," he provided up-to-the-minute data and analysis that kept the students engaged. He wanted to have time to work with each student, so he aimed for an enrollment of 30. When the first-class day was standing room only, Jorgenson was forced to pare down the nearly 150 applications to a more manageable 40. In his mid-70s, Dale began forming meaningful personal and academic bonds with students nearly 60 years his junior.

Dale's faculty assistant, Trina Ott, says that students found Jorgenson intimidating, with his requisite sport coat, tie and stiff upper lip. But it was a course requirement that students meet with him. So students would come with trepidation to their first meeting, carrying notes and reading materials. But then Dale would ask about their hobbies, hometown, siblings, and extracurricular activities, as well as economics. He became a familiar face at Harvard House dinners, where students were encouraged to invite favorite professors each semester.
Dale and his wife Linda reciprocated by inviting the students to their home. The students would chat with Jorgenson about their aspirations and interests. Dale would tell stories of his work throughout the world, such as a spring-break visit to meet with Japan's Prime Minister Shinzo

[7] Warsh (1994) focuses on Richard Caves's role in rejuvenating Harvard economics.

Abe, or a summer visit with Republic of China's President Ma Ying-jeou. Two consecutive Harvard senior classes voted Dale as one of their favorite professors.

Linda often travels with Dale and attends his conferences and seminars. Linda is a lively, energetic, and personable attorney. "Linda is a lot more colorful than Dale," a Harvard colleague told me. That comment is more a reflection of Linda than Dale. Professionally, Linda is one of the foremost legal experts on cases of sexual misconduct by psychiatrists and psychologists. But despite her professional obligations, she actively engages with Dale's research: They talk about his research over dinner, she analyzes the reactions of audiences to Dale's talks, and she happily interacts with his colleagues.[8] Those who know Dale regard the couple as a close team.

Dale and Linda's teamwork was evident in the raising of their two children, Eric and Kari. Eric has Ph.D. in human genetics from Stanford; Kari has a law degree from Columbia. Eric and Kari reportedly say that their father was primarily responsible for raising them. Dale worked from home three days a week, so he was often there when the kids came home from school. However, Linda was always responsible for discipline because, she told me, "Dale is really, really nice."

Dale travels extensively, mostly internationally. He began research on Japan in the 1970s; he started research on China in the mid-1980s. He went to Japan and China at least once a year from 1990 until the pandemic (with the exception of 2018). His World KLEMS work has

[8] In 2004, Dale discussed a paper of mine. Dale's comments were delivered with his habitual politeness, even as they were quite critical, even dismissive, of aspects of the paper. The next day, Linda apologized to me, and said she'd given Dale a hard time for being unnecessarily critical in tone.

regularly taken him to Europe, Latin America, and Asia. He has received nine honorary degrees from universities around the world, including six in Europe and three in Asia. Few if any Harvard economics professors have had as much global impact.

Dale has contributed in many ways to the economics profession beyond his research. Here are just a few examples. He served as president of the Econometrics Society (1987) and the American Economic Association (2000). He was elected to the National Academy of Sciences in 1978 and served as Chairman of the Economic Sciences section from 2000 to 2003. In 1991, he was a Founding Member of the Board on Science, Technology, and Economic Policy of the National Research Council; he served as the Board's Chair from 1998 to 2006.

A number of his roles helped advance Jorgenson's long-standing interest in having data and data systems that were grounded in economic theory. For example, he has served for several decades on the Bureau of Economic Analysis's (BEA) Advisory Committee, including serving as Chair from 2004 to 2011. He was also a member of the U.S. Commerce Secretary's Advisory Committee on Measuring Innovation in the 21$^{st}$ Century Economy from 2006 to 2008.

## 4. Major research themes

As already noted, Jorgenson has written prolifically and broadly. Some of Dale's early work was pure economic theory. But most of his research has been empirical, typically motivated by big-picture academic and policy debates. Of course, even his most applied research has been solidly grounded in economic theory.

Nobel prize winner Kenneth Arrow has described Jorgenson as “one of [the] deepest and most energetic students” of “neoclassically based empirical analysis.”[9] Jorgenson typically has found little role for externalities or non-constant returns. In several areas, Jorgenson’s research opened up and has shaped entire fields. These include the empirical modeling of investment, where the field was shaped by his classic (1963) article. It also includes productivity and growth accounting, where modern practice follows the path that Dale blazed in a number of important papers.

Jorgenson’s research has addressed a wide range of policy-relevant macroeconomic questions. These include, but are certainly not limited to, the following:

- Understanding the process of economic growth in the United States and other countries (e.g., Jorgenson and Griliches, 1967; Jorgenson, Gollop, and Fraumeni, 1987).
- Understanding the role of information technology in the productivity acceleration of the 1990s (e.g., Jorgenson, Ho, and Stiroh, 2005).
- Characterizing the economic effects of energy-price shocks and policies designed in response to those shocks (e.g., Hudson and Jorgenson, 1974).
- Modeling and measuring welfare in a world with heterogeneous agents; and considering the empirical implications for standards of living, inequality, and the cost of living (e.g., Jorgenson, Lau, and Stoker, 1982; Jorgenson and Slesnick, 1984, and Jorgenson, 1990).
- Assessing how alternative tax policies would affect growth and well-being (e.g., Jorgenson and Yun, 1986a, 1986b).
- Considering fiscal policies that would address climate change *and,* simultaneously, improve the efficiency of the economy (e.g., Jorgenson, Goettle, Ho, and Wilcoxen, 2014).

Often, he addressed policy debates by building theoretically consistent, multi-sector, intertemporal general equilibrium models that could be estimated econometrically. For the models to be internally consistent and for the estimation to be reliable, it was important to

[9] Quoted on the bookjacket of Jorgenson (1998a).

measure the data accurately and appropriately—in a way consistent with theory. With the estimated model in hand, Jorgenson and his collaborators could undertake policy counterfactuals.

As noted in the introduction, Jorgenson is perhaps best known in the broader economics profession for his seminal work on investment, growth accounting, and the econometric modeling of producer behavior. Certainly, in terms of both theory and practice, these contributions have been profound, pervasive, and lasting for the economics profession.

I discuss those areas in some detail below. But as the discussion highlights, his contributions go well beyond those areas. One could equally highlight his important breakthroughs in the econometric modeling of consumption with heterogeneous households, or in developing new tools for applied welfare analysis. Where possible, I bring other contributions into the discussion. In Section 5, I discuss some of the ways in which Jorgenson's research and advocacy have influenced official economic measurement.

Three themes run through this discussion. First, investment and the cost of capital play an important role in many of Jorgenson's papers, because they allow a dramatic simplification of the complicated intertemporal environment. Second, different parts of Jorgenson's research form crucial building blocks for constructing realistic, econometrically estimated, intertemporal general equilibrium models. These models are necessary for policy counterfactuals. Third, Jorgenson consistently uses economic theory to inform data collection and measurement

We now turn to investment, where Jorgenson's (1963) paper on "Capital Theory and Investment Behavior" started him on an intellectual path he would follow for the next six decades.[10]

## 4.1. Investment

Understanding investment is crucially important for understanding both business cycles and economic growth. The volatility of business investment contributes to the volatility of aggregate activity and business cycles. And, through the accumulation of tangible and intangible capital, investment is a central driver of economic growth.

Jorgenson's seminal 1963 paper transformed theoretical and empirical work on investment. Indeed, the way economists model investment has been critically shaped by what the investment literature refers to as "Jorgenson's Neoclassical Model" (e.g., Chirinko, 1993).

Why was Jorgenson's investment research so transformative? As the opening sentence of Jorgenson (1963) reads, "There is no greater gap between economic theory and econometric practice than that which characterizes the literature on business investment in fixed capital." The 1963 paper closed that gap.

The key insight of Jorgenson's approach was that the demand for investment is a derived demand from the value of capital as a factor of production. Jorgenson started from a neoclassical model of production. The optimizing first order conditions implied that the

[10] Lau's (2000b) excellent survey of the first three decades of Jorgenson's research career highlights these two themes of the cost of capital and intertemporal general equilibrium modeling. Other chapters in Lau (2000a) focus in more detail on other aspects of Jorgenson's research. I mention several of those chapters in what follows.

marginal product of capital should be equated to the user cost of capital, that is, its implicit rental rate.

The model gave a closed form for the cost of capital. That cost in general depends on the nominal interest rate, the depreciation rate, and the rate of change in the price of the investment good. It also depends on various tax considerations.[11] Jorgenson showed how to take the first order condition for the optimal capital stock and use it to obtain the demand for investment under the assumption that there were gestation lags. Indeed, the paper introduced new econometric methods for modeling these gestation lags in a parsimonious way (methods formalized in Jorgenson, 1966).

The paper was at the methodological forefront of empirical work: It used an optimizing theory to organize and guide data measurement and statistical analysis. Bob Hall, an undergraduate advisee of Dale's at Berkeley (and later Dale's coauthor and prominent academic in his own right), told me, "We take that paper structure for granted today. But previous empirical work on investment was largely ad hoc, guided loosely by intuition rather than clear theory."

The key feature of the model, the cost of capital, showed how to measure the service flow of capital. The cost of capital is the "shadow price or implicit rental of one unit of capital service per period of time" (Jorgenson, 1963, p. 249.) Given an appropriately measured cost of capital, the inherently multi-period, dynamic problem of the firm can be modeled as a static

---

[11] Jorgenson (e.g., 1996a, p. xiv) defines the "user cost of capital" as the rental price of capital services, given by the product of the cost of capital and the real price of the investment good. In what follows, I will often refer simply to the cost of capital, which is the rental rate per real dollar of capital.

problem. The cost of capital incorporates all of the information about (expected) future prices that affect the current behavior of the firm.

In subsequent work, tax considerations loomed particularly large. Jorgenson's initial 1963 exposition included taxes on capital. Hall and Jorgenson (1967) extended the model and showed how the framework could incorporate quite detailed features of the tax code. Those taxes affected the cost of capital formula, which in turn affected the desired capital stock and, as a result, demand for investment. They further showed how to use the model for counterfactuals regarding how changes in the tax code would affect capital accumulation and economic activity over time.

The cost of capital became the central theoretical concept for studying the effects of taxes, and changes in taxes, on capital accumulation. For example, the effects of a wide range of taxes can be summarized through a single marginal effective tax rate (Auerbach and Jorgenson, 1980).[12]

In 2011, the *American Economic Review* (Arrow et al., 2011) looked back on its first century, and sought to identify the 20 most important papers it had published over that period. Jorgenson (1963) was one of the 20. Interestingly, it was a *Papers and Proceedings* paper, rather than a "regular" AER paper. The AER citation reads:

> This paper provided a theoretical framework for investment behavior based on a neoclassical theory of optimal capital accumulation. The paper introduced the user cost of capital as the key variable that combines the cost of finance (interest rates and equity

[12] In my conversation with Bob Hall on 24 August 2021, I referred to Jorgenson (1963) several times as the "cost of capital paper." Bob chided me. "It's the investment paper!" he said. It is, of course, both. As emphasized by Lau (2000a, b), as well as the research summary on Jorgenson's website, the cost of capital is a thread that connects much of Jorgenson's research. The reason is that the cost of capital allows a link between static optimization and intertemporal dynamics.

> yields) and tax rules (tax rates, depreciation schedules) and combined this user cost measure with the Cobb-Douglas production technology to obtain a desired stock of capital. Jorgenson then used the resulting implied optimal capital stock to derive an econometric equation for investment. Generalizations of the Jorgenson framework (e.g., to allow for more general production functions) made this the standard approach to the empirical study of the determinants of investment. The user cost of capital also became the key concept for the theoretical study of the effects of alternative tax rules.

The concept of the cost of capital is largely taken for granted by economists today; only rarely are Jorgenson (1963) or Hall and Jorgenson (1967) cited explicitly. Other economists had written about the general concept of the cost of capital.[13] But Jorgenson showed how to use the theory to derive investment demand under a broad set of conditions.

Dale's research started the investment literature on a path that it has continued to this day. Chirinko's (1993) survey observes that, because of the logical clarity of the Jorgenson approach—where the modeling assumptions are clear and explicit—it provided a roadmap for a vast range of subsequent theoretical, empirical, and policy-oriented research. The results have sometimes been complementary, sometimes competing. But the Jorgenson framework has remained the benchmark for comparison. For example, Hayashi (2000) explicitly relates the Jorgenson cost-of-capital approach to more recent q-theories of investment as well as theories of investment irreversibility. He highlights the essential role played by Jorgenson's cost of capital in these different approaches.

[13] Lau (2000b) provides a discussion of previous uses and derivations of the cost of capital, with additional context on the novelty of Jorgenson's contribution. See also the preface to Jorgenson (1996a).

In 1971, the American Economic Association awarded Jorgenson its John Bates Clark medal, given every other year to the top economist under the age of 40. The Association's (1971) citation reads:[14]

> Dale Jorgenson has left his mark with great distinction on pure economic theory (with, for example, his work on the growth of a dual economy); and equally on statistical methods (with, for example, his development of estimation methods for rational distributed lags). But he is preeminently a master of the territory between economics and statistics, where both have to be applied in the study of concrete problems. His prolonged exploration of the determinants of investment spending…will certainly long stand as one of the finest examples of the marriage of theory and practice in economics.

The citation highlights the hallmarks of Jorgenson's research: Clear theory, data that is consistent with theory, and sound econometrics. His central focus has always been applied, but his research was grounded in theory.

The 1963 paper set Jorgenson on the research path that he has followed for the rest of his career. As we discuss below, Jorgenson has consistently emphasized the role of investment in tangible and human capital in driving economic growth.

In addition, the cost of capital is a thread that connects the 1963 paper with production theory, growth accounting, national income accounting, measurement, and econometric modeling—all areas where Jorgenson has made seminal contributions. For Jorgenson's 60th birthday, in 1993, a group of his long-time collaborators organized a surprise birthday conference. The proceedings of that conference were published as Lau (2000a), under the title "Econometrics and the cost of capital." The papers covered a wide range of topics related to Jorgenson's research, and the cost of capital played an important role in almost every chapter.

[14] https://www.aeaweb.org/about-aea/honors-awards/bates-clark/dale-jorgenson (accessed October 15, 2021).

## 4.2. Productivity and growth accounting

Economic growth has driven massive gains in economic well-being around the globe. But where does output come from, and why does it grow? A considerable body of Jorgenson's research has focused on understanding the sources of economic growth in the United States and other countries. Jorgenson has consistently emphasized the role of factor accumulation in explaining growth, with a particular focus on tangible and human capital investment.

Ultimately, output depends on the ability of firms to produce goods and services, which in turn depends on their technology and the inputs they employ. Growth accounting seeks to understand, at least proximately, the role of these different contributors to growth. It provides insights into the resource constraints societies face.

As Zvi Griliches (1996) discusses, the first attempts at accounting for the sources of growth—by relating deflated output to deflated measures of inputs—go back at least to the 1930s. Solow's celebrated 1957 paper brought neoclassical theory to bear on the growth accounting. Solow's theory provided a framework and language to organize thinking.

Jorgenson and Griliches drove much of the subsequent development of that research agenda. For this reason, Hulten (2002) refers to modern growth accounting as "the Solow-Jorgenson-Griliches revolution."

The seminal paper was Jorgenson and Griliches (1967), which conceptualized aggregate growth accounting in a way that has remained standard ever since. That paper integrated elements of previous research by both Jorgenson and Griliches, including an earlier joint paper on capital services (Griliches and Jorgenson, 1966). As Griliches (1991, p. 193) describes Jorgenson and Griliches (1967):

> It brought together Jorgenson's work on Divisia indexes, on the correct measurement of cost of capital, and on the right aggregation procedures for it, with my own earlier work on the measurement of capital prices and quality change and the contribution of education to productivity growth.

Jorgenson and Griliches (1967, p.249) took as their starting point that "…the economic theory underlying the measurement of real product and real factor input has not been fully exploited." They emphasized the importance of measuring quantities of output and quantities of inputs in a theoretically correct manner—as suggested by the Griliches quote above. They argued that using theoretically appropriate measures made an enormous difference in accounting for the sources of growth.

The first challenge they addressed was to use appropriate measures of real output. Economic theory implies that, for measuring productivity, output growth should be measured as a Divisia index—as share-weighted growth in the components of expenditure. In discrete time, this means that prices should be allowed to change period by period, that is, the indexes should be "chain linked." At the time, and for many years afterwards, the national accounts defined the level of real output using constant base-year prices, which is only appropriate for productivity measurement if consumption and investment goods are perfect substitutes in production. Almost thirty years later, in 1996, the U.S. national accounts finally introduced chain-linked indexes.[15]

---

[15] Solow (1957) had introduced Divisia aggregates of inputs, which Jorgenson and Griliches (1967) confirmed. Jorgenson's (1966) production possibilities frontier had pointed to the theoretical superiority of Divisia output aggregates, as well. In that paper, Jorgenson introduced a production possibilities frontier between consumption and investment goods, rather than assuming they were perfect substitutes in production. See also Jorgenson and Griliches (1971).

Second, Jorgenson and Griliches argued that official constant-quality price indices for investment goods overstated price increases and, therefore, understated quality-adjusted growth in investment and output. Griliches was, of course, one of the key players in introducing hedonic methods to control for quality changes.[16] And Jorgenson, throughout his career, emphasized the importance of accurate constant-quality price indices. Starting in the 1980s, the U.S. national income and product accounts began measuring constant-quality price indexes for computers and eventually other products as well.

Third, Jorgenson and Griliches showed how to aggregate capital and labor services in a setting with heterogeneous inputs of capital and labor. With a neoclassical production function, heterogeneous inputs should be weighted by marginal products in order to allow for imperfect substitutability across inputs. With perfect competition, these marginal products are given by factor prices—wages and capital rental rates. Jorgenson's (1963) work on investment showed that the cost of capital provided the appropriate, if implicit, rental prices for different types of capital. For example, a dollar's worth of equipment needs to rent for a higher price (and provide a higher annual service flow) than a dollar's worth of an office building, because the equipment will depreciate much more quickly. Similarly, highly educated, high-wage workers presumably have a higher marginal product than less educated, low-wage workers. Hence, even if total hours worked didn't change, labor input could rise if the composition of hours shifted towards higher wage, higher marginal product workers.

[16] Griliches (1991) discusses his work on hedonics, including antecedents to Jorgenson and Griliches (1967).

Aggregating the service flows from different types of capital and labor has remained central to growth accounting ever since, and it is now the standard in international statistical practice (officially endorsed decades later, as discussed in Section 5). Previous work, including Solow (1957), had used the aggregate capital *stock*, which weights heterogeneous capital based on investment prices rather than user costs; and most of previous work had used crude measures of labor input—whether hours worked or, even cruder, the number of workers. A considerable body of research since Jorgenson and Griliches has found that, (mainly) because of rising educational attainment, labor input grows more rapidly than raw hours.[17] And appropriately measured capital services has grown faster than the capital stock because of substitution over time towards faster depreciating types of capital.

Jorgenson and Griliches (1967) proposed the extreme hypothesis that, correctly measured, input growth would account for all of output growth, so that the residual of "total factor productivity" (TFP) would be negligible. In contrast, prior research, including Solow's important 1957 paper, typically found that TFP accounted for the majority of economic growth. Jorgenson and Griliches seemed to find evidence that, after correcting output and inputs for measurement errors, input growth *did* explain almost all output growth. Subsequent work has eroded the stark nature of this finding—including fairly soon thereafter by Jorgenson and Griliches themselves (1972), in a reply to a range of criticisms by Edward Denison (1969) as well as their own improved data.

---

[17] Griliches (1960) had earlier developed a similar index of weighted labor input for agriculture. See also Denison (1962), who also constructed labor input measures that accounted for worker heterogeneity.

Nevertheless, the broad takeaway has remained true in subsequent work: Input growth explains the bulk of observed output growth. Input growth, of course, includes growth in both tangible and human capital. These forms of capital, in turn, depend on investment—whether by individuals (deciding how much education to receive), businesses (deciding on equipment and structures), or governments (deciding on infrastructure). This takeaway thus dovetailed nicely with Jorgenson's research on investment. In addition, it helps motivate the policy focus of Jorgenson's general equilibrium modeling, described below, in which growth is sensitive to policies that stimulate investment and, thereby, factor accumulation.

Jorgenson and Griliches (1967) was written when Jorgenson was at Berkeley and Griliches was at Chicago. In 1969, they became colleagues at Harvard. Despite their continuing interest in understanding economic growth and the role of technical change, they did not continue joint research. As Jorgenson told me, "After our work together, Zvi and I went off in different directions. I worked on macro data, he worked on micro data. And eventually, we came to similar conclusions." For example, both emphasized the role of investment. Jorgenson focused especially on tangible investment and human capital; Griliches highlighted the role of research and development (R&D) as a capital stock of knowledge, and its role in explaining residual growth in TFP.

In following decades, Jorgenson continued to develop, refine, and extend growth-accounting methods, with an aim of better understanding the sources of overall economic growth as well as its welfare implications. An important byproduct of this growth-accounting agenda is what has been called "The Jorgenson System of National Accounts" (Fraumeni, 2000, and Reamer, 2021). Fraumeni (2000, pp. 111) writes:

> The Jorgenson system of national accounting, with the cost of capital formulation at its core, has made a singular contribution to economic analysis… The Jorgenson system of national accounts is a complete and integrated set of national accounts with a production account, income and expenditure account, an accumulation account and a wealth account in current and constant dollars. This set of accounts taken together forms a complete and consistent set of accounts suitable for economic analysis…

The standard national accounts include some pieces of the Jorgenson system, including a production account in nominal terms, as well as expenditure in nominal and real terms. But it has not, historically, included inputs in real terms (let alone adjusted for input heterogeneity along the lines of Jorgenson and Griliches, 1967); nor is saving explicitly linked with the accumulation of assets and liabilities, that is, with a national balance sheet.

Jorgenson developed his distinctive system of national accounts with a range of collaborators. A few key landmarks were the Christensen-Jorgenson (1973) national accounts, the Jorgenson, Gollop, and Fraumeni (1987) sectoral accounts, and the Jorgenson-Fraumeni (1989, 1992a, 1992b) human capital accounts. I discuss each of these in turn.

First, Christensen and Jorgenson (1973) extended the existing national accounts. The goal was to record all the links in the economy consistently in both current and constant prices. Production is linked to income; income is linked to consumption and saving; saving is linked to capital formation and changes in balance sheets. Balance sheets are then linked to service flows of capital assets into production and consumer durables into consumption.

Christensen and Jorgenson focused on the private sector, though Jorgenson subsequently applied the same ideas to the public sector. The <u>production account</u>—the one most closely linked to conventional growth accounting à la Jorgenson and Griliches (1967)—included nominal and real output. But, unlike the standard national accounts, the production account also included inputs in real terms. These constant-quality input measures extended

Jorgenson and Griliches's approach of weighting heterogeneous capital and labor input growth using factor prices.

The Christensen-Jorgenson income and expenditure accounts were more directly related to welfare. Expenditures were divided into consumption and saving. Unlike the standard national accounts, spending on consumer durables were counted as a form of saving, with the service flow from the resulting stock, estimated via their user costs, added to the flow of consumption services.

An accumulation account mapped saving and investment to changes in national wealth and capital formation. The wealth account showed the value of the stock of assets. Finally, the service flows from these assets, measured with user costs, showed up in various earlier accounts—including inputs in the production account and the service flow from consumer durables in the expenditure account. Thus, the system was internally consistent in showing how any transaction tracked through the economy.

A second major innovation in the Jorgenson System of National Accounts was to disaggregate by industry. For many purposes, such as understanding productivity slowdowns and speedups, such disaggregation is desirable; the insights available from assuming the existence of an aggregate production function are necessarily more limited. Considerable work by Jorgenson and his collaborators in the 1970s and 1980s (starting with Berndt and Jorgenson, 1973, and extended in Fraumeni and Jorgenson, 1981) culminated in the seminal book by Jorgenson, Gollop, and Fraumeni (1987), which provided a granular, industry-by-industry analysis of the sources of U.S. economic growth.

This project required “a truly massive empirical research effort” (Jorgenson, 1988, p. 39). For example, it required nominal and real inputs and outputs at an industry level that were fully consistent with economic theory and with the aggregate values for these variables. The underlying data sources had often been collected for different purposes, so they required considerable merging and reworking.[18]

At an economy-wide level, the appropriate concept of output is value added. But at an industry level, it is gross output. As Domar (1961, p.716) put it, value added is “shoes lacking leather and made without power.” Understanding the nature of shoe production, for example, requires data on the nominal and real purchases of leather, power, and other purchased intermediates. Thus, to construct the industry data, it was necessary to compile a complete set of annual interindustry input-output tables in both real and nominal terms that were consistent with the national accounts. The output of one industry may be another industry’s intermediate input. Hence, productivity or other changes in one industry may affect other industries through these input-output linkages. This industry focus thus provided a conceptual link between aggregate growth accounting and Leontief’s (1953) input-output analysis.

Jorgenson, Gollop, and Fraumeni differentiated four main categories of inputs: primary inputs of capital, K, and labor, L; and intermediate inputs of energy, E, and materials, M. Subsequent so-called KLEMS datasets largely follow their lead, but also break out services, S, from intermediate purchases of materials. All inputs, of course, are differentiated by industry

[18] See the data appendix to Jorgenson (1988) for a concise presentation of the underlying sources.

and are each constructed as Törnquist or Divisia indices of heterogeneous subcomponents, which allows for imperfect substitutability among them.[19]

A third innovation in the Jorgenson system of national accounts was complete accounting for human capital and the value of non-market time (Jorgenson and Fraumeni, 1989, 1992a, 1992b).[20] On the human capital side, the basic idea is that individuals each own some stock of human capital; their wage is the annual service flow from that stock. Individuals can augment their human capital stock through investments in education. Thus, given lifetime incomes, it is possible to estimate that capital stock.

The values of human capital and non-market activity are enormous. As Fraumeni (2000, p.142) notes, "...the incorporation of human capital and nonmarket activities results in aggregates that are higher by an order of magnitude…" The flow of educational investment is treated as part of market output. Hours not spent on necessary maintenance (such as sleep) are used to work, go to school, or for non-market purposes. Jorgenson and Fraumeni added the value of those hours to overall output. The Jorgenson- Fraumeni approach reflects Jorgenson's consistent focus on theory-driven measurement.

As we discuss in Section 5, the first two innovations (consistent social accounts for production, income, expenditure, and wealth; and KLEMS datasets) have had considerable impact on practical (and often official) measurement across countries. Indeed, the official

---

[19] Jorgenson has regularly updated the U.S. industry KLEMS dataset with a range of coauthors, including Barbara Fraumeni, Mun Ho, Kevin Stiroh, and Jon Samuels.

[20] The basic vision for human-capital accounting was previewed in the conclusion to Jorgenson and Griliches (1967, p. 275): "Investment in human capital could be cumulated into stocks…The flow of investment could be treated as part of total output."

accounts have moved closer to the Jorgensonian ideal over time. The Jorgenson-Fraumeni human capital accounts have also had an important conceptual impact, as well as some practical impact, by showing the massive importance of human capital and related investments as sources of wealth.

Growth accounting, including the Jorgenson System of National Accounts, is interesting in its own right for understanding the drivers of economic growth. But Jorgenson has always focused on developing tools and approaches to address major economic issues. These included understanding why productivity growth slowed in the 1970s—even after controlling for the various sources of mismeasurement discussed in Jorgenson and Griliches (1967) and accounting for the further refinements introduced in Jorgenson's later work. In Jorgenson's analysis, as summarized in Jorgenson, (1988), energy-price increases played a key role in the productivity slowdown. In his econometric work, higher energy prices were associated with an endogenous reduction in TFP growth in 29 out of 35 industries.

But in the mid-1990s, the productivity slowdown ended. From the mid-1990s to the mid-2000s, productivity growth returned to a very rapid pace. Jorgenson's analysis of the productivity speedup helped shape and quantify the broader consensus on the central role of information technology in that speedup (e.g., Jorgenson and Stiroh, 2000; Jorgenson, 2001; and Jorgenson, Ho, and Stiroh, 2005). Jorgenson's insights built on his earlier research on the cost of capital and investment, as well as his growth-accounting findings concerning the role of investment and capital accumulation as a driver of economic growth.

In particular, the relative prices of information technology (IT) equipment and software were falling rapidly, a reflection of rapid technical progress in IT-producing industries. This IT price decline provided a powerful incentive for the diffusion of IT. The economy saw a massive accumulation of IT capital as well as a substitution of IT for non-IT inputs. This factor accumulation drove the growth acceleration even beyond the direct TFP acceleration in producing IT equipment and software.

One can see many threads of Jorgenson's earlier research in the analysis of the 1990s productivity pickup. First, it was essential that the U.S. national income and product accounts had developed constant-quality price indices for computers and other IT equipment—a recommendation of Jorgenson and Griliches (1967). Second, the incentives for massive IT investments could be analyzed in the framework of Jorgenson (1963). Third, rapidly falling IT prices meant that the cost of capital—the implicit rental cost of a dollar of computers—was very high; in other words, businesses needed a high return per dollar of IT capital, to offset the fact that IT goods would be much cheaper the following year. (This is in addition to the fact that IT capital depreciates quickly, which also raises its cost of capital). This meant that fast-growing IT capital received a very high weight in a capital-services index. As a result, adjusting appropriately for the composition of the capital stock boosted the measured contribution of capital to growth. Finally, to identify the importance of IT intensity in different sectors, as well as substitution possibilities, Jorgenson's research relied on an updated and extended industry KLEMS dataset (see Jorgenson, Ho, and Stiroh, 2005).

Jorgenson always had an interest in studying economic growth beyond the United States. For example Ezaki and Jorgenson (1974) constructed national accounts for Japan that paralleled the Christensen-Jorgenson (1973) U.S. accounts; Conrad and Jorgenson (1975) presented comparable accounts for West Germany. Jorgenson and Nishimizu (1978) pioneered a methodology for bilateral comparisons of output, input, and productivity. Christenson, Cummings, and Jorgenson (1981) provided international comparisons for the G7 and beyond.[21]

More recently, Jorgenson has applied his growth-accounting techniques to the study of China's economy. Jorgenson serves as the head of the economics group of the Harvard-China Project on Energy, Economy and Environment (also known as the "Harvard-China Project"). For example, Cao et al (2009) analyze the industry sources of China's rapid economic growth, finding that rapid growth in the 1980s and 1990s mainly reflected factor accumulation.

## 4.3. Econometric and general equilibrium modeling

Jorgenson's research on investment and growth accounting stand on their own. But they also form an important foundation for Jorgenson's continuing goal of building realistic, empirically estimated, intertemporal general equilibrium models that can be used for policy analysis. Indeed, one impetus for careful and detailed growth-accounting data was to develop the required input for econometric estimation of producer behavior. That producer block, in turn, was a central piece of general equilibrium models.

Econometric estimation has been a key point of differentiation of Jorgenson's general equilibrium modeling. Many computable general equilibrium models instead employ more easily available parameters that might be estimated over data that are not the subject of the model—for example, using data from different countries, periods, or sectors.

[21] Masahiro Kuroda was an important collaborator in research on Japan. See, for example, Jorgenson, Kuroda, and Nishimizu (1987) and Jorgenson and Kuroda (1990).

Several of Dale's earliest theoretical papers had focused on general equilibrium growth models. These included his PhD thesis (published as Jorgenson, 1960), which explored the stability of dynamic input-output growth models. They also included his 1961 paper on the "Development of a Dual Economy." That paper looked at an economy with a traditional and modern sector. Both sectors followed neoclassical principles. In that way, it contrasted with W. Arthur Lewis's "classical" model where agriculture had surplus labor—that is, where the marginal product of labor in the agricultural sector was zero. The policy implications of the Jorgenson and Lewis models were quite different. In Jorgenson's neoclassical model, the key to breaking out of a low-level equilibrium trap was to develop an agricultural surplus, which freed workers for the industrial sector. In contrast, in Lewis's classical model, some external impetus to industrialization was necessary to draw zero-marginal-product workers away from the agricultural sector.

In the early 1970s, energy prices rose sharply. In response, Jorgenson began developing econometric general equilibrium models to address how economies responded to changes in energy prices and to understand the effects of energy-conservation policies. This led to a number of papers with Edward Hudson (e.g., Hudson and Jorgenson, 1974, 1978) that examined the link between energy prices, energy conservation, and economic growth.[22]

These models disaggregated across sectors of the economy. Energy use differs across sectors, and they respond differently to changes in energy and other input prices. Equally

[22] Jorgenson (1998a, p.xvi) describes the beginnings of this research agenda in 1972, under the auspices of the Ford Foundation's Energy Policy Project. That volume summarizes Jorgenson's early work using econometric general equilibrium models to understand energy markets. The description below draws heavily on volume's preface.

importantly, an energy shock is, by its very nature, a shock transmitted through inter-industry (input-output) relationships.

Jorgenson's general-equilibrium models use the neoclassical production theory underlying the growth-accounting methods described earlier. Starting with Christensen, Jorgenson, and Lau (1971, 1973), Jorgenson steadily refined his econometric modeling of producer behavior.[23] That 1973 paper introduced the transcendental logarithmic (translog) functional form for production, cost, or profit functions. With that flexible functional form, factor substitution, factor biases, and other features of technology could be determined econometrically by the data, not pre-specified by the functional form. For example, input-output coefficients were endogenous variables, depending on input prices.[24]

Hudson and Jorgenson used the nine-industry dataset constructed in Berndt and Jorgenson (1973), along with the econometric approach to modeling producer behavior from Christensen, Jorgenson, and Lau (1973). The endogeneity of input-output coefficients was crucial for allowing a role for energy conservation policies, whose inherent goal was to reduce the energy intensity of production. This flexibility contrasts with the exogenous, fixed coefficients assumed by Leontief (1953) and many general equilibrium models that followed.

---

[23] Both Christensen and Lau were Ph.D. students of Jorgenson's at Berkeley.

[24] Diewert (1976) links flexible functional forms, such as the translog, to index numbers used in growth accounting. Remarkably, if the production function takes the translog form that Jorgenson and his collaborators assumed, then the Törnquist (or translog) growth-accounting formulas used by Jorgenson is exactly correct, not just an approximation. Christensen, Jorgenson, and Lau (1973) also estimate a production possibility frontier with two not-perfectly-substitutable outputs—consumption and investment.

Indeed, factor shares did change dramatically following the energy-price shocks, so the flexibility mattered for fitting the data and capturing the economic trade-offs.

In these early general equilibrium models, household preferences were given by a translog indirect utility function for a representative consumer, as introduced by Christensen, Jorgenson, and Lau (1975). This function allows a greater degree of flexibility compared to the Cobb-Douglas (or, slightly more general, the constant elasticity of substitution) functions that were commonly used. With these preferences, budget shares could change endogenously as a function of energy (and other) prices. This provided an additional channel for policy to influence energy use. Because leisure entered the utility function, labor input was also endogenous.

The cost of capital played a central role in making the general equilibrium model intertemporally consistent. As Jorgenson (1963) had shown, the cost of capital was a key determinant of demand for capital services; it incorporated the expectations about future relative prices that mattered for decisions today. The accumulation of capital, in turn, played an important role in the process of economic growth. The cost of capital also mattered for consumption-savings decisions of households, since household decisions about consumer durables (including owner-occupied housing) are also an intertemporal decision.

In addition, the Hudson-Jorgenson model was consistent with the Christensen-Jorgenson (1973) national accounting system, described earlier. That system integrated production, investment, the capital stock, and capital services into a consistent set of accounts.

Estimating these models econometrically required new statistical tools, since the model was nonlinear and prices were endogenous. Jorgenson and Laffont (1974) developed new econometric methods appropriate for estimating this kind of non-linear system of equations.

Gallant and Jorgenson (1979) provided tools for statistical inference in such models. (Lars Hansen, 1982, extended and generalized the approach with his generalized methods of moments.)

Jorgenson continued to develop and refine his econometric intertemporal general equilibrium models in later decades. In terms of the intertemporal block of the model, Jorgenson and Yun's (1986a, b) analysis of alternative tax policies introduced several innovations that improved the intertemporal consistency of the model, beyond simply incorporating the cost of capital. First, the paper incorporated a forward-looking econometric model of household behavior, based on Hall's (1978) Euler equation approach. Second, the paper added an intertemporal price system, in which asset prices equal present values of future prices of capital services. Finally, the model was then solved with rational expectations, making the model fully internally consistent intertemporally.

Other refinements to Jorgenson's general equilibrium modeling involved adding blocks that were developed in Jorgenson's ongoing research on econometric modeling of production, consumption, and welfare. I mention a few examples here.

In terms of industry disaggregation, Fraumeni and Jorgenson (1981) extended the general equilibrium model to include an econometric model of production for 35 industries, the same later ones used in Jorgenson, Gollop, and Fraumeni (1987). That 35-industry/commodity model was used in later general equilibrium models as well.

On the household side, Jorgenson's early general equilibrium models had assumed there was a representative consumer. Jorgenson's first steps in relaxing this assumption focused on modeling consumer demand on its own, rather than fitting it into a general equilibrium model. Unfortunately, Jorgenson and his collaborators (starting with Christensen, Jorgenson, and Lau, 1975) found that statistical tests "…have strongly adverse implications for models of consumer demand based on the model of a representative consumer…" (Jorgenson, 1997a, p. xvii).

Given that the representative consumer paradigm had neither a theorical nor a statistical rationale, Jorgenson introduced econometric methods to allow household heterogeneity in preferences. Allowing every household to have unique and idiosyncratic preferences would not have been implementable without detailed accounting for every household over time. But Jorgenson, Lau, and Stoker (1982) implemented a practical method by allowing preferences to depend on a parsimonious set of household demographic characteristics (e.g., family size and the age of children).[25]

As was often the case with Jorgenson's research, estimating the model required Jorgenson to develop new econometric techniques, in this case for pooling aggregate time series and individual cross sections. Jorgenson and Stoker (1986) presented the required statistical methodology.

Welfare analysis was a relatively short additional step. Conceptually, Jorgenson, Lau, and Stoker (1982) were estimating indirect utility functions for each individual in the economy. Welfare analysis is then a question of how to weight the utilities of different individuals. Doing so requires a social welfare function (as originated by Abram Bergson, 1937) as well as cardinal measures of individual welfare that can be compared (see Amartya Sen, 1977).

[25] This work implemented Lau's (1982) theory of exact aggregation empirically. Stoker (2000) surveys the literature on modeling consumer demand, with a focus on Jorgenson's contributions.

Jorgenson (1990) summarizes his research on integrating econometric models of household behavior and social welfare measurement.[26] Several notable early papers were Jorgenson and Slesnick (1983), who presented an econometric approach to cost-of-living measurement; and Jorgenson and Slesnick (1984), who discussed how to decompose social welfare into the contributions of equity and efficiency.

This body of research on econometric modeling of production, consumption, and applied welfare analysis are, of course, important contributions in their own right. But an important goal was to incorporate these building blocks into an econometric, multi-sector, intertemporal, general equilibrium model. Jorgenson and Wilcoxen (1990) implemented these refinements to analyze environmental regulation.

Since that time, Jorgenson (especially in collaboration with Pete Wilcoxen) has written extensively about policies to combat climate change, using increasingly refined versions of their intertemporal general equilibrium model. This application follows naturally from his early work with Hudson on energy policies in a general equilibrium context.

A notable example of this work is in Jorgenson, Goettle, Ho, and Wilcoxen (2014). The acknowledgement to that book says it is based on “version 18” of the intertemporal general equilibrium model that began with Jorgenson and Wilcoxen (1990)—and which was, as noted, itself built on a foundation of many earlier papers and models. The 2014 book finds that there is potential “double dividend” from a properly designed package of tax changes. A carbon tax

[26] Slesnick (2000) surveys Jorgenson’s approach to applied welfare measurement and discusses applications of the approach to the social welfare impact of changes in carbon taxes, as well as measures of the cost of living, the standard of living, inequality, and poverty. Jorgenson (2018) discusses welfare measures in the context of production and the national accounts.

would induce firms to reduce carbon emissions while simultaneously raising revenue. That revenue could then be used to reduce capital taxes, thereby reducing the cost of capital and promoting capital accumulation and growth. As Jorgenson (2014) puts it,

> Taxing energy and reducing the cost of capital leads to large gains in the efficiency of the economy overall, as goods and services are produced less energy-intensively. For society as a whole, you end up with a positive impact on economic well-being because the large gain in the efficiency of the economy outweighs the increase in inequality.

Note that, in their model, the positive impact on economic well-being occurs even apart from any environmental benefits.

Jorgenson has also applied these ideas to China. For example, Jorgenson, Cao, and Ho (2013) discuss how to design a system of taxes and revenue recycling that would allow China to reduce their pollution while maintaining economic growth.

## 5. Jorgenson's influence on official statistical measurement

Jorgenson's research has had a notable influence on official (and semi-official) measurement, especially in the national accounts and growth accounting. The influence reflects Jorgenson's focus on measuring variables in a way that is consistent with theory. It is equally a testament to his tireless "proof of concept" efforts—showing that these theoretically consistent measures could be implemented in practice.[27]

Jorgenson and Landefeld (2006) recommended a range of changes to the U.S. national accounts to improve the theoretical and empirical consistency of data measures—both within the existing national accounts and across official data providers. Jorgenson (2009) presented an

---

[27] My informal observation is that, in measurement and growth-accounting circles, Dale is treated as a godlike figure.

updated version of this recommendation. In large part, the new architecture would implement important aspects of the "Jorgenson system of national accounts" discussed earlier—which built on the vision first presented in Christensen and Jorgenson (1973). The cost of capital plays an important role in these recommendations by linking capital services and wealth accounts to the U.S. national accounts. Some steps in the Jorgenson and Landefeld recommendations have since been implemented; others remain on the radar screen of statistical authorities.[28]

Landefeld (2020) describes the evolution over time in the U.S. national accounts and highlights ways in which Jorgenson's research has influenced the official accounts. These include implementing several of the innovations recommended in Jorgenson and Griliches (1967), such as the use of chain-weighted indices and substantially improved quality-adjusted price indexes for investment and other goods. As Landefeld writes (p. 31-32)

> Most of the changes for the national accounts proposed by Jorgenson and Landefeld were a summary of the extensions and suggestions in the integrated frameworks put forth earlier by Jorgenson, Fraumeni, and others. The New Architecture, Jorgenson's chairmanship of the [Bureau of Economic Analysis, BEA] Advisory Committee, and his work with [the Bureau of Labor Statistics, BLS] and the Federal Reserve [FRB], helped to foster long-term work that evolved from prototypes to the regular production by BLS and BEA (Integrated aggregate production MFP accounts (2006–16), Integrated industry level production MFP accounts (2012–15) and by FRB and BEA of estimates of integrated financial and production accounts (2007–16).

Jorgenson's influence on measurement has been particularly notable for growth accounting. Since 1983, the U.S. Bureau of Labor Statistics (BLS) has produced annual growth-accounting measures for the private business economy and for major sectors. Those accounts include capital services measured along the conceptual lines initially laid out by Jorgenson and

[28] Jorgenson (2018) reviews advances in the measurement of production and welfare within the national accounts. Some of those advances are discussed below.

Griliches (1967), and refined in Jorgenson's later work, which allowed for heterogeneous capital weighted with implicit rental rates (costs of capital). Since 1993, the BLS accounts have measured labor input along Jorgensonian lines, allowing for heterogeneous labor. [29]

More recently, the Bureau of Economic Analysis and the BLS have begun producing an integrated industry-level production account that is explicitly modeled on Jorgenson, Gollop, and Fraumeni (1987). It integrates BEA's GDP by industry data with constant-quality capital and labor input measures that are consistent with Jorgenson's methods.[30] This production account implements one of the recommendations of Jorgenson and Landefeld (2006).

Many other countries have, similarly, developed official growth accounts that follow the Jorgenson template. The Organization of Economic Cooperation and Development (OECD) manuals on capital (Schreyer, 2009) and productivity growth (Schreyer, 2001) recommend that countries implement the Jorgenson growth-accounting system at an aggregate and industry level. The United Nation's (2009) *System of National Accounts 2008* recommends that constant-quality inputs of labor and capital be implemented along Jorgensonian lines as part of the production account. As of 2015, at least 50 countries produced constant-quality measures of labor input (that is, labor-input measures that incorporate changes in the composition of hours).[31] Jorgenson and Schreyer (2013) discuss how to integrate industry-level production accounts with the System of National Accounts 2008. They note that statistical authorities in a

---

[29] See Dean and Harper (2001). Their discussion emphasizes that the BLS uses "measurement techniques developed by Jorgenson…." (p.79).

[30] https://www.bea.gov/data/special-topics/integrated-industry-level-production-account-klems. Accessed February 21, 2022.

[31] Cited by Dale Jorgenson in email correspondence with the author, October 3, 2015.

number of countries (Canada plus a number in Europe) already have production accounts that are consistent with Jorgenson's long-standing recommendations.

Jorgenson's research has also stimulated the development of datasets that may not be part of the official national accounts of particular countries, but that are nevertheless coordinated across countries. The EU KLEMS and World KLEMS projects have developed industry KLEMS datasets for a large number of countries that follow the Jorgenson, Gollop, and Fraumeni (1987) template. The EU KLEMS project began in the early 2000s as a collaboration among 18 research institutions, with a common methodology given by the OECD productivity and capital manuals (Schreyer, 2001, 2009). The India KLEMS project came to fruition in 2009, following a meeting with Jorgenson and several economists in India. The Asia KLEMS project followed in December 2010. The World KLEMS project was inaugurated in 2010 by Dale Jorgenson (in collaboration with Marcel Timmer and Bart van Ark), with a goal of extending the EU KLEMS database to a number of emerging and transition economies.[32]

These datasets allow researchers to properly understand the industry sources of growth across countries on an internationally consistent basis. They are consistent with the United Nations' (2009) System of National Accounts and follow recommendations in Jorgenson and Landefeld's (2006) and Jorgenson's (2009) "new architecture" for the production account.

Data produced for the Penn World Tables (a standard source of cross-country data, currently maintained by the University of Groningen's Growth and Development Centre) have

---

[32] For EU KLEMS, see Timmer et al, (2010) as well as http://www.euklems.net/ (accessed February 22, 2022). For background on the World KLEMS Productivity and Growth Accounting initiative, see https://www.worldklems.net/wkabout (accessed February 22, 2022). Jorgenson et al. (2014, p. 16-17) also discuss the EU KLEMS and World KLEMS initiatives.

been influenced by Jorgenson's recommendations.[33] The Jorgenson system is data intensive and cannot easily be implemented for every country in the world. But as Inklaar et al (2019) describe, the PWT version 9.1 (released in 2019) implemented a new measure of capital input for a large number of countries, following Jorgenson and Nishimizu (1978). Inklaar et al. (2019) show that, properly measured, capital input explains a larger share of cross-country income differences than does a naïve capital stock measure.

In 2018, the World Bank (Lange et al 2018) published a blockbuster report that focused on a wealth account for a large number of countries that includes human capital measures that follow the lifetime income approach of Jorgenson and Fraumeni (1989, 1992b). (The World Bank (2021) has updated these estimates.)

## 6. Conclusion

In his long and productive career, Dale W. Jorgenson has had an enormous influence in economic and policy circles. His research has shaped entire fields—perhaps most notably in the areas of investment and growth accounting. His seminal work on investment integrated the theory and econometric practice of investment in a transformational way. The field has continued to evolve over time, of course. Nevertheless, Jorgenson's research on investment from the 1960s and 1970s continues to echo and reverberate into the 2020s.

In growth accounting, Jorgenson's ongoing research over more than half a century showed the value of drawing out all of the implications of theory. More than that, he has

[33] See https://www.rug.nl/ggdc/productivity/pwt/ (accessed 21 February 2022).

showed that, with massive amounts of effort, those implications could be implemented in the data. For this reason, modern growth accounting is Jorgenson's growth accounting. Indeed, Jorgenson's work has moved far beyond academic corridors and into the practical business of compiling economic data by statistical authorities. Statistical authorities around the world follow Jorgenson's lead when it comes to productivity measurement; and other areas of the national accounts increasingly follow Jorgenson's theoretically-driven precepts as well. Researchers in many areas of economics use KLEMS datasets that wouldn't exist—certainly not in their theoretically coherent form—without Jorgenson's determination and resolve.

Jorgenson has contributed much more broadly. An important area is the econometric modeling of producer behavior, where Jorgenson pioneered the flexible translog functional form and showed how to estimate it. He applied similar insights to the econometric modeling of consumer behavior. And he has put the different building blocks together into practical, econometrically estimated, intertemporal and multi-sectoral general equilibrium models. These models provide a coherent vision of the economy, in which policies that influence investment have first-order effects on growth and well-being.

Along the way, Dale's contributions to Harvard were enormous. He helped bolster the reputation of the economics department worldwide, to the benefit of many other Harvard scholars—including those yet to come.

## 7. Major works by Dale W. Jorgenson

Auerbach, Alan J., and Dale W. Jorgenson. 1980. Inflation-Proof Depreciation of Assets. *Harvard Business Review* 58, no. 5 (September-October): 113-118. Reprinted in Jorgenson, 1996b.

Bernanke, Ben and Dale W. Jorgenson. 1975. “The Integration of Energy Policy Models.” *Computers and Operations Research* 2, no. 3 (1975): 225-249.

Berndt, Ernst R., and Dale W. Jorgenson. 1973. “Production Structures.” In *U.S. Energy Resources and Economic Growth*, eds. Dale W. Jorgenson and Hendrik S. Houthakker, ch. 3, Washington, DC: Energy Policy Project.

Jing Cao, Mun S Ho, Dale W Jorgenson, Rouen Ren, Linlin Sun, and Ximing Yue. 2009. “Industrial and aggregate measures of productivity growth in China, 1982-2000.” *Review of Income Wealth* , 55, s1, Pp. 485-513.

Christensen, Laurits R., Dianne Cummings, and Dale W. Jorgenson. 1981. “Relative Productivity Levels, 1947-1973: An International Comparison.” European Economic Review 16, no. 1 (1981): 61-94.

Christensen, Laurits R., Dale W. Jorgenson, 1973. "Measuring Economic Performance in the Private Sector.” In *The Measurement of Economic and Social Performance*. ed. M. Moss. Studies in Income and Wealth, vol. 37. New York, NY: Columbia University Press. Reprinted in Jorgenson, 1995a.

Christensen, Laurits R., Dale W. Jorgenson, and Lawrence J. Lau. 1971. “Conjugate Duality and the Transcendental Logarithmic Production Function.” *Econometrica* 39, no. 4 (July): 255-256.

Christensen, Laurits R., Dale W. Jorgenson, and Lawrence J. Lau. 1973. "Transcendental Logarithmic Production Frontiers.” *The Review of Economics and Statistics* 55, no. 1 (February): 28-45. Reprinted in Jorgenson, 2000.

Christensen, Laurits R., Dale W. Jorgenson, and Lawrence J. Lau. 1975. "Transcendental Logarithmic Utility Functions.” *American Economic Review* 65, no. 3 (June): 367-383. Reprinted in Jorgenson, 1997a.

Conrad, Klaus, and Dale W. Jorgenson. 1995. *Measuring Performance in the Private Economy of the Federal Republic of Germany 1950-1973*. Tubingen: J.C.B. Reprinted in Jorgenson, 1995b.

Ezaki, Mitsuo, and Dale W. Jorgenson. 1973. “Measurement of Macroeconomic Performance in Japan, 1951-1968”. In *Economic Growth: The Japanese Experience Since the Meiji Era, vol. 1*, eds. Kazushi Ohkawa and Yujiro Hayami, 286-361, Tokyo: Japan Economic Research Center. Reprinted in Jorgenson, 1995b.

Fraumeni, Barbara M., and Dale W. Jorgenson. 1981.“Relative Prices and Technical Change.” In *Modeling and Measuring Natural Resource Substitution* , edited by E Berndt and B Field, 17-47. Cambridge: M.I.T. Press.

Gallant, A. Ronald, and Dale W. Jorgenson. 1979. “Statistical Inference for a System of Simultaneous, Nonlinear, Implicit Equations in the Context of Instrumental Variable Estimation.” *Journal of Econometric*s 11, nos. 2/3 (October/December): 275-302.

Griliches, Zvi, and Dale W. Jorgenson. “Sources of Measured Productivity Change: Capital Input.” The American Economic Review 56, no. 2 (1966): 50-61.

Hall, Robert E., and Dale W. Jorgenson. 1967. “Tax Policy and Investment Behavior.” *The American Economic Review* 57, no. 3 (June): 391—414. Reprinted in Jorgenson, 1996b.

Hudson, Edward A., and Dale W. Jorgenson. 1974. “U.S. Energy Policy and Economic Growth, 1975-2000.” *Bell Journal of Economics and Management Science* 5, no. 2 (Autumn): 461-514. Reprinted in Jorgenson, 1998a.

Hudson, Edward A., and Dale W. Jorgenson. 1978. Energy Policy and U.S. Economic Growth. American Economic Review 68, no. 2 (May): 118-123. Reprinted in Jorgenson, 1998a.

Jorgenson, Dale W. 1963. “Capital Theory and Investment Behavior.” *American Economic Review* 53, no 2 (May): 247-259. Reprinted in Jorgenson, 1996a.

Jorgenson, Dale W. 1966. “The Embodiment Hypothesis.” Journal of Political Economy 74, no. 1 (1966): 1-17. Reprinted in Jorgenson, 1995a.

Jorgenson, Dale W. 1988. “Productivity and Postwar U.S. Economic Growth.” Journal of Economic Perspectives 2, no. 4 (1988): 23-42. Reprinted in Jorgenson, 1995a.

Jorgenson, Dale W. 1990. “Aggregate Consumer Behavior and the Measurement of Social Welfare.” *Econometrica* 58, no. 5 (1990): 1007-1040. Reprinted in Jorgenson, 1997b.

Jorgenson, Dale. 1995a. *Productivity, Volume 1: Postwar U.S. Economic Growth*. The MIT Press

Jorgenson, Dale. 1995b. *Productivity, Volume 2: International Comparisons of Economic Growth*. MIT Press

Jorgenson, Dale. 1996a. *Investment - Volume 1: Capital Theory and Investment Behavior*. MIT Press.

Jorgenson, Dale. 1996b. *Investment - Volume 2: Tax Policy and the Cost of Capital*. MIT Press.

Jorgenson, Dale. 1997a. *Welfare, Volume. 1 Aggregate Consumer Behavior*. MIT Press, 1997.

Jorgenson, Dale. 1997b. *Welfare, Volume 2: Measuring Social Welfare*. MIT Press, 1997.

Jorgenson, Dale W. 1998a. *Growth, Volume 1: Econometric General Equilibrium Modeling.* MIT Press, Cambridge, MA.

Jorgenson, Dale W. 1998b. *Growth, Volume 2: Energy, the Environment, and Economic Growth.* MIT Press.

Jorgenson, Dale W. 2000. *Econometrics, Volume 1: Econometric Modeling of Producer Behavior*. MIT Press.

Jorgenson, Dale W. 2001 “Information Technology and the U.S. Economy.” American Economic Review 91, no. 1: 1-32.

Jorgenson, Dale W. 2009. “A New Architecture for the U.S. National Accounts.” Review of Income and Wealth 55, no. 1 (2009): 1-42.

Jorgenson, Dale W. 2012. "The World KLEMS Initiative," International Productivity Monitor, Centre for the Study of Living Standards, vol. 24, pages 5-19, Fall.

Jorgenson, Dale W. 2014. “Time to Tax Carbon: Enhancing environmental quality and economic growth.” *Harvard Magazine* (interview with Dale Jorgenson), September-October 2014. https://www.harvardmagazine.com/2014/09/time-to-tax-carbon (accessed 27 February 2022).

Jorgenson, Dale W. 2018. “Production and Welfare: Progress in Economic Measurement.” Journal of Economic Literature LVI, no. 3 (2018): 867-919

Jorgenson, Dale W., and Ben Bernanke. 1975. “The Integration of Energy Policy Models.” Computers and Operations Research 2, no. 3 (1975): 225-249.

Jorgenson, Dale W, Jing Cao, and Mun S Ho. 2013. “The Economics of Environmental Policies in China.” In *Clearer Skies over China*, 329-372. Cambridge, MA: The MIT Press.

Jorgenson, Dale W. and Barbara M. Fraumeni 1989. “The Accumulation of Human and Nonhuman Capital, 1948– 84.” In *The Measurement of Saving, Investment, and Wealth*, eds. R. E. Lipsey and H. S. Tice. Studies in Income and Wealth, vol. 52. Chicago, IL: University of Chicago Press.

Jorgenson, Dale W. and Barbara M. Fraumeni. 1992a. “The Output of the Education Sector,” in Z. Griliches, T. Breshnahan, M. Manser, and E. Berndt (eds.), *The Output of the Service Sector*. Chicago, NBER, 1992, pp. 303-341. Reprinted in Jorgenson, 1995a.

Jorgenson, Dale W. and Barbara M. Fraumeni. 1992b. “Investment in Education and U.S. Economic Growth.” *Scandinavian Journal of Economics* 94 (supplement): S51–70. Reprinted in Jorgenson, 1995a.

Jorgenson, Dale W., Richard J. Goettle, Mun S. Ho, and Peter J. Wilcoxen. 2013. *Double Dividend: Environmental Taxes and Fiscal Reform in the United States*, Cambridge, The MIT Press.

Jorgenson, Dale W., Frank M. Gollop, and Barbara M. Fraumeni. 1987. *Productivity and U.S. Economic Growth*, Cambridge , Harvard University Press.

Jorgenson, Dale W. and Zvi Griliches. 1967. The Explanation of Productivity Change.” *Review of Economic Studies* 34, No. 99 (July): 249– 280. 4. Reprinted in Jorgenson, 1995a.

Jorgenson, Dale W., and Zvi Griliches. 1971. “Divisia Index Numbers and Productivity Measurement.” *Review of Income and Wealth* 17, no. 2 (1971): 53-55.

Jorgenson, Dale W. and Zvi Griliches. 1972. “Issues in Growth Accounting: A Reply to Edward F. Denison.” *Survey of Current Business* 52, No. 5, Part II (May): 65– 94. 5.

Jorgenson, Dale W., Mun S. Ho, and Kevin J. Stiroh. 2005. *Productivity, Volume 3: Information Technology and the American Growth Resurgence.* MIT Press.

Jorgenson, Dale W. and Masahiro Kuroda. 1990. "Productivity and International Competitiveness in Japan and the United States, 1960-1985." In *Productivity in the U.S. and Japan*, Studies in Income and Wealth, Vol. 51, edited by CR Hulten, 29-58. Chicago: University of Chicago Press, 1990.

Jorgenson, Dale W., Masahiro Kuroda, and Mieko Nishimizu. 1987. "Japan-U.S. Industry-Level Productivity Comparisons, 1960-1979." *Journal of the Japanese and International Economies* 1, no. 1 (1987): 1-30.

Jorgenson, Dale W., and Jean-Jacques Laffont. 1974. "Efficient Estimation of Nonlinear Simultaneous Equations with Additive Disturbances." *Annals of Social and Economic Measurement* 3, no. 1 (January): 615-640.

Jorgenson, Dale W., and J. Steven Landefeld. 2006. "Blueprint for Expanded and Integrated U.S. Accounts: Review, Assessment, and Next Steps." In *A New Architecture for the U.S. National Accounts*, edited by Dale W. Jorgenson, J. Steven Landefeld, and William D. Nordhaus, 13–112. Chicago and London: University of Chicago Press.

Jorgenson, Dale W, Lawrence J. Lau, and Thomas M. Stoker. 1980a. "Welfare Comparison under Exact Aggregation." *American Economic Review* 70, no. 2 (May): 268-272.

Jorgenson, Dale W, Lawrence J. Lau, and Thomas M. Stoker. 1982. "The Transcendental Logarithmic Model of Aggregate Consumer Behavior." In *Advances in Econometrics 1*, eds. Robert L. Basmann and G.F. Rhodes, vol. 1, 97-238, Greenwich: JAI Press.

Jorgenson, Dale W. and Mieko Nishimizu. 1978. "U.S. and Japanese Economic Growth, 1952-1974: An International Comparison," *Economic Journal*, Vol. 88, No. 352, pp. 707-726. Reprinted in Jorgenson, 1995b.

Jorgenson, Dale W, and Paul Schreyer. "Industry-level Productivity Measurement and the 2008 System of National Accounts." *Review of Income and Wealth* 59 (2013): 185–211.

Jorgenson, Dale W. and Daniel T. Slesnick. 1983. "Individual and Social Cost of Living Indexes." In *Price Level Measurement* , edited by W Erwin Diewert and C Montmarquette, 241-323. Ottawa: Statistics Canada, 1983. Reprinted in Jorgenson, 1997b.

Jorgenson, Dale W. and Daniel T. Slesnick. 1984. "Inequality in the Distribution of Individual Welfare." In *Advances in Econometrics* , edited by RL Basmann and G Rhodes, 67-130. Greenwich: JAI Press. Reprinted in Jorgenson, 1997b.

Jorgenson, Dale W. and Kevin J. Stiroh. 2000. "Raising the Speed Limit: U.S. Economic Growth in the Information Age." *Brookings Papers on Economic Activity*, vol. 2000, no. 1, Brookings Institution Press, 2000, pp. 125–235, http://www.jstor.org/stable/2667350.

Jorgenson, Dale W and Thomas M. Stoker. 1986. "Nonlinear Three Stage Least Squares Pooling of Time Series and Cross Section Data." In *Advances in Statistical Analysis and Statistical Computing, Vol.1*, edited by RS Mariano, 87-115. Greenwich: JAI Press, 1986. Reprinted in Jorgenson, 1997a.

Jorgenson, Dale W. and Peter J. Wilcoxen. 1998b. “Environmental Regulation and U.S. Economic Growth.” *Rand Journal of Economics* 21, no. 2 (1990): 314-340. Reprinted in Jorgenson, 1998b.

Jorgenson, Dale W., and Kun-Young Yun. 1986a. “The Efficiency of Capital Allocation.” *Scandinavian Journal of Economics* 88, no. 1: 85-107. Reprinted in Jorgenson, 1996b.

Jorgenson, Dale W., and Kun-Young Yun. 1986b. “Tax Policy and Capital Allocation.” *Scandinavian Journal of Economics* 88, no. 2: 355-377. Reprinted in Jorgenson, 1996b.

**Additional References**

American Economic Association. 1971. “Dale Jorgenson, Clark Medalist 1971: Citation on the Occasion of the Presentation of the Medal”. https://www.aeaweb.org/about-aea/honors-awards/bates-clark/dale-jorgenson (accessed October 15, 2021).

Arrow, Kenneth J., B. Douglas Bernheim, Martin S. Feldstein, Daniel L. McFadden, James M. Poterba, and Robert M. Solow. 2011. "100 Years of the American Economic Review: The Top 20 Articles." *American Economic Review*, 101 (1): 1-8.

Bergson, Abram. 1937. “Real Income, Expenditure Proportionality, and Frisch’s ‘New Methods of Measuring Marginal Utility.’” *Review of Economic Studies* 4, no. 1 (October): 33-52.

Chirinko, Robert S. 1993. “Business Fixed Investment Spending: Modeling Strategies, Empirical Results, and Policy Implications.” *Journal of Economic Literature*, vol. 31, no. 4, American Economic Association, pp. 1875–911, http://www.jstor.org/stable/2728330.

Dean, Edwin and Michael Harper, 2001. "The BLS Productivity Measurement Program.” In Charles Hulten, Edwin Dean, and Michael Harper, eds., *New Developments in Productivity Analysis,* pages 55-84, National Bureau of Economic Research, Inc.

Denison, Edward F., 1962. “The Sources of Economic Growth in the United States and the Alternatives Before Us.” *Supplementary Paper No. 13*, New York, Committee for Economic Development.

Denison, Edward F. 1969. “Some Major Issues in Productivity Analysis: An Examination of Estimates by Jorgenson and Griliches.” *Survey of Current Business* 49, no. 5, pt. 2 (May): 1-27.

Diewert, W. Erwin. 1976. “Exact and Superlative Index Numbers.” *Journal of Econometrics* 4, no. 2 (May): 115-146

Domar, Evsey D. 1961. “On the Measurement of Technological Change.” *The Economic Journal*, Volume 71, Issue 284, 1 (December), Pages 709–729, https://doi.org/10.2307/2228246.

Barbara M. Fraumeni. 2000. “The Jorgenson System of National Accounting,” in Lawrence J. Lau, editor, *Econometrics Volume 2: Econometrics and the Cost of Capital: Essays in Honor of Dale W. Jorgenson*, MIT Press, pp. 111–142.

Barbara M. Fraumeni, editor. 2020. *Measuring Economic Growth and Productivity: Foundations, KLEMS Production Models, and Extensions*. Elsevier Press

Griliches, Zvi (1960). “Measuring Inputs in Agriculture: A Critical Survey.” *Journal of Farm Economics*, Proceedings Issue, vol. 17, no. 5 (December): 141 1-33.

Griliches, Zvi. 1991. "Hedonic Price Indexes and the Measurement of Capital and Productivity: Some Historical Reflections." In Ernst R. Berndt and Jack E. Triplett, editors *Fifty Years of Economic Measurement: The Jubilee of the Conference on Research in Income and Wealth*, pages 185-206, National Bureau of Economic Research, Inc.

Griliches, Zvi. 1996. “The Discovery of the Residual: A Historical Note.” *Journal of Economic Literature*, 34(3), 1324–1330. http://www.jstor.org/stable/2729504

Hall, Robert E. 1978. “Stochastic Implications of the Life Cycle-Permanent Income Hypothesis: Theory and Evidence.” *Journal of Political Economy* 86, no. 6 (December): 971-987.

Hansen, Lars P. 1982. “Large Sample Properties of Generalized Methods of Moments Estimators.” *Econometric*a 50, no. 4 (July): 1029-1054.

Hayashi, Fumio. 2000. “The Cost of Capital, Q,and the Theory of Investment Demand.” In Lawrence J. Lau., editor. *Econometrics, Volume 2 : Econometrics and the Cost of Capital*. The MIT Press, 2000. pp.55-83.

Hulten, Charles R. 2002. “Review of ‘R&D, Education, and Productivity: A Retrospective,’ by Z. Grilliches.” *Journal of Economic Literature*, 40(3), 961–963. http://www.jstor.org/stable/3217145

Inklaar, Robert, Pieter Woltjer, and Daniel Gallardo Albarrán. 2019. "The Composition of Capital and Cross-Country Productivity Comparisons," *International Productivity Monitor*, Centre for the Study of Living Standards, vol. 36, pages 34-52, Spring.

Landefeld, J. Steven. 2020. “Expanding the conceptual foundation, scope, and relevance of the US national accounts: the intersection of theory, research, and measurement.” Chapter 2 of Barbara M. Fraumeni, ed., *Measuring Economic Growth and Productivity*. Academic Press, Pages 17-35.

Lange, Glenn-Marie; Wodon, Quentin; Carey, Kevin. 2018. *The Changing Wealth of Nations 2018 : Building a Sustainable Future*. Washington, DC: World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/29001 License: CC BY 3.0 IGO.

Lau, Lawrence J. 1982. “A Note on the Fundamental Theorem of Exact Aggregation.” *Economics Letters* 9, no. 2 (February): 119-126.

Lau, Lawrence J. (editor). 2000a. *Econometrics, Volume 2 : Econometrics and the Cost of Capital: Essays in Honor of Dale W. Jorgenson.* The MIT Press.

Lau, Lawrence J. 2000b. “Research on the Cost of Capital: Past, Present, and Future.” in Lawrence J. Lau, editor, *Econometrics Volume 2: Econometrics and the Cost of Capital: Essays in Honor of Dale W. Jorgenson*, The MIT Press.

Leontief, Wassily W. 1953. “Dynamic Analysis.” In *Studies in the Structure of the American Economy*, ed. Wassily Leontief, 53-90. New York: Oxford University Press.

Reamer, Andrew D. 2021. “Dale Jorgenson's Profound and Extended Influence on the National Economic Accounts.” *Survey of Current Business*, June 2021.

Shreyer, Paul, 2001. *OECD Productivity Manual: A Guide to the Measurement of Industry-Level and Aggregate Productivity Growth.* OECD Publishing, Paris. https://www.oecd.org/sdd/productivity-stats/2352458.pdf

Schreyer, Paul, 2009. *Measuring Capital - OECD Manual 2009*. Second edition, OECD Publishing, Paris, https://doi.org/10.1787/9789264068476-en.

Sen, Amartya. 1977. “On Weights and Measures: Informational Constraints in Social Welfare Analysis.” *Econometrica* 45, no. 7 (October): 1539-1571.

Slesnick, Daniel T. 2000. “Innovations in Applied Welfare Economics.” In *Econometrics, Volume 2: Econometrics and the Cost of Capital*. Laurence J. Lau, editor. The MIT Press.

Solow, Robert M. 1957. “Technical Change and the Aggregate Production Function.” *Review of Economics and Statistics* 39(3):3 12-20.

Stoker, Thomas M. 2000. “The Cost of Capital and Consumer Behavior.” In *Econometrics, Volume 2: Econometrics and the Cost of Capital*. Laurence J. Lau, editor. The MIT Press.

Timmer, Marcel, Robert Inklaar, Mary O'Mahony, and Bart van Ark. 2010. *Economic Growth in Europe : A Comparative Industry Perspective*. Cambridge University Press.

United Nations. 2009. *System of National Accounts 2008*. https://unstats.un.org/unsd/nationalaccount/docs/SNA2008.pdf

Warsh, David. 1994. “The sad end, or the man who replaced the great men.” *The Boston Globe*. March 20 (p.75).

“World Bank. 2021. *The Changing Wealth of Nations 2021: Managing Assets for the Future*. Washington, DC: World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/36400 License: CC BY 3.0 IGO.”