BIOGRAPHICAL MEMOIRS

Kenneth Joseph Arrow

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A Biographical Memoir by Simon A. Levin and Avinash Dixit

Kenneth Joseph Arrow ranks among the greatest economists of the twentieth century, indeed of any century. When one takes into account the breadth and depth of his impact on thought and research outside economics, for example in politics, philosophy, and finance, he is second to none.

It is hard to know where to start in remembering Ken Arrow, since he was a giant in so many dimensions. Perhaps the greatest tribute to him is to note that, despite his unparalleled achievements in advancing the science and practice of economics, he was a *mensch* in every sense of the word. Ken was unfailingly kind, not just to his peers, but especially to his younger colleagues; and though he must have known that there were few at his level, he maintained a humility and modesty that went along with his thirst for learning something new from anyone with whom he crossed paths. At one of his eightieth birthday parties, one of his admirers offered the perfect encapsulation of Ken as a scientist, paraphrasing: "The truth about Ken Arrow," he said, "is that he never stopped being a graduate student." Ken's own take, when asked if he was interested in getting involved in a new subject, was often, "That's a topic I know virtually nothing about. Therefore, I am especially interested in getting involved and learning about it." Of course, once he did get involved in such things, it was clear that he knew a lot more about it than he let on, or maybe than even he realized. Ken was a renaissance scholar, with expertise across the spectrum of human knowledge. And beyond his own contributions, he created new fields and inspired countless others, well beyond the forty-five graduate

Kenneth J. Arrow, 2009. *Photo by Agneta Sundin.*

students listed in the *Mathematics Genealogy*. Until Esther Duflo's win at forty-six in 2019, Arrow remained the youngest winner of the Nobel Prize in Economics, and at least four scholars whom he mentored directly or indirectly went on to win the Prize afterwards.

A Brief Biography

Kenneth Arrow grew up in New York City during the Great Depression, the child of Russian Jewish immigrants from Romania, a history that influenced his economic

perspectives. He studied mathematics as an undergraduate at the City College of New York and went on to receive his master's in mathematics from Columbia University in 1941 before being convinced by Harold Hotelling to continue towards a Ph.D. in economics. His studies were interrupted by the war effort, however, and he spent 1942–46 as a weather officer in the U.S. Army Air Forces. In 1947, he resumed his studies part-time, also serving as a research associate at the Cowles Commission at the University of Chicago, while simultaneously serving (with just a master's degree) as an assistant professor of economics at Chicago, as a member of the Rand Corporation, and then as acting assistant professor of statistics at Stanford University. He received his Ph.D. from Columbia in 1951, with Hotelling as advisor. His thesis, *Social Choice and Individual Value* was a monumental piece of work; we discuss it in more detail later in this article.[1]

Arrow left Stanford in 1968 to take up a position as a professor of economics at Harvard University, returning to Stanford in 1979 as the Joan Kenney Professor of Economics and also as a professor of operations research. He was a founding member of the Pontifical Academy of Social Sciences, founded (with Brian Arthur) the Economics Program at the Santa Fe Institute, and was a crucial member from its inception of the Beijer Institute of Ecological Economics (within the Swedish Academy of Sciences). Arrow was deeply committed to using his economic perspectives to forge new partnerships between ecologists and economists in the search for a sustainable future for humanity, and his active participation within the Beijer Institute and unparalleled influence in the economics community and beyond were central to the success of the Beijer's mission under the leadership of its first director, the distinguished Swedish economist Karl-Göran Mäler. Arrow also was in 1990 the founding director of the Jerusalem School of Economic Theory, at the Israel Institute for Advanced Studies (Hebrew University of Jerusalem) and directed it for eighteen years until turning it over in 2008 to Eric Maskin.

Scholarly Work and Influence

Arrow's work, in toto, without question laid cornerstones for modern economics and its application to public policy. He was an exceptional mathematician but knew how to translate the implications of technical work into equation-free discursions meant for broader audiences. His contributions to economics and to society cover so many areas that it is hard to be complete. In what follows, we will highlight some of his contributions and influence.

When one thinks of Ken Arrow, perhaps one thinks first of his aforementioned work on social choice. Arrow's doctoral dissertation introduced the famous "impossibility theorem,"[2] in which he proved that no mechanism or procedure for choosing a social outcome from a menu of alternatives could simultaneously satisfy a small number of intuitive conditions, each clearly desirable on its own—for example, that if one of a pair of alternatives is unanimously preferred, it should also be the preferred social choice from that pair, and that no single individual's preferences should dictate social choice regardless of the preferences of others. In the next half century, uncounted attempts were made to escape from this conundrum, to complicate the issue further by introducing the fact that some information about preferences and capabilities is privately known by individuals who usually do not have the incentive to reveal it to the social choice designer, and so on. Arrow's short book *Social Choice and Individual Values* has almost 25,000 citations on Google Scholar; a large number of these citations are from scholars in political science and philosophy.

Another major area of work associated with Arrow's name is general equilibrium. In joint work with Gerard Debreu, Arrow gave the first fully rigorous and general proof of the existence and efficiency of a competitive equilibrium simultaneously in all markets for goods and services in the economy.[3] This is not only the logical foundation of market economics, but by making explicit the conditions under which this result holds, and therefore pointing out various ways in which it can fail when the conditions are not met, it qualifies and tempers extremist advocacy of laissez-faire in political debates.

An expanded interpretation of the general equilibrium work to include time and uncertainty underlies the whole modern theory of finance. All the mathematics for arbitrage-based pricing of derivative securities, options, and others ultimately derive from the Arrow-Debreu model of pricing state-contingent claims, that is, contracts for supply and demand of a commodity if, and only if, a specified state of the world materializes at a specified time after resolution of the relevant uncertainty.

It is pointless and indeed impossible to count the numbers of Google citations, because the theory is too well-known to need actual cites any longer. If Arrow and Debreu got a dollar every time someone said or wrote the "Arrow-Debreu" theory or model, they would have both been very rich men!

Arrow's work was also fundamental in the economics of technology and growth. His best-known contribution in these fields is the theory of "learning by doing," and his 1962 article on the topic in *The Review of Economic Studies* has nearly 20,000 citations.[4] Based on observations such as the reduction in the cost of manufacturing airframes as engineers and workers gained experience from the cumulative numbers they produced over time, Arrow constructed a general model of the dynamics of this process, and its implications for wages, profits, investment, and aggregate

economic growth. The model has found very wide uses. It was one of the basic mechanisms underlying the large literature on "new" or "endogenous" theories of growth, which showed how technology and increasing returns could sustain growth, countering diminishing returns to labor and capital.[5] In business and industrial economics, A. Michael Spence formalized the idea of "pricing ahead of the learning curve,"[6] which has proved very important in practice as well as theory. Partha Dasgupta and Joseph Stiglitz showed how slight initial differences among competing firms in an industry could result in emergence of monopolies,[7] and this dovetails nicely with Arrow's work on path dependence, which we discuss later. Learning by doing continues to find new uses, for example in modeling how learning can reduce the cost of green technologies like wind and solar power generation, and the optimal subsidy policies (pricing ahead of the learning curve) to promote this process (another nice link to Arrow's interest, in this case in environmental and climate policy). One of us (Dixit) is currently engaged in building a model of cost-reduction in green technologies through learning by doing and the optimal policies for replacement of traditional carbon-emitting technologies, and fitting it to data on learning curves.

Another high-impact contribution is a paper coauthored with Hollis Chenery, Bagich Singh Minhas, and Robert Solow modeling how the degree of substitutability between capital and labor affects economic growth.[8] This paper introduced the "constant elasticity of substitution" production function, which has become the workhorse model in growth theory and many other fields. It also has broad potential application to other fields, for example the growth of biological populations limited by multiple resources.

Arrow also contributed fundamentally to the area of uncertainty and asymmetric information. We mentioned the Arrow-Debreu model of general equilibrium, which takes account of uncertainty by generalizing the concept of a commodity to condition it on a specific state of the world after resolution of the relevant uncertainty and interpreting the market for a commodity as the market for a claim to that good or service contingent upon the materialization of that specific state. But Arrow has other important contributions in the economics of uncertainty. One pertains to modeling individual preferences to reflect their attitudes to risk. The Arrow-Pratt measure of risk-aversion captures this in a neat way, as the percentage of income a person would be willing to forgo in a trade-off for eliminating the risk associated with it. This has also proved useful to large numbers of other researchers in their own models of behavior in the face of uncertainty. Probably the best exposition can be found in Arrow's 1965 Yrjö Jahnsson Lectures, "Essays in the Theory of Risk-Bearing."[9] With one of us, Ken also explored the influence of demographic uncertainty in dictating the level of intergenerational transfer of resources, an exploration that also has fundamental implications for life-history theory in ecology and evolutionary biology.[10]

A paper dealing with uncertainties that pervade the health care industry, with over 11,000 citations, is perhaps even more important in its impact within and outside economics.[11] It is unusual for an Arrow paper in that it does not give us a single mathematical model for the great generality of the subject it tackles; instead, its valuable contribution is more conceptual, raising issues and ideas that have led to a huge research literature. The key issue in various markets for healthcare services—insurance, physicians' and surgeons' services, pharmaceuticals, for example—is information, and specifically, its asymmetry. Some individuals have greater information about some good or service than others: individuals know more about the habits that affect their health than do insurance companies, doctors have more precise diagnoses of diseases than do patients, and so on. This leads to failure of a key requirement for the operation of a perfect market, namely that the transacting parties both know the precise details of specification of the good or service they are supplying or purchasing. The resulting market imperfections or failures can be classified in two broad categories, which have come to be labelled (although sometimes not fully appropriately) moral hazard and adverse selection. Moral hazard means that the existence of a market for risk-bearing affects individual behavior; for example, the availability of insurance can lead people to take excessive risks so long as the insurer cannot observe or access this information. Adverse selection means that the existence of a market with asymmetric information selectively attracts those users or suppliers who stand to need that facility the most; for example, the existence of a market for used cars selectively attracts sellers with cars of poor quality, so long as the quality is not symmetrically observable to potential buyers. Arrow offers several thoughtful remarks and some mini-models on markets, and (importantly and novel for that time) non-market institutions. When this paper was published, guilds were viewed by economists as collusive institutions that enabled professions to monopolize their markets. Arrow shifted our understanding of the place of guilds and professional associations. He showed that they are also a means of guaranteeing product quality.[12] But in this paper, Arrow was perhaps too far ahead of the ripe time for progress of research on the economics of information. It was only in the 1970s that the field surged ahead, with ideas about the design of optimal incentive schemes to affect behavior and control moral hazard, and screening and signaling to elicit and convey private information correctly and credibly. Many economics Nobels have been awarded for these contributions, with perhaps more to come.

A problem of great practical relevance involving time and uncertainty is the evaluation of public investments; today it has acquired even greater importance and urgency in view of climate change and other ecological challenges facing humanity. Arrow contributed to our understanding of many issues in these arenas. The most notable publications are the book with Mordecai Kurz and a paper with Robert Lind.[13,14] The Arrow-Kurz book begins with an overview of the essential new features of public investment in contrast with private investment: first, the former is mostly in projects to provide public or collective goods, the returns to which cannot be fully recaptured in markets, and second, the government should be a trustee for the public interest, including that of generations to come and otherwise underrepresented citizens, which is not adequately (or at all) reflected in market prices. In addition, public investments share, or add to, the general problems of uncertainty and the inadequate or asymmetric information that create market imperfections. The book then formulates these issues in the framework of optimal growth theory, which at the time of their writing was quite a new innovation. This resulted in several useful prescriptions for policy, especially clarifying how the threshold return for evaluating public investments depends on other aspects, such as the prevailing income tax policy. An even more striking result comes from the Arrow-Lind paper: if the uncertain return to the public project is statistically independent of the uncertainty in GDP as a whole, and the uncertainty is shared over the whole population, then the total cost of risk-bearing for the economy (not just the per capita cost) goes to zero as the size of the population increases. (Very loosely and heuristically, when each person bears $(1/n)^{th}$ of the risk, his/her cost of risk-bearing is proportional to the variance and therefore to $1/n^2$, so the total cost for the economy is proportional to $1/n$.) Therefore public investments whose costs are widely shared should ignore uncertainty and be valued using the risk-free rate of time-discounting. Using this lower rate of discounting raises the relative importance of the future and can justify several investments that otherwise might have seemed too remote or contingent. This result has generated a lot of controversy in the research literature, often focusing on conditions where and reasons why it would not hold, but it stands as the central point of departure for these debates.[15]

In his mid-to-later years, Arrow became committed to the view of economic systems as complex adaptive systems, and to the linkages between economic and environmental systems. As already mentioned, with Brian Arthur, he created the economics program at the Santa Fe Institute, as evidenced through their collaboration on path dependence in the economy, reflected in the book by Arthur with a foreword by Arrow.[16] And, also as mentioned earlier, he gave his full support to Karl-Göran Mäler and Partha Dasgupta in building the Beijer Institute, the leading institution bringing together mainstream economists and ecologists in the quest for creating dialogue and a new discipline.[17,18,19] With Paul Ehrlich and one of us, he brought these perspectives together in a paper in honor of Dasgupta.[20] He was active on a variety of panels on these topics, including his chairmanship of the Advisory Panel for Extending the Cure, a major effort led by the economist Ramanan Laxminarayan to address the overuse of antibiotics.[21] The Beijer Institute hosted annual meetings of its core groups under spartan conditions on the Swedish island Askö, and Arrow rarely missed these, taking part in deep discussions and jovial repasts and leading to a large number of collaborations with ecologists. A major focus was always sustainable development, and he took part in on some two dozen policy briefs and scientific papers on the topic, mostly emerging from those meetings.

His commitment to environmental issues was in part driven by his concerns about equity, both intragenerational and intergenerational, and his belief that markets were ill-equipped to deal with the social costs and externalities of our societal activities. He was at heart a utilitarian. As Partha Dasgupta has pointed out to us,[22] Ken's own brand of utilitarianism rested on individuals' expressed preferences, a utilitarianism embedded in a democratic wrapper.[23]

Early in his career, Arrow made a number of important contributions to the emerging field of operations research. Perhaps the most notable and lasting of these was on optimal inventory policy. Managing the stock of inventory in the face of fluctuating or uncertain demand requires balancing two types of costs: ordering costs, which are largely independent of the order size, and carrying costs, which are mostly proportional to the amount of the stock. In joint paper with Theodore Harris and Jacob Marschak,[24] Arrow proved the optimality of a policy that places an order only when the stock falls below a level s, and then orders enough to bring it up to a larger level S. Both of these target levels can be calculated as functions of the underlying parameters of the problem, such as the rate of demand flow, the penalty for running out, and the time-discount or interest rate. A proof of optimality of this policy under much more general conditions would come from Herbert Scarf.[25]

In 1947, Ken married a fellow research associate, Selma Schweitzer, with whom he had his two sons, David, an actor and writer, and Andrew, also an actor. Selma, who produced work on input-output projections and other topics while at the Rand Corporation, went on to train as a psychotherapist, and continued to practice from her apartment into her 80s, even as her eyesight succumbed to macular degeneration, until her death in 2015. His younger sister Anita Summers also had a distinguished career and is an emerita professor at the Wharton School, University of Pennsylvania. Anita's

husband Robert Summers (also a professor at the University of Pennsylvania, and incidentally, brother of the famous economist Paul Samuelson) did pioneering work on international comparisons of standards of living, and developed indexes of purchasing power parity that are widely used when comparing gross domestic products of countries. Her son, Lawrence Summers, Ken's nephew, also a distinguished economist, was president of Harvard and Secretary of the U.S. Treasury.

Kenneth Arrow reshaped economics, through his own work, through his mentorship of so many others, through his inspiration of generations of others, and through his encouragement and support for young economists and other scientists throughout the world. His thirst for learning and for contributing to making a better world for all, and his ability to contribute to so many disciplines, created a model that can serve as an inspiration for many, but is unlikely to be matched by any. His loss is immeasurable, but his influence lives on in the pieces of him that so many carry with them. Ken Arrow is survived by his two sons, David and Andrew, and by his sister Anita.

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References

1 Arrow, K. J. 1951. *Social Choice and Individual Values*. New York: Wiley.

2 Arrow, K. J. 1951.

3 Arrow, K. J., and G. Debreu. 1954. Existence of an equilibrium for a competitive economy. *Econometrica* 22:265–290.

4 Arrow, K. J. 1962. The economic implications of learning by doing. *Rev. Econ. Stud.* 29:155–173.

5 Romer, P. 1994. The origins of endogenous growth. *J. Econ. Perspect.* 8:3–22.

6 Spence, A. M. 1981. The learning curve and competition. *Bell J. Econ.* 12:49–70.

7 Dasgupta, P., and J. Stiglitz. 1988. Learning by doing, market structure and industrial and trade policies. *Oxf. Econ. Pap., New Series* 40:246–268.

8 Arrow, K. J., H. B. Chenery, B. S., H. B., Minhas, B. S., and R. M. Solow. 1961. Capital-labor substitution and economic efficiency. *Rev. Econ. Stat.* 43:225–250.

9 Arrow, K. J. 1970. *Essays in the Theory of Risk-Bearing*. New York: Elsevier.

10 Arrow, K. J., and S. A. Levin. 2009. Intergenerational resource transfers with random offspring numbers. *Proc. Natl. Acad. Sci. U.S.A.* 106:13702–13706.

11 Arrow, K. J. 1963. Uncertainty and the welfare economics of medical care. *Am. Econ Rev.* 53:941–973.

12 Dasgupta, P. *Kenneth Arrow on Public Goods, Public Policy, and Environmental Economics.* Econometrica Society, September 18, 2017; https://www.econometricsociety.org/uploads/inmemoriam/arrow_dasgupta.pdf.

13 Arrow, K. J., and M. Kurz. 1970. *Public Investment, the Rate of Return, and Optimal Fiscal Policy.* Baltimore: Johns Hopkins Press for Resources for the Future.

14 Arrow, K. J., and R. C. Lind. 1970. Uncertainty and the evaluation of public investment decisions. *Am. Econ. Rev.* 60:364–378.

15 Dasgupta, P. 2017.

16 Arthur, W. B. 1994. *Increasing Returns and Path Dependence in the Economy*. Ann Arbor: University of Michigan Press.

17 Arrow, K., et al. 1995. Economic growth, carrying capacity, and the environment. *Science* 268:520–521.

18 Arrow, K., et al. 2004. Are we consuming too much? *J. Econ. Perspect.* 18:147–172.

19 Söderqvist, T., A. Sundbaum, C. Folke, and K. G. Mäler, eds. 2011. *Bringing Ecologists and Economists Together: The Aksö Meetings and Papers*. Dordrecht: New York: Springer.

20 Arrow, K. J., P. R. Ehrlich, and S. A. Levin. 2014. Some perspectives on linked ecosystems and socio-economic systems. In: *Environment and Development Economics: Essays in Honor of Sir Partha Dasgupta*, eds. S. Barrett, K. G. Mäler, and E. S. Maskin, pp. 95–116. Oxford: Oxford University Press.

21 Laxminarayan, R., A. Malani, D. Howard, and D. L. Smith. 2007. *Extending the Cure: Policy Responses to the Growing Threat of Antibiotic Resistance.* Washington, D.C.: Resources for the Future.

22 Dasgupta, P. 2017.

23 Arrow, K. J. 1974. T*he Limits of Organization (Fels Lectures on Public Policy)*. New York: W. W. Norton and Company.

24 Arrow, K. J., T. Harris, and J. Marschak. 1951. Optimal inventory policy. *Econometrica* 19:250–272.

25 Scarf, H. 1959. The optimality of (*S*,*s*) policies in the dynamic inventory problem. In: *Mathematical Methods in the Social Sciences*, eds. K. J. Arrow, S. Karlin, and P. Suppes, pp. 196–202. Palo Alto: Stanford University Press.

Selected Bibliography

1951 *Social Choice and Individual Values.* New York: John Wiley and Sons.

With T. Harris, and J. Marschak. Optimal inventory policy. *Econometrica* 19:250–272.

1954 With G. Debreu. Existence of an equilibrium for a competitive economy. *Econometrica* 22:265–290.

1961 With H. B. Chenery, B. S. Minhas, and R. M. Solow. Capital-labor substitution and economic efficiency. *Rev. Econ. Stat.* 43:225–250.

1962 The economic implications of learning by doing. *Rev. Econ. Stud.* 29:155–173.

Selected Bibliography (cont.)

1963 Uncertainty and the welfare economics of medical care. *Am. Econ. Rev.* 53:941–973.

1970 *Essays in the Theory of Risk-Bearing.* New York: Elsevier.

With M. Kurz. *Public Investment, the Rate of Return, and Optimal Fiscal Policy*. Baltimore: Johns Hopkins Press for Resources for the Future.

With R. C. Lind. Uncertainty and the evaluation of public investment decisions. *Am. Econ. Rev.* 60:364–378.

1995 With B. Bolin, et al. Economic growth, carrying capacity, and the environment. *Science* 268:520–521.

2004 With P. Dasgupta, et al. Are we consuming too much? *J. Econ. Perspect.* 18: 147–172.

2009 With S. A. Levin. Intergenerational resource transfers with random offspring numbers. *Proc. Natl. Acad. Sci. U.S.A.* 106: 13702–13706.