Jerry R. Green (1946-)[1]

by Eddie Dekel,[2] John Geanakoplos,[3] and **Scott Duke Kominers[4]**

Introducing Jerry Green

The origin of Jerry Green's unbounded intellectual curiosity dates back to his childhood and teenage years in New York City. Classes and lectures at the Museum of Natural History and the Hayden Planetarium filled his Saturdays from early on thanks to his mother's nurturing of his talents. He studied at Stuyvesant High School which specialized in math and science and was – and still is – one of the best high schools in the city. While in high school he participated in a special program that enabled him to take classes at Columbia University, where he studied formal logic, quantum mechanics, and genetics. Despite all this advanced work, Jerry graduated high school at the young age of 16. As this chapter will demonstrate, he continued to be an "early starter" in his later years, with much of his research introducing new ideas years – and even decades – before the rest of the profession caught up. In any case, all these early studies stimulated his interests in math and science and, as he says, provided experiences that gave him "the confidence to believe that by dint of hard work I could learn and appreciate very advanced material" (Jerry Green's personal correspondence).

This curiosity and interest in understanding the world continue to motivate and underpin Jerry's work and life today. One of his defining characteristics is his deep interest in the work of others as well as excitement about his research. Another is his modesty about his own contributions which derives from his perspective that "knowledge evolves only slowly" (Jerry Green's personal correspondence) through small steps taken by many. This pure seeking of knowledge is why through his roles as a teacher, advisor, colleague, and researcher he has had significant impact on the world of economics, and thereby has had an indirect, but profound, impact on our society.

After high school, Jerry went to the University of Rochester where he majored in mathematics. He stayed in NY state due to a requirement of grants he received that were important for financing his education. Another feature of Rochester that attracted him was that it was a co-ed

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school, unlike his high school and Columbia. While at Rochester, he fell in love with economics after participating in a second-year graduate seminar in economic theory. Jerry was invited by Professor Emmanuel Drandakis to join this seminar even though he was only a junior at the time. This, and Professor Drandakis's support and encouragement throughout the seminar, was a key force in Jerry eventually to pursuing academic economics as a career. This seminar was usually led by Professor Lionel McKenzie, who also played a key role in Jerry's academic career, inspiring him to stay at Rochester to pursue his PhD in economics and then becoming his thesis advisor.

During the summer after his second year in graduate school, Jerry participated in a seminar on economic theory organized by the Rand Corporation. The seminar – organized by Lloyd Shapley and attended by two other future Nobel laureates Robert Aumann and Gerard Debreu – revolved around a central topic in economic theory at the time: the core. As most readers of this chapter will know, the core is the set of outcomes for the economy that cannot be overturned by the action of any group of people and, in that sense, represents the set of potential steady states of an economy. Jerry was troubled by the narrow focus on steady states without asking how they are reached. He therefore began to research dynamic equilibration processes, and explored when they would lead to core outcomes. This is the first of many instances of Jerry's being a pioneer, in this case exploring the study of transitional dynamics in economic markets when beforehand the discipline had focused on static descriptions of equilibrium. Jerry proved that a large class of stochastic adjustment processes, which are derived from rational actions of market participants as they try to change the state for their own benefit, would converge to a steady state in the core, while deterministic processes may, to the contrary, cycle.

After finishing this work, he followed McKenzie's encouragement and submitted his thesis in his third year of graduate school, at age 23(!), and applied for jobs that winter. He received several enticing offers but the decision boiled down to going to Berkeley, where Gérard Debreu was the leading theorist, or Harvard, where Ken Arrow was present. Arrow's breadth of interests outside of theory attracted Jerry and led him to join Harvard. Possibly for similar reasons, it was around this time that Harvard was able to recruit other junior faculty members such as Truman Bewley, Michael Rothschild, and Michael Spence.

After one year as a member of the Harvard Economics Department, Jerry visited the Centre for Operations Research and Econometrics (CORE) in Belgium, for the fall term of 1971, as they were having a long-planned special year devoted to economic theory at that time. He was seeking to gain some further experience prior to immersing himself in the large and world-class economics department at Harvard. This stay in Europe would turn out to be another key moment in Jerry's career as it was then that he serendipitously met and subsequently started collaborating with his long-time coauthor and friend Jean-Jacques Laffont.

Upon his return to Harvard in 1972, Jerry launched a graduate seminar in economic theory, which was attended by Bob Cooter, George Feiger, Elchanan Helpman, and Eric Maskin – who was a senior at the time – and, of course, Laffont. Laffont had courageously left an assistant professor position to become, with Jerry's support, a graduate student in Economics at Harvard. Maskin's participation as an undergraduate was the first among many undergraduates whom Jerry invited to his graduate seminar over the years, perhaps partially in recognition of the important role that Professor Drandakis' invitation played in his own development. This remarkable experience set a high benchmark: In Jerry's own words, after decades of interacting and running reading groups with outstanding graduate students, and advising over one hundred PhD students, "there was never again anything quite like 1972" (Jerry Green's personal correspondence). Also in 1972, he became associate editor of the Quarterly Journal of Economics (QJE) and was in charge of handling all papers with formal mathematical analysis. This was precisely the period in which QJE began to transition into publishing papers that used mathematics, such as Rothschild and Stiglitz (1976).

Before turning to Jerry's research that eventually grew out of this seminar, especially his joint work of over thirty years, 1973-2004, with Laffont, it is insightful to understand his development and influence as an economist through his teaching. Jerry's first teaching assignment when he arrived at Harvard was to give lectures in Economics 2010, the required first-year course in microeconomic theory for students in the Economics and the Business Economics PhD programs. He has continued to be involved with this course ever since. He took over as course head in 1976, and as it was lacking a standard textbook in microeconomics with which to structure the class, he produced a set of notes for the course that would circulate in the department into the 1980s. Around that time, Andreu Mas-Colell and Mike Whinston joined Harvard and began to teach Economics 2010 together with Jerry. This collaboration led them to collaborate on a textbook, culminating in the 1995 publication of the well-known "Microeconomic Theory" (Mas-Colell, Whinston, and Green) – often known colloquially by the initials of the authors, "MWG." This book quickly became the leading text for graduate microeconomics courses throughout the world and continues to shape graduate students' understanding of microeconomics today, 25 years after its publication.

As one would expect from Jerry, during the 25 years before publishing "Microeconomic Theory," and in the 25 years since, he has continually guided the evolution of the course material so as to be current, challenging and inspiring to the incoming students. Even on a topic that has lasted throughout – Arrow's impossibility theorem – the emphasis has changed significantly to practical issues like the computability and manipulability of voting systems, and the more practical flaws and advantages of various systems. Of course, another shift has been the addition to the curriculum of game theory, incentive theory, mechanism design, and related topics. What is now taught in those topics is indeed based on the pioneering work of Jerry and Laffont, among others, and the important subsequent developments. He also makes sure to mention (albeit briefly due to time constraints) the intellectual origins of the theory being taught. Finally, consistent with his desire to contribute to the growth of knowledge, Jerry continues to produce slides, problems, examples and lecture notes to supplement the book, all of which are available to anyone who asks. At this point, the reader will not be surprised to learn that Jerry donates all his royalties from the book to Harvard, feeling that the book benefited so much from his teaching of the students there.

Jerry has engaged in many activities, in addition to his teaching and research, many focusing on supporting the growth of scholarship at Harvard. One important example is his work as Senior Fellow of the Harvard Society of Fellows, where he participates every year in the demanding process of selecting the incoming cohort of Junior Fellows (a three-year postdoc position that draws applicants across all fields of scholarly inquiry). This contributes to his personal goals of supporting excellent research and expanding his own learning within and beyond economics through reading the work of the excellent nominees and through interacting with the Junior Fellows and the other Senior Fellows. Jerry also served as Provost of Harvard, and was chair of both Harvard's Economics Department and its PhD program in Business Economics – the latter which he reworked dramatically, creating what is now widely recognized as one of the best such PhD programs. He has been a visitor at numerous economics departments, served on many committees, is a fellow of various prestigious academic societies, and served on editorial boards of leading journals. Yet another significant, and quite different, contribution of Jerry to the Harvard community was that he served as chair of the Faculty Committee on Athletic Sports for over a decade.

Someone who would only know Jerry through his graduate microeconomics textbook or his research might well be surprised to learn that he was head tutor of the Environmental Sciences and Public Policy concentration (major) at Harvard which he co-founded, and that he has taught freshman seminars numerous times (on behavior in high-risk situations) and is on the Freshman Seminar Committee. Once again, we see his breadth of interest in economics and his desire to pass on knowledge. Consistent with this, Jerry responded to numerous student requests by creating a PhD course, with the help of guest lecturers, on the history of economic thought. At the undergraduate level, meanwhile, he has created a course "Great Theorems of Microeconomic Theory" that brings together the history of economic thought with deep mathematics.

Having understood Jerry’s evolution in his teaching and development of economics at Harvard, it is time to turn to his research. Too vast to be discussed comprehensively in this document, Jerry’s research has covered many topics and has influenced economic thought extensively within – and also beyond – the field of microeconomic theory. The subsequent sections discuss, with a bit more detail, some of Jerry's key papers, as well as of course his book with Laffont. In the remainder of this Introduction, we review Jerry's work from a bird’s eye view.

One example of Jerry's influential and pioneering work is his early research in **general equilibrium theory and rational expectations equilibrium,** elaborated on below. Within this area, the first paper that he wrote (Green (1973a)) extended the notion of temporary equilibrium with exogenous expectations in Jean-Michel Grandmont’s (1971, 1977) work to allow for the possibility that agents trade futures contracts and face uncertainty when forming beliefs about future prices. He proved the existence of equilibrium. In his paper of 1977 (Green (1977a)), Jerry replaced the exogenous expectations with rational expectations. Prices then determine the terms of trade and simultaneously communicate information. Here, he showed that under some reasonable conditions – namely, the dimensionality of the variables about which traders face uncertainty is equal to the number of markets – an equilibrium may fail to exist on a dense, full measure set of underlying parameters. This finding by Green continues to pose a challenge for the validity of many rational expectations models used in macroeconomics and finance, which are non-robust in the sense that they rely on knife-edge assumptions.

Jerry’s collaboration with Laffont on **incentive theory** led to seminal contributions which reshaped our understanding regarding how efficiency can be obtained by a central planner who has to elicit information from agents who act strategically to benefit themselves. Green and Laffont (1977) characterized the complete class of mechanisms that solve this problem, which they show must be variants of *VCG mechanisms* – which they named for William Vickrey, Edward H. Clarke, and Theodore Groves, who had first developed them. Green and Laffont (1977) also provided conditions on the environment under which the method succeeds. The importance of this work cannot be overstated – it is the building block of subsequent decades of research on what later became known as *mechanism design*. As the detailed discussion later in this chapter explains, this body of work is a prime example of Jerry’s work influencing and predating work by others by years and decades.

His seminal work with Nancy Stokey (1983) is also discussed in more detail below. They compared in full generality tournaments and contract schemes for incentivizing labor effort, extending the work of Edward Lazear and Sherwin Rosen (1981). This is Jerry’s most cited paper, and it provided the foundation for much subsequent work (Oliver Hart and Bengt Holmström (1987), James Malcolmson (1999)).

As part of another long-time collaboration, with Nancy Stokey, Jerry coauthored a pair of papers on **the value of information and information design**, with a special focus on what would later become known as *sender-receiver games.* Green and Stokey (1978, 2007), contemporaneously with Vincent Crawford and Joel Sobel (1982), formalized the study of situations in which one player (the sender) has information about a payoff relevant state and communicates using non-verifiable messages with another player (the receiver) who later takes an action. In settings in which the sender's and the receiver's preferences are not fully aligned, the question arises as to what the scope for the sender to credibly communicate with the receiver is, and how communication affects equilibrium outcomes. Again, the body of work that followed these contributions is enormous.

Inspired by the example set by Arrow, Jerry's research did not remain confined to the realm of economic theory, and he worked on practical economic problems and the applicability of the theories that he helped develop. This led him to work in **health economics, public finance and taxation, law and economics,** and **empirical macro and finance**, some of which is discussed in more detail in subsequent parts of this chapter. Jerry worked with a group of 35 researchers on a book, *Costs, Risks and Benefits of Surgery* (John Bunker, Benjamin Barnes, and Frederick Mosteller (1977)), that combined different data sources on surgeries to systematically analyze the outcomes (Green (1977b)). A retrospective appraisal of the book in the *Journal of the Royal Society of Medicine* (Klim Mcpherson and Bunker (2007)), 30 years after its publication, called it "one of the most influential books on health services and health care policy" because of "interplay of conceptual, analytical, and mathematical approaches to the subject." With Martin Feldstein and Eytan Sheshinski, Jerry worked on public finance and taxation (Feldstein, Green and Sheshinski (1978, 1979), Feldstein and Green (1983)).

In Green (1976), he studied liability law, and with Suzanne Scotchmer he wrote several papers on patent law (Scotchmer and Green (1990), Green and Scotchmer (1995)). Earlier work in economics on patents focused on its role in providing incentives for one-shot innovations (Richard Gilbert and Carl Shapiro (1990), Paul Klemperer (1990)). This direction, initiated by Scotchmer (1991) in her influential paper "Standing on the Shoulders of Giants,"[5] opened the door to studying the interaction between patents for a given innovation and its effect on other R&D – specifically sequential and cumulative innovation.

As we also discuss later in this chapter, John Shoven and Jerry (Green and Shoven (1986)) had the seminal insight to explore the endogeneity of mortgage prepayment decisions, preceding by

[5] The title "Standing on the Shoulders of Giants" goes back to the Middle Ages, but everyone thinks of it as originating with Isaac Newton (1675).

years a revolution within the mortgage industry around this issue. This paper further illustrates Jerry's breadth of style and interests because it combines his normal path breaking theoretical-mathematical insight with a proprietary data set and fairly advanced applied empirical techniques to estimate parameters in the prepayment function.

Another area of theory to which Jerry contributed is **decision theory / behavioral economics** (Green (1987), Green and Bruno Jullien (1988)). In the first of these papers Jerry examined the extent to which “Dutch book,” or “money pump” arguments can be used against individuals whose preferences violate the famous (von Neumann–Morgenstern) independence axiom. Such arguments – whereby anyone with certain preferences is vulnerable to having wealth being taken away from them by being offered a sequence of myopic “improvements” – were informally used to justify “rational” (expected utility) preferences; Jerry’s work formally showed the limitations of this argument. The second paper, with Jullien, provides an axiomatization of functional forms for choice over real-valued consequences in a class of preferences more general than EU. The axiom they provide has a compelling intuition, which is that preferences over two distributions F and G should be independent of what happens at the tail of the distributions whenever the tails of F and G are equally distributed.

More recently (Green (2005), Christopher Chambers and Green (2005)), Jerry has worked on a novel version of the classical **social choice** problem of Arrow (1951), but with the twist that after a social choice is made, the agents can transfer utility among themselves. Unlike in the original Arrow problem, Jerry showed that there are solutions satisfying reasonable axioms. John Nash (1950) had found a unique solution, but in a context in which players had threats they could make. Jerry’s work on social choice with transfers had its origins in Green (1983) and in his 2005 paper he characterized the solution for two players. He showed with Chambers (2005) that with more than two players, the axioms Green originally proposed lead to a large multiplicity of solutions. He is still at work looking for an additional axiom to pin down a unique solution. Related to this normative work on bargaining theory, Katherine Baldiga (Coffman) and Green (2013) brought a novel decision-theoretic perspective to social choice, as we also discuss in a bit more detail below.

This exceptionally brief summary of Jerry’s life and work amply demonstrates several remarkable features of this influential economist. As a teacher, advisor, and colleague, Jerry's broad interests, devotion to supporting the institution and students, and contribution to the growth and spread of knowledge are all outstanding. As a scholar and researcher, his curiosity, breadth, and above all innovative perspective repeatedly led him to questions and seminal research papers that influenced subsequent work greatly, and often predated it significantly. It’s an honor for us to be able to write this chapter reflecting on Jerry’s extraordinary contributions to economics.

Exploring Jerry Green's Research

General Equilibrium

Prices and Information in General Equilibrium: Temporary Equilibrium

Jerry's work in pure general equilibrium centered on the complications created when prices convey information and simultaneously define the terms of trade. In this he was a pioneer. This work benefitted from his complete mastery of the then new convexity and fixed-point methods used to prove the existence of equilibrium.

John Hicks (1939) and J. M. Grandmont (1971) invented *temporary equilibrium*, in which agents must act today on the basis of their (exogenous) expectations about the future, which might themselves be influenced by what is happening today. Jerry made the first important theoretical advances on the questions of the existence and efficiency of temporary equilibrium, and then (after Roy Radner) on *rational expectations equilibrium*, in which the expectations are not exogenous but correct.

Jerry considered a world today of k_1 commodities and k_2 futures contracts, with corresponding prices p_1 and p_2. Each futures contract promises one unit of one of the k_2 commodities tomorrow. Each trader has fixed endowments of commodities today and tomorrow, and her own exogenous expectations, mapping prices (p_1, p_2) today to a probability measure $m(p_1, p_2)$ on the possible prices q of the k_2 commodities tomorrow. With these expectations, each trader acts to maximize her expected utility of consumption by choosing the best budget balancing trades of commodities and futures contracts today, as well as a plan of budget balancing trades of commodities tomorrow, contingent on the realized prices q and the futures contracts she has entered into today. She must have a plan that satisfies her budget constraint no matter which q in the support of her expectations materializes. Jerry defined equilibrium as any prices (p_1, p_2) that lead to maximizing choices for every individual and that collectively clear today's commodity markets and futures markets. He did not require market clearing tomorrow (hence the name temporary equilibrium).

In his 1973 Econometrica paper "Temporary Equilibrium in a Sequential Trading Model with Spot and Futures Transactions" (Green (1973a)), Jerry showed how existence of equilibrium can be guaranteed with the right hypotheses on how price expectations behave. Jerry posited that the expectations map from prices to measures is continuous. However, he observed that this is far from sufficient to guarantee existence.

If for example (p_1, p_2) is mapped into a single point q with probability 1, where q is not a scalar multiple of p_2, then there is an arbitrage opportunity, and demand will not be defined. For example, suppose the futures price $p_{2,a}$ of an apple is 1, the same as the futures price $p_{2,b}$ of a banana. Suppose, however, that the spot price of apples q_a is expected to be 1 for sure, while the spot price of bananas q_b is expected to be 2 for sure. By selling y apple futures and buying y banana futures, any agent can satisfy her budget constraint today, since $-1 \times y + 1 \times y = 0$. Yet tomorrow the agent will have $-1 \times y + 2 \times y = y$ dollars free and clear. This arbitrage shows that demand cannot be well-defined.

Jerry assumed that agents are never sure about the future, so that the support of $m(p_1, p_2)$ always has non-empty interior. With that assumption, he showed via the separating hyperplane theorem that demand is well-defined at any strictly positive (p_1, p_2) – or equivalently, does not permit arbitrage – if and only if the normalized futures prices $q = \frac{p_2}{|p_2|}$ lie in the interior of the convex hull of the support of $m(p_1, p_2)$. Jerry then assumed that the set of (p_1, p_2) that do not permit arbitrage, given the expectations mapping m, is non-empty, convex, and open.

Finally, he assumed that there is some commonality of expectations: the intersection of every agent's set of non-arbitrage prices (p_1, p_2) is non-empty, and therefore, as a finite intersection, convex and open. With these assumptions, plus the usual assumptions about the concavity and continuity and strict monotonicity of agent vNM utilities, he showed that equilibrium must exist.

The result is by no means obvious, because the limitation to the (perhaps small) set of common non-arbitrage prices seemingly limits the flexibility of the price system to balance supply and demand. Nevertheless, Jerry shows that as prices get near the boundary of the common non-arbitrage price set, somebody's demands must go to infinity. So even though the set of non-arbitrage prices might be small, it allows enough price variation to induce all the demand variation necessary to prove existence of temporary equilibrium.

In a follow-up paper (Green (1974)), Jerry worked with the same framework of commodities and futures, but he took a great leap and allowed for default. Since agents do not know for sure what prices will prevail at time 2, it is natural to suppose that they might make futures trades at time 1 that will force them into bankruptcy at time 2. Since his framework did not require market clearing at time 2, Jerry incorporated the effect of default on market clearing into time 1 by extending his framework to agents who begin with exogenous debts (denominated in commodities) and ownership of exogenous promises from others (again denominated in commodities), as well as the usual endowments of commodities.

In order to maintain perfect competition and the idea that everybody trades with an anonymous market, not with individuals, Jerry supposed that all debts are pooled. Thus an agent who owns the fraction f of all the apple promises gets delivered the same fraction f of all the apples actually delivered. This rather profound notion of pooling went virtually unnoticed in the literature until it was taken up by Pradeep Dubey, John Geanakoplos, and Martin Shubik (1989, 2005). Jerry went on to envisage that debts might be owed to individuals, as the result of bilateral contracts. These bilateral debts are effectively the same as pooled debt provided that each creditor is owed the same fraction of each debtor's apple promises, and so on.

Jerry also had to worry about the motivation to deliver anything on the promises. He assumed that every agent is forced to keep as many promises as she can, defaulting by the same percentage on every promise if her wealth is less than her debts.

These rules on what people deliver, and how the deliveries are divided among the promise holders, are not obviously consistent or uniquely defined, because what agent i delivers depends on what the market delivers to i, which depends on what i delivers to the market. Surprisingly, by constructing a fixed-point map that necessarily has a unique fixed point, Jerry showed that indeed for any given prices, consistent deliveries exist and are uniquely defined.

Jerry also imagined a disutility for defaulting. This does not affect default in period 1, since all the promises have already been made. The disutility of default in period 2 leads agents to curtail reckless selling of futures in period 1. However, the disutility of default coupled with the mandatory delivery of as much as possible creates non-concave payoffs. Two years later in 1977, Martin Shubik and Charles Wilson imposed a similar disutility of default but allowed agents to choose to default and pay the penalty, even if they had wealth enough to pay, thereby restoring the concavity of the utility. Despite the non-concavity, Jerry was able to prove that with a continuum of agents, temporary equilibrium always exists even with default, under the same conditions described earlier.

Prices and Information in General Equilibrium: Rational Expectations Equilibrium

In two more papers with the same framework of commodities and futures (Green (1973b, 1977a)), Jerry dropped the possibility of default and exogenous debts, but he took the big step of replacing the arbitrary exogenous expectations of temporary equilibrium with rational expectations.

The central conceptual issue in rational expectations equilibrium is that a rational agent i must recognize that other agents might know information that would affect i's desired trades. Presumably that information affects their trades – and thus the prices. Hence the rational agent i should try and work backward to deduce their information from the prevailing prices before trading. Prices thus define the terms of trade and at the same time convey information that affects desired trades. Jerry showed that these two roles for prices might be incompatible.

More formally, Jerry allowed each agent i to get a signal s_i about the objective probabilities $m(s) = m(s_1, \ldots, s_I)$ of future states q of the world. Unlike in the temporary equilibrium model, agent i's beliefs are not exogenous, but depend on her signal and potentially on others' signals.

Rational expectations equilibrium is a *function* $(p_1(s), p_2(s))$ of the entire vector $s = (s_1, \ldots, s_I)$ of signals for all agents $i \in I$. Knowing this function, however, each rational agent i infers as much as she can from any realized price vector (p_1, p_2) about what the other agents' signals might have been, thus acting on the probability $m_i = E[m(s_1, \ldots, s_I)|s_i, (p_1, p_2)]$.

Radner (1966) had already formulated a similar definition of rational expectations equilibrium with a finite number of possible signals, highlighting the informational role of prices. Jerry had not seen this because it was published in Econometrica in French, though as Jerry said, that is hardly any excuse since he reads French. Radner also observed that a tiny change in price might discontinuously change the inference agents make about the other agents' signals, which he speculated could cause a non-existence of equilibrium. For example, when $(p_1(s), p_2(s)) = (p_1(t), p_2(t))$, nothing is learned from prices about whether signals s or t have been seen. If $(p_1(t), p_2(t))$ moves by the tiniest amount, the prices suddenly reveal that one or the other of the signals s, t has not occurred.

Radner (1979) used the concept of a full-information equilibrium to prove that generically, with a finite state space, rational expectations equilibrium must exist despite this discontinuity. In a full-information equilibrium, every agent is given all the signals of every agent, leading to a full-information equilibrium price function $(p'_1(s), p'_2(s))$. With only a finite number of signals, generically these full-information equilibrium prices are distinct across distinct signals. The full-information equilibrium price function would then be a fully revealing rational expectations equilibrium for the asymmetric signal economy because the prices alone would fully reveal all the signals.

In his 1973 paper, Jerry made an important conceptual advance by distinguishing signals s_j that might affect j's demand but would have no bearing on i's demand conditional on the price (such as idiosyncratic news about j's endowment of goods or j's utility), from news (such as about the future payoffs of durable goods) that would, if known, also affect i's demand for goods today. In a model with both kinds of news, when agent i observed a price fluctuation she might attribute most of it to the first kind of idiosyncratic news. Jerry suggested that this idiosyncratic news might attenuate the significance of the inferred signals and restore continuity to the demand functions, perhaps restoring the universal (not just generic) existence of equilibrium. He also thought this model was more realistic. He presented a class of models with independently fluctuating endowments in which rational expectations equilibrium must indeed always exist.

In his 1977 paper, Jerry shocked the profession by showing that in a modified version of his class of independently fluctuating endowments, there is a subset of examples in which rational expectations equilibrium (REE) of any kind, fully revealing or not, could not exist. For this class of examples defined by a space of parameters, the subset of parameters for which REE do not exist is dense and even of full measure. On the other hand, the subset of parameters for which equilibrium does exist is also dense. Jerry's expansion of the signal space to include idiosyncratic news, which he had at first regarded as a lever to guarantee the existence of rational expectations equilibrium, now could be seen as a reason why rational expectations equilibrium might robustly fail to exist. The discontinuity discovered by Radner does not go away, and the device of fully revealing equilibrium is powerless when there are as many or more dimensions of independent signals than prices. The upshot is that price-taking and rationality are not necessarily compatible; economists cannot ignore price formation mechanisms, in which agents do not know the final prices before they are forced to act.

Radner's early work and these two examples of Jerry's started a boom in the rational expectations literature that culminated in the proofs by Beth Allen (1981, 1982) that when the dimension of the price space exceeds the dimension of the signal space (as in Radner's case where the signal space had zero dimension), equilibrium must generically exist. James Jordan and Radner (1982) meanwhile generalized Jerry's examples by showing that whenever the signal space and the price space have the same dimension, neither the existence or nonexistence of rational expectations equilibrium is generic. When the state space has higher dimension than the price space, Jordan and Radner found a troublesome kind of rational expectations equilibrium that moves discontinuously when the economy is perturbed. These later authors took advantage of the methods of differential topology that Debreu introduced into economics in 1970, which Jerry did not. Nevertheless, to this day there does not seem to be a fully satisfactory resolution to the non-existence of rational expectations equilibrium puzzle Jerry raised in 1977.

Mechanism Design

Incentives in Public Decision-Making

One of Jerry's most influential contributions was *Incentives in Public Decision-Making*, a book joint with Jean-Jacques Laffont (Green and Laffont (1979)). This important work opens with a discussion of a central issue in economics: what mechanisms can obtain (as close as possible to) Pareto-efficient outcomes for a society? That is, can we design a rule specifying how decisions will be made, based on inputs from the individuals who constitute the society, regarding their private information (e.g., about their preferences), that will be (approximately) Pareto efficient? For this, the mechanism must elicit (either directly or implicitly) individuals' private information. However, individuals will typically have an incentive to strategically mis-represent or manipulate the mechanism in a way that benefits themselves. Can this tension be overcome? This question is particularly important for public decisions. Indeed, for environments such as exchange economies with private goods, the incentive to misrepresent is small when the economy is large (Donald John Roberts and Andrew Postlewaite (1976)), whereas the opposite is true for public decisions (Roberts (1976)).

This is the focus of *Incentives in Public Decision-Making*. As the authors say, they "study how privately held information can be elicited for public use, and the effect of the elicitation process on economic efficiency." Given the centrality of this question and the wide-ranging contributions in this book, it is not surprising that it provides crucial building blocks for chapters in the handbooks of experimental economics (John Ledyard (1995)), environmental economics (Sandeep Baliga and Eric Maskin (2003)), public economics (David Martimort, Philippe De Donder, and Etienne Billette de Villemeur (2005), Wolfgang Blümel, Rüdiger Pethig, and Oskar von dem Hagen (1986)), mathematical economics (Amartya Sen (1986)), and social choice (Salvador Barberà (2011)). Citations can be also found in many related surveys written in the fifty years since the publication of the book, most recently in the currently active research on dynamic mechanism design.

The starting point for studying this topic is the result due to Allan Gibbard (1973) and Mark Satterthwaite (1975) (and the related impossibility result due to Arrow) demonstrating the impossibility of solving this problem in general, and the contrasting possibility results of Vickrey (1961), Clarke (1971) and Groves (1973), commonly referred to now as VCG. These latter authors showed in particular contexts that the problem can be solved; specifically, that there is a mechanism in which it is a dominant strategy for individuals to report truthfully and in which the Pareto efficient public decision will be taken. This can be achieved using what Green and Laffont called "pivotal" mechanisms. In such mechanisms, the profile of reports determines the efficient decision and each individual is required to make transfers that depend on their own actions (their elicited private information) only insofar as they change, i.e., are "pivotal" in determining, the decision taken.

A major contribution of *Incentives in Public Decision-Making* is to characterize fully when such satisfactory mechanisms exist, that is, when there are mechanisms in which truth-telling is a dominant strategy and Pareto efficiency is achieved. Green and Laffont (1977, 1979) essentially showed that quasilinear preferences (in which each individual's preference over the public decision and money are additively separable) are necessary to successfully elicit the individuals' private information in dominant strategies and to obtain a Pareto efficient decision. Moreover, they showed that any mechanism that achieves this favorable result is what is now known as a VCG mechanism (a slight generalization of the pivotal mechanism).[6] In addition, they showed that an efficient, incentive-compatible mechanism cannot maintain a balanced budget – the total amounts collected from and paid to the individuals cannot be guaranteed to add up to zero (or to the total cost of the public project when it is costly). Identifying these two limitations – quasilinearity and failure of budget balance – is crucial for understanding when efficient and strategy-proof mechanisms can be successfully applied.

Green and Laffont were not only interested in the abstract theory they develop, beautiful as it is. Their goal in characterizing what is necessary to obtain Pareto efficient decisions was also driven by the desire to understand the usefulness of the model. They next used their characterization results to show the limitations of this approach for important economic problems. In their words, "It is unfortunate, however, that trying to use this idea in several highly desirable directions turns out to involve necessary contradictions to the assumptions used above." They considered three (related) applications to demonstrate the limitations.

First, they considered the income distribution as a public good, with the hope that the methods derived in this book might enable achieving a socially optimal income distribution in an incentive-compatible manner. Here agents have preferences over the distribution of transfers (payments) that all agents receive. Next, they built on the fact that a public project can be financed in different ways and the decision about which to use is also a public decision that one would want

[6] This result was in turn extended by Holmström (1979).

to choose optimally and incentive compatibly. In both of these environments, they used their characterization results to show that Pareto efficiency, unfortunately, cannot be attained.

Finally, they examined welfare criteria other than maximizing the sum of agents' utilities. This they studied in two ways. First, they showed that if one wants to maximize a weighted sum of individual utilities for given weights for each individual, then results previously established with the utilitarian objective function apply immediately: it is not possible to achieve information revelation, Pareto efficiency and budget balance. Next, they showed that if the weights society wants to use depend on unobservable characteristics of the agents – characteristics that must be elicited in an incentive-compatible manner – then this is impossible when the environment studied is suitably differentiable (see Green and Laffont (1979) Section 4.6.4 for details). This chapter is another example of Jerry's work with Laffont foreshadowing current research by decades – see, e.g., the work on redistributive market mechanisms by Piotr Dworczak ® Scott Duke Kominers ® Mohammad Akbarpour (2021), and Akbarpour ® Dworczak ® Kominers (2020).

Incentives in Public Decision-Making is remarkably comprehensive. It touches on a range of issues of both current and classical interest. Jerry and Laffont proved an impossibility result regarding coalitional deviations. They also considered maxmin strategies, foreshadowing the recent interest in mechanism design using this objective for players as a way of studying robustly optimal mechanisms (see, e.g., Alexander Wolitzky (2016)). They obtained a strong possibility result for the maxmin environment: not only can truth-telling and Pareto efficiency be obtained, but also budget balance.[7]

Jerry and Laffont also discussed the early work of Groves and Ledyard (1974) and of Leonid Hurwicz (1979) that started the very rich path of considering what can be achieved in Nash equilibria of the mechanism (rather than insisting on dominance solvability). In later parts of the book, Jerry and Laffont considered the fact that agents might need to invest resources to discover their private information, and how that can be incentivized. This is a topic that remains active through today (see, e.g., the Dirk Bergemann and Juuso Välimäki (2006) survey on information and mechanism design), and is one that Jerry continues to believe merits further research.

Another often cited part of the book focuses on large economies. Here Jerry and Laffont obtained results showing that, with large numbers, the limitations discussed above – namely budget imbalance, the necessity of quasilinearity of preferences, and the lack of robustness to coalitional deviations – can be partially resolved. They also introduced the potential of (optimally) sampling among the individuals. Large-market approaches like those Jerry and Laffont used have since become a mainstay of game theory for understanding everything from equilibrium efficiency and robustness (see, e.g., Jeroen Swinkels (2001), Guilherme Carmona (2004), and especially Ehud Kalai (2004) and the references therein) and the scale of manipulation incentives (see, e.g., Fuhito Kojima and Parag Pathak (2009), Eduardo Azevedo and Eric Budish (2019)) to matching with complementarities (see, e.g., Kojima, Pathak, and Alvin Roth (2013), Itai Ashlagi, Mark Braverman, and Avinatan Hassidim (2014), Yeon-Koo Che, Jinwoo Kim, and Kojima (2019),

[7] Their study is based on a mechanism due to Lester Dubins (1977).

Azevedo and John William Hatfield (2018), and Ravi Jagadeesan and Karolina Vocke (2022)). Meanwhile, the question of optimal sampling has become a significant focus in the literature on economics and computation (see, e.g., Richard Cole and Tim Roughgarden (2014), Jamie Morgenstern and Roughgarden (2015), Jason Hartline and Samuel Taggart (2019), Moshe Babaioff, Noam Nisan, and Aviad Rubinstein (2018), and Yannai Gonczarowski and Matthew Weinberg (2021)).

The last part of *Incentives in Public Decision-Making* gives an early study of how to incorporate concerns about bounded rationality into mechanism design. Specifically, Jerry and Laffont explored whether it is possible to ask agents to report less demanding information than a complete description of their preferences. They did so in a dynamic model, and asked whether one can obtain truth-telling and dynamically converge to the Pareto optimality we seek. The idea is to look at planning as a dynamic process in which local information about the direction of improvement is more accurate than (global) information about production possibilities that are not close to the current (known) production plan.[8] In this part of the book, Green and Laffont developed a dynamic process that achieves this goal -- optimality through local improvements -- using the VCG approach they explored throughout this insightful manuscript.[9]

This book (and the related 1977 paper) is at once a remarkable classic with seminal results and a first foray into topics that continue to be relevant and appear in current research.

Posterior Implementability

The challenge of identifying the right solution concept for mechanism design has been approached from various perspectives. Requiring dominance solvability, as noted above, is far more restrictive than Bayesian-Nash equilibrium. At the same time, it is a more robust concept. In an insightful Econometrica paper, Green and Laffont (1987) introduced a different solution concept, motivated by a novel form of robustness.

Their main motivation is one of timing: when do the agents commit to the mechanism? The perspective Jerry and Laffont bring is that only after agents finish communicating can they be committed to the mechanism. Therefore, since agents learn about what others have communicated by observing the outcome of the mechanism, the mechanism has to be robust to this additional information. This notion lies "in between" insisting that strategies be ex post optimal in the sense of being best replies to the full information being revealed to the players on the one hand, and that they constitute a Nash equilibrium (with no robustness to additional information being revealed) on the other. However, in sharp contrast to these other two notions, the revelation principle does not hold for posterior implementation. After all, the revelation

[8] Two early papers that discussed this issue – without the mechanism design framework needed to fully address it, and that inspired Jerry and Laffont – are those of Edmond Malinvaud (1971), and Jacques Drèze and Dominique de la Vallée Poussin (1971).

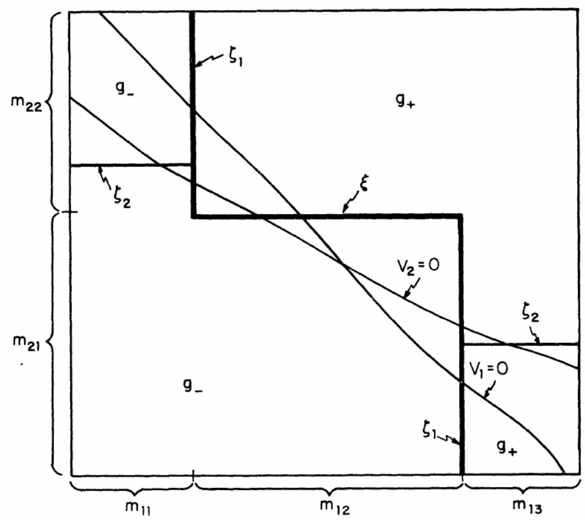
[9] Jerry continued this line of research in his paper with Francoise Schoumaker (1980), and others also followed up on the perspective due to Malinvaud (1971) and Drèze and de la Vallée Poussin (1971), including John Roberts (1979a, b), Claude Henry (1979), and Schoumaker (1976).

principle says that without loss of generality, agents can reveal all their information. In that case, their actions have to be robust to learning everything; posterior implementability only requires that they be robust to the information revealed *through the mechanism*. Put differently, unlike under the revelation principle, posterior implantability makes it possible to study the action spaces used for communication. This uncovers a novel tradeoff: richer communication mechanisms can help achieve efficiency, but coarser ones limit the information learned and hence are more robust. This ability to study the action spaces is one of the most interesting (and still underexplored) feature of this paper.

It might be useful to specify a bit of the formal framework. Two agents choose between a status quo, q, that gives them zero utility and an alternative, a. Each player observes a signal, s_i drawn from a closed interval S_i of the reals, with joint density $f(s_1, s_2)$, and their utility from a is $v_i(s_1, s_2)$.[10] The mechanism specifies message spaces, M_i for each player, and a probability of choosing the alternative as a function of the messages the agents send, $g(m_1, m_2)$. Any such mechanism, and any equilibrium choices of messages $a_i: S_i \to M_i$ by the players generates an outcome function $h(s_1, s_2)$ that specifies for each signal pair the probability of the alternative being selected. Now, given one's own signal and an opposing player's message, a player can calculate an updated belief about the other player's signal. Posterior implementability requires that the player will not want to change to a different message after updating beliefs in this way. Formally, if h is implemented by a Bayesian equilibrium of a mechanism, let $r(s_{-i}|s_i, m_{-i})$ be the conditional belief over the opponent's signal given one's own signal *and given the opponent's message*. Then, for the equilibrium to be posterior implementable, each player's message choice $a_i(s_i)$ given any signal s_i has to maximize her expected utility with respect to r.

Green and Laffont studied this notion in detail for the case of two-action public decisions with a standard monotonicity structure on the private information. They obtained an interesting, and surprisingly restrictive, characterization for this environment. They showed that the posterior implementable decision functions have the following features: the agents have at most three distinct reports, each report is made on a subinterval of their private signal, and, in particular, the separation of the states of Nature into the two regions in which each of the two public decisions are made is given by an increasing step function.[11] An example is given in the figure below, taken from the paper, where the axes are the possible signals, the equilibrium messages partition those intervals, and the mechanism specifies taking one decision, g_+, above the bold step function and the other, g_-, below.[12]

[10] The utility v_i is continuous, strictly increasing, and generically non-zero. The density *f* is continuous and strictly positive on its support and satisfies a monotone likelihood ratio property.
[11] Not every such step function can be posterior implemented; Green and Laffont fully characterized the set.
[12] The curved lines and other labels are not relevant for this abbreviated presentation.



Yet again, Green and Laffont here insightfully introduced questions that were followed up on in the years to come: both modeling robustness in mechanism design and the connection between various notions of equilibrium and these robustness ideas (see, e.g., Bergemann and Välimäki (2006), Philippe Jehiel, Moritz Meyer-Ter-Vehn, Benny Moldovanu, and William Zame (2006), Paul Milgrom (2011), Bergemann and Stephen Morris (2012)).

Contract Theory

Jerry also made seminal contributions to contract theory. Green and Nancy Stokey (1983), for example, provided the first fully general comparison between tournament and contract schemes for incentivizing labor effort. Their model built on the earlier framework of Edward Lazear and Sherwin Rosen (1981), who had compared linear piece rates, fixed standards, and tournaments in a two-agent model. Like in Lazear and Rosen (1981), Green and Stokey considered a principal employing ex ante identical agents, each of whose output depends stochastically on both their individual effort level and a common productivity shock. Contracts reflect only individuals' own output levels, whereas tournaments implicitly link those outputs because they depend on the rank order.

Agents are risk-averse. They receive signals about the common shock before choosing their effort levels, but must undertake effort before the returns to that effort are realized. (The returns to effort and the common shock/signal structure are assumed independent of each other; moreover, the common shock is assumed to have mean 0.) For example, as Green and Stokey illustrated, the model could reflect local salespeople with ex ante symmetric territories, whose sales depend in part on regional conditions. The model allows for arbitrary signal structures – so for example the salespeople could all observe regional conditions perfectly, or alternatively they might have varying noisy signals.

The first observation in this framework is that because the common shock affects all agents equally, the agents' ordinal ranking in terms of output depends only on agents' realized returns to effort. Formally, agent i's output will be higher than agent j's precisely when $z_i + \eta > z_j + \eta$, where z_i and z_j are i's and j's (stochastic) returns to effort, respectively, and η is the realization of the common shock; this means i will beat j in a ranked tournament if and only if $z_i > z_j$. Thus, neither the realization of the common shock nor the agents' signals affect gameplay under a ranked tournament – the optimal tournament depends on the number of agents and the distribution of the returns to effort, but not on the common shock. This observation dramatically simplifies the analysis. It also stands alone as an argument in favor of tournaments because it shows that tournaments are robust to lack of information (or agreement) about agents' signals.

Green and Stokey next compared the performance of optimal contracts and tournaments. As they explained:

> "[T]ournaments tend to reduce the randomness of any agent's compensation by filtering out the common shock term. However, they also tend to increase the randomness in any agent's compensation by making his reward depend on the idiosyncratic shocks of his peers. [… T]he relative advantage of tournaments vis-a-vis contracts depends on which effect dominates."

Green and Stokey showed first that when there is no common shock to agents' performance, contracts always dominate tournaments. Indeed, they demonstrate more generally that for any tournament, it is possible to construct a feasible contract that dominates it – specifically, the contract that assigns to each output level the mean payoff that an agent with that output would get in a tournament in which all other agents choose the optimal effort level. This contract provides the same incentives as the associated tournament but eliminates the additional risk agents face from randomness in the *ex post* rank-ordering.

Meanwhile, tournaments dominate contracts when the distribution of the common shock becomes diffuse, since then the common shock introduces significant noise – making the agent's output less directly linked to effort. When the common shock is a significant-enough driver of output, the benefits of eliminating the resulting noise through a tournament dominates, relative to avoiding the (lesser) noise that the tournament introduces by basing compensation on the stochastic rank ordering.

A surprising consequence of the Green and Stokey (1983) logic is that in the limit as the number of agents grows large, the optimal tournament will *always* dominate the optimal contract. Indeed, for a large enough group of agents, observing all the agents' outputs effectively reveals the value of the common shock, and an agent's rank-order then provides a nearly perfect signal about their individual output level net the shock. In that sense, the optimal tournament effectively implements the optimal interdependent contracts for a setting in which the common shock is known(!).

Jerry with Charles Kahn (1983), meanwhile, examined how worker–firm contracting under uncertainty affects the optimal level of employment. The late 1970s and early 1980s were a time of high inflation and economic recession; a series of theory models at the time tried to provide explanations for these phenomena as consequences of labor contracting under incomplete information (see, e.g., Sanford Grossman and Oliver Hart (1981); Costas Azariadis (1983)). But as Green and Kahn (1983) showed, the contract theory framework in general would lead to *over-employment* – rather than under-employment, which was the case empirically at the time.

In Green and Kahn (1983), the firm's output value is a function of the employment level and a stochastic term – reflecting, for example, uncertainty in market demand for the firm's product. The firm is assumed to be risk neutral, while the workers are risk-averse.

Only the firm can observe and interpret the value shock; hence, the firm needs to be able to set the level of employment unilaterally, given the wage contract and realized shock. The need for risk-sharing then distorts employment away from full efficiency.

Green and Kahn demonstrated that the resulting outcomes typically involve over-employment, in the sense that if workers could re-contract *ex post*, knowing the value of the shock, then the resulting employment would be lower. Indeed, to effect risk-sharing, the firm keeps workers employed more than would be efficient in cases of low profitability. To compensate for this, however, workers' utility ends up being decreasing in firm profitability – as Green and Kahn remarked, "'[g]ood times' are not shared by all."

The Green and Kahn finding ran counter to the intuition at the time that a firm's control over the level of employment was likely to lead to involuntary unemployment – excessive layoffs – in times of negative macroeconomic fluctuations. Moreover, and importantly, the work showed that under a reasonable set of assumptions, single-period implicit contracting models could not match the empirically observed unemployment at the time, much less "explain unemployment" or "yield the underpinnings for a theory of macroeconomic fluctuations."

In addition to being foundational within the literature on employment contracting (Hart and Bengt Holmström (1987), James Malcolmson (1999)), Jerry and Kahn also introduced a significant methodological contribution: to solve the optimal contracting problem in their setting, they imported methods from the theory of mechanism design (especially drawing on Green and Laffont (1979) and Laffont and Maskin (1980)). By now, of course, these methods are so ingrained into contract theory that it is hard to even imagine that there was a moment when they were first introduced.

Communication and Delegation

In seminal papers with Nancy Stokey and with Laffont, Jerry brought insightful perspectives to the topic of communication in games. Green and Stokey (1980) is another important contribution to information economics, this one to the literature on delegation.

In the late 1970s Green and Stokey (1978, 2007) and Crawford and Sobel (1982), introduced what has become the standard workhorse model to study strategic conveyance of information: a model with unrestricted communication that has no effect on payoffs – commonly known as *cheap talk*. In these environments, one player receives private information and can then communicate it to the other; the second player then chooses an action based on the information communicated.

These cheap-talk models have become ubiquitous in applications and theoretical studies (a few early examples include David Kreps and Sobel (1994), Joseph Farrell and Matthew Rabin (1996), and Crawford (1998)). Green and Stokey not only contemporaneously introduced this framework, but studied natural and different questions, and in a more general class of models than those explored by Crawford and Sobel. Interestingly, both groups of authors saw the value in studying partitional equilibria, in which the sender partitions the signals they receive and sends one common pooled signal for each cell in the partition. Crawford and Sobel focused on a model with an interval of actions and states and concave preferences and showed that this implies partitional equilibria; in fact, they show these are partitions into subintervals. Green and Stokey considered a general finite model, and showed why partitional equilibria are the natural ones on which to focus, even though other equilibria exist in their general framework. To make this case, they characterized the set of non-partitional equilibria and showed that they fall into two classes depending on whether the receiver plays a mixed strategy: the class where the receiver doesn't mix is shown to be non-generic and the other class is shown to be unstable to perturbing the preferences. This clearly justifies their focus on partitional equilibria.

The paper with Stokey on delegation (Green and Stokey (1980)) relates closely to their paper on cheap talk as both explore the extent to which improved information is beneficial for the parties. The delegation problem, first studied by Holmström (1980), differs from cheap talk in that the receiver is able to commit to an action as a function of the sender's report before communication happens. By studying a more general environment, Green and Stokey found that making the sender better informed about the state may make both the sender and the receiver worse-off in equilibrium, which contrasts the results found under the specific payoff and information structures originally considered by Holmström.

Green and Laffont's paper on communication (1986) was the first to develop a general model of hard evidence (partial verifiability) in mechanism design, and was among the first papers to bring partial verifiability / hard evidence into economics (see also Milgrom (1986)). In the cheap-talk model discussed earlier, agents can send any message regardless of their type (private information). By contrast, this work explores mechanism design in an environment where different types have access to possibly different sets of messages. For example, an agent might be able to assert they have a specific medical condition if they can provide evidence that they do indeed have it. Alternatively, they might be able to assert a skill at some task only if they actually have that skill and can demonstrate it.

Because of the richness of this environment that allows for cheap talk and hard evidence, the principal's problem might have to allow for such a wide range of mechanisms that it would become impractical to study. Yet Jerry and Laffont obtained a revelation principle à la Roger Myerson (1981), showing that the principal's problem can be studied by considering only mechanisms in which agents are restricted to reporting their types and report truthfully (and imposing the condition that truthful reporting is optimal, i.e., *incentive compatible*). Jerry and Laffont proved that such a result holds whenever a *nested-range condition* (NRC) is satisfied. The nested-range condition states that if an agent of type t_1 can misreport and claim she is another type t_2, and t_2 can claim to be, say t_3, then t_1 can also credibly claim to be t_3.

The paper gives interesting examples satisfying and violating the NRC. For example, environments in which any type can either prove nothing (be silent), or have the choice of proving the truth (what type they are) or being silent would satisfy the NRC. Similarly, situations where types are ordered and any type can claim to be the true type or any "higher" type satisfy the NRC. However, if each type can only "overstate" by a certain amount, then the NRC is violated. This is one more instance where Jerry's work introduced a notion – in this case, partial verifiability – that was followed up in a wide body of subsequent research. For example, the specific question of when the revelation principle applies was explored by Jesse Bull and Joel Watson (2007), and Raymond Deneckere and Sergei Severinov (2008), among others. The study of mechanism design with partial verifiability more generally has had a recent re-awakening, including Elchanan Ben-Porath, Eddie Dekel, and Barton Lipman (2019), Jacob Glazer and Ariel Rubinstein (2004, 2006), Sergiu Hart, Ilan Kremer, and Motty Perry (2017), Konrad Stahl and Roland Strausz (2017), and Frédéric Koessler and Vasiliki Skreta (2019), among others.

Mortgage Prepayments

Jerry's versatility and prescience also shine through in his mortgage prepayment paper published in 1986 with John Shoven (Green and Shoven (1986)). Mortgages give homeowners the right to terminate their mortgages by paying the remaining balance, which is the present value of the remaining fixed payments discounted at the original mortgage interest rate. The value of mortgages held, say, by a bank, depend on how homeowners exercise their option to prepay. As Jerry and Shoven pointed out, in the mid-1980s many banks valued mortgages via simple rules of thumb, supposing for example that they prepaid at a constant rate that gave them an average life of 7 years. As interest rates changed, the banks' valuation of the mortgages would change to reflect the new discount on the cash flows.

Green and Shoven argued that the change in interest rates would also cause a change in homeowner prepayments, and thus a change in the duration of the mortgage cash flows. This change in duration has a powerful negative effect on mortgage values, which as Green and Shoven pointed out, was being ignored by many banks that held them. Green and Shoven emphasized the lock-in effect: when interest rates go up, the old mortgage becomes a very good deal for the homeowner but makes the mortgage worth less to the bank. If the homeowner moves, she might have to take out a new mortgage at a much higher rate. Hence, she might not move, and might not prepay her mortgage. So prepayment rates will slow, and average duration will get longer, which is bad for the bank. This was very important in the early 1980s because interest rates soared as the Fed tried to curb inflation. On the other side, if mortgage rates decline, the homeowner might prepay by moving or refinancing into a new, cheaper mortgage. Prepayment rates will speed up, and average duration will get shorter, which is bad for the bank.

Green and Shoven built a model of homeowner behavior in which prepayments depend on the age of the loan multiplied by a function of the prepayment incentive, which they took to be the difference in present value of the mortgage calculated with the original mortgage rate and then with the new mortgage rate, divided by the house price. They used a maximum likelihood estimation of the parameters of their model on proprietary data (prepay or not) given to them by a bank for 4,000 California loans for each month between 1975 and 1982. Their method of data analysis was borrowed from clinical research in medicine, where patients are followed for a long time, but the observations are often necessarily truncated by the end of the study before the resolution of the illness.[13] Using their estimated parameters, they showed how different the valuations became relative to the old rules of thumb, over various interest rate scenarios. They suggested that some naïve bank managers might not be aware that their banks were effectively insolvent.

This paper showed the keen eye of the authors for an important topic. Within a few years, mortgage prepayment modeling became one of the central problems of finance and Wall Street. The new prepayment models used some of the machinery of Green and Shoven (1986), but also moved on in several important directions. First, more recent models have recognized that the reaction to increases in mortgage rates is not symmetric with the reaction to decreases – the rise in mortgage rates affects prepayments only among those who might have intended to move but become locked in, whereas the fall in prepayments stirs people who had no intention of moving to refinance. Second, one might more succinctly summarize the problem by saying that homeowners have a prepayment option, whose value must be subtracted from the present value of the non-prepayable cash flows to get the value of the mortgage to the bank. Underestimating the option value means inflating the mortgage value. Third, and much more importantly, newer models have recognized that people are heterogeneous. Some people are oblivious to prepayment opportunities or costs. As homeowners miss opportunities to refinance when interest rates go down, they are more likely to be of the oblivious type.[14] In keeping with the macroeconomic tendency of the time to focus on the representative consumer, Green and Shoven had not incorporated heterogeneity. Nevertheless, Jerry once again was years ahead of

[13] See Bunker, Barnes and Mosteller (1977). Jerry (personal communication) relates that the empirical analysis in this work was conducted "via a terminal connected to a mainframe computer located somewhere in the Boston suburbs, [… in] FORTRAN code (which [he] learned as a college freshman and had not touched in the intervening twenty years)."

[14] Green and Shoven had assumed that aside from age, the past has no bearing on the current probability of prepaying.

the academic profession in identifying and analyzing this subject of first-order importance for the world.

Public Finance

Jerry (Green (1977c, 1988)) introduced an early model of Social Security-style policies as a way of insuring against demographic risks, which preceded similar intergenerational transfer frameworks of Alasdair Smith (1982), and Roger Gordon and Hal Varian (1988). The key ideas are twofold: First, a given age cohort's return on savings depends on the size of the next (younger) cohort – if the younger cohort is larger than expected, then the older cohort sees an increase in the real return on its savings. Second, the younger cohort's wages depends on the cohort's size – if the cohort is larger, then wage earnings are lower. Thus, the older and younger cohorts "have negatively correlated risks with respect to variation in the size of the [younger] cohort"; this naturally creates an opportunity for cross-generational social insurance.

Moreover, as Green (1988) noted, it is difficult for private markets to provide the type of social insurance needed here because the younger cohort would not be able to contract over it until that cohort is born – at which point the uncertainty about cohort size has been resolved. Thus, it makes sense for a government to implement the social security system – in effect, committing all generations to the insurance scheme.

Note that here the optimal intergenerational subsidy could flow in either direction – from old to young or young to old – depending on which cohort is larger. It follows that an individual's overall preference for such a system depends on the likelihood that the individual expects to be subsidized or taxed under the scheme. A bit paradoxically, Green (1988) observed that "the individuals least likely to benefit from social insurance are those most likely to be born," since those individuals are most likely, on average, to be alive in circumstances when their cohort is small – and thus face a tax rather than a subsidy.

Foreshadowing many of the issues seen in debates around Social Security today, Green (1977c) observed, in particular, that for the government's budget to balance:

> "[T]axes on the young would [have to] be higher when there are few of them, and per capita taxes would therefore be adversely intensified. High total taxes would be borne by fewer young workers, and high total subsidies would be spread out over many."

In order for Social Security to be efficient, the benefits from pooling cohort size risk have to outweigh this "population bias" effect, as well as the concern that the availability of social insurance may reduce savings.

Law and Economics

Using insights and frameworks from game theory, Jerry also made an early and fundamental contribution to the emerging field of law and economics.

John Prather Brown (1973) introduced a model of optimal liability law, in which the structure of law influences parties' incentives to take precautions (see also Peter Diamond (1974) and Steven Shavell (2007)). The main results of Brown (1973) suggest that a range of liability rules support optimal levels of precautions in equilibrium so long as the "due care" standards that determine when a party has been negligent are chosen optimally. Inspired by Guido Calabresi's classic book *The Cost of Accidents*, Green (1976) showed that Brown's (1973) conclusion relies on a strong implicit assumption that the cost of precautions for each type of agent (injurer or injured) are constant.

To make this point, Jerry developed a simple and intuitive extension of the Brown (1973) model in which insurers and injured can each have varying costs of care. Even when there are just two costs of care per side, the choice of optimal liability rule becomes quite subtle. As Jerry observed, there is "an informational constraint on the court's behavior […] it does not know, or must disregard, differences in the cost of care involving otherwise identical individuals"; moreover, unlike in Brown (1973) and other prior models of liability law, the court may play an active adjudicatory role in equilibrium.

When the cost differences are small on either side, the optimal rule can approximate the first-best by placing liability on the side with the smaller cost spread, and instituting a particular due care standard for the other side. However, when the cost differences are large, it can become optimal to reconfigure the legal rule so that a separating equilibrium arises, with distinct cost classes on a given side having distinct liability statuses in equilibrium.

This work highlighted how core modeling primitives understood to be essential in game theory – in this case, heterogeneous types and imperfect information – could have significant impact on the conclusions of classic optimal legal rule frameworks. In this sense, Jerry foreshadowed similar subsequent exercises by Winand Emons (1990), and Emons and Sobel (1991) a decade and a half later, as well as a wide array of research using detailed game-theoretic approaches to make sense of other law and economics questions.

Intellectual Property

The core economic intuition behind the institution of patents is that providing sole commercialization rights for a period of time enables inventors to capture value from their inventions – and thus incentivizes them to undertake costly research and development. But this intuition alone is not enough to set the optimal patent policy. Indeed, parameters of the patent system's design – such as duration and scope (Richard Gilbert and Carl Shapiro (1990); Paul

Klemperer (1990)), as well as licensing terms (Nancy Gallini (1984); Shapiro (1985)) – affect the returns to innovation, and hence shape firms' R&D incentives. Yet much of the early work on these topics emphasized models of single-shot patenting: while firms might "race" to achieve an innovative breakthrough, the question was confined to firms' incentives to invest towards that breakthrough, and the resulting distribution of surplus from commercialization.[15]

Jerry's work with Suzanne Scotchmer highlighted that innovation is often cumulative – and observed that in the presence of such "sequential innovation," the impact of the patent system's design is particularly subtle and significant.

Scotchmer and Green (1990) considered a model of two-stage innovation, and compared "strong" and "weak" novelty requirements for patenting in a model with two stages of innovation – first the development of intermediate technology, followed by an advanced technology that builds upon it. Under strong novelty, only the advanced technology created after the second successful innovation is patentable; under weak novelty, the intermediate technology created in the first stage is patentable as well. Patenting entails disclosure, so a firm that invents the intermediate technology and chooses to patent it runs the risk that a competitor will be able to build upon the information in the patent to successfully develop the more valuable advanced technology.

As Scotchmer and Green (1990) noted, there is thus "a trade-off between the profit of [patenting and] marketing the small advance and the value of maintaining a competitive advantage in technical knowledge for later stages of the [innovation] race."[16] This means that – contrary to what we might have expected without examining a game-theoretic framework – firms will not always choose to patent intermediate technologies even when the option of doing so is available; this can in principle reduce the welfare benefit of instituting a weak novelty requirement rather than a strong one.

Nevertheless, the weak novelty requirement effectively provides firms with an option value, in the sense that in the Scotchmer and Green (1990) model, whenever a firm's *ex ante* profit is positive under a strong novelty requirement, that firm's *ex ante* profit is also positive under the weak novelty requirement. This can be socially valuable because it sometimes leads to disclosure of the intermediate technology.

However, for some parameter values, strong novelty dominates because it can lead to higher (*ex ante*) profits:

> "The weak novelty requirement leads to competition between close substitutes – either competition between the first innovation and the base technology, or

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[15] In addition to the references above, see, e.g., Jennifer Reinganum (1981), Drew Fudenberg, Richard Gilbert, Joseph Stiglitz, and Jean Tirole (1983), and Ignatius Horstmann, Glenn MacDonald, and Alan Slivinski (1985).

[16] The Scotchmer and Green (1990) framework assumes that there is no way to market the intermediate technology without it being reversed-engineered, so a firm can only bring the intermediate technology to market profitably if it is able to obtain a patent.

> between the more advanced second innovation and the first innovation. With the strong novelty requirement, there can only be competition between the most advanced technology and the base-level technology, and therefore the innovator is assured of a higher profit flow."

Under weak novelty, when a firm initially chooses not to patent (and thus not to disclose the details of) the intermediate technology, there is still the possibility of patenting it later. Under a "first-to-file" patent system, that opportunity may accrue to a competitor if it manages to achieve the same invention; under "first-to-invent" patenting, that value instead accrues to the original inventor. This means that under weak novelty, a firm that is behind in the R&D race may have too strong an incentive to continue investing in innovation under the first-to-file rule or under a strong novelty requirement, since both of these policies can reward duplicate innovation on the margin. Meanwhile, a competitor's incentive to continue innovating is generally too weak under weak novelty with first-to-invent patenting.

Green and Scotchmer (1995), meanwhile, examined how patent scope, duration, and licensing affect firms' incentives to engage in sequential innovation. They considered a simple model in which a first firm must decide whether to innovate; and if it does, then a second firm can choose to engage in innovation that might build upon that of the first firm's. The firms can in principle reach an *ex ante* agreement before the second firm begins investing in R&D; or alternatively could bargain *ex pos*t once the second firm makes the investment and discovers whether its new product is actually infringing on the product of the first firm's. Broader patents mean that the second firm's product is more likely to be infringing; meanwhile, longer-duration patents raise the total profit collected by the two firms by extending the period of monopoly pricing.

Unlike in the single-shot innovation frameworks of Gilbert and Shapiro (1990) and Klemperer (1990), in the Green and Scotchmer (1995) model, the per-period profits from innovation are fixed because the firms in equilibrium act like a joint monopolist. The key dynamic is instead that that the choice of patent policy affects the second innovator's *ex ante* bargaining power, and thus determines the division of surplus between the two firms. The division of surplus, in turn, can have substantial impact on the firms' incentives to innovate.

The first key observation is that "[i]f the division of profit is too unfavorable to one innovator or the other, the patent must last a long time to ensure that the less-favored innovator covers his cost [of R&D]." This means, in general, that when innovation occurs sequentially across firms – rather than within a single firm – patent duration should be longer. Indeed, when innovation occurs only within a single firm, patents should be calibrated so that product sales exactly cover total costs. But in the context of sequential innovation across firms, the first innovator's investment is sunk by the time the two firms bargain, which means that the second innovator will be able to bargain for some positive profit; a patent term that just covers total costs then leaves the first innovator with negative profits, dissuading that firm from investing in R&D in the first place.

Meanwhile, broad patents serve to protect the first innovator's profits in the event that both firms successfully innovate, but at the same time, broad patents can potentially dissuade the second firm from entering. As Green and Scotchmer (1995) explained, this counterintuitively means that the first firm might actually prefer a narrower patenting scope, as that reduces the second firm's bargaining power by making a threat not to enter less credible. Similarly, the possibility of *ex post* licensing – as opposed to simply blocking infringing products – benefits the first firm because it reduces the second firm's bargaining power *ex ante*.

Each of these papers is a *tour de force*, and their dual approaches are highly complementary; together, Scotchmer and Green (1990) and Green and Scotchmer (1995) comprehensively assessed how different patenting standards, licensing terms, and scope/duration decisions affect sequential innovation among competing firms. Patent policy affects who invests at different stages of a multi-step patent race, as in Scotchmer and Green (1990). Moreover, and quite generally, the optimal patent policy depends not just on the structure of the innovation process, but also on the role of bargaining in shaping how profits are shared through licensing – as illustrated by Green and Scotchmer (1995).

This work has been central in the subsequent theory and empirical research on the design and impact of the patent system (see, e.g., Mark Lemley and Shapiro (2005), Lee Branstetter, Raymond Fisman, and Fritz Foley (2006), James Bessen and Maskin (2009), and Bronwyn Hall and Rosemarie Ham Ziedonis (2001)). Additionally, on the methodological side, Green and Scotchmer broadened the application of the extensive-form game approach to modeling competition in sequential innovation, which remains in use to this day (see, e.g., Jay Pil Choi and Heiko Gerlach (2017), and Lauren Cohen, Umit Gurun, and Kominers (2019)).

Social Choice

Social Choice with Transfers

Jerry is still passionately at work on the question of fair social choice that he posed in an unpublished paper in 1983 (Green (1983)). In 1951, Arrow had shown there is no solution to the general social choice problem that satisfies a few simple axioms. John Nash (1950) found a unique solution, but in a setting that incorporated threat points, which gave the analysis a non-cooperative game-theoretic flavor. Cooperative game theory incorporates similar dynamics by recognizing the threats coalitions of players can make. Spurred by the success of quasi-linear utilities in sharpening the theory of incentives, Jerry sought to find a solution to the social choice problem, while avoiding any non-cooperative threats, by specializing to situations where utility transfers are possible (such as would occur if money transfers were possible and everyone had constant marginal utility of money).

More formally, consider a set of feasible social choices that each provide (different) utilities to N individuals, as in the general social choice problem. Suppose that after a social choice is made, utility transfers are allowed. What might be a fair way of jointly deciding the social choice and the transfers?

Jerry published a corrected version of his 1983 paper on this question under the title "Compensatory Transfers in Two-Player Decision Problems" in 2005 (Green (2005)). He presented three axioms for $N = 2$ players that ensure that there is just a one parameter family of solutions. One solution in the family is to start with any social choice that maximizes the sum of utilities. Then let each player "demand from the other" the most she could gain had another (possibly inefficient) social choice been made. Then average the two demands and make that the transfer.

The other solutions, indexed by a common (transfer parameter) t, are obtained by shrinking each player's demand by the loss in total utility that her alternative social choice would entail, multiplied by t. Christopher Chambers and Green (2005) extended the analysis to $N > 2$ players; this yielded far more solutions, also of great interest. Jerry is still looking for a last axiom that will pin down the solution to the quasi-linear social choice problem (Jerry Green's personal correspondence).

Jerry's model has been studied further by others, including by Hervé Moulin (1985a, 1985b, 1987) and Youngsub Chun (1986, 1989, 2000). The kind of harmonic analysis Jerry introduced to solve his social choice problems also appears to have been novel to economics. Jerry introduced the axiom of recursive invariance, which says that if there is a social choice and transfer that satisfies the axioms, and if a new social choice is added that gives the same direct utility to the agents as they would obtain after the transfer in the original solution, then there must be a solution to the new problem giving those same final utilities to the players. Something like this axiom of recursive invariance has also been taken up in recent work by Elon Kohlberg and Abraham Neyman (2018, 2021).

Assent-Maximizing Social Choice

Jerry also brought his knack for finding novel and unique approaches to bear on classic problems in social choice theory. Katherine Baldiga and Green (2013), for example, examined social choice rules with a perspective informed by decision theory: they introduced a family of social choice rules that "maximize assent" within a population under a distribution of possible social choice problems that might be faced. Formally, Baldiga and Green consider a population represented by a probability distribution λ over different preferences over alternatives, as well as a distribution ν of choice problems that might be faced. In this context, a social choice rule π^* is *assent-maximizing* if minimizes the expected conflict between a candidate social ordering and individual preferences in the population:

$$\pi *= argmin_{\pi'} \left\{ \sum_{\pi} [f(\pi, \pi'; \nu)\lambda(\pi)] \right\}$$

where $f(\pi, \pi'; \nu)$ is a function that measures the frequency with which π and π' lead to different social choices under the choice problem distribution ν.

The John Kemeny (1959) rule maximizes agreement among the population when the choice problems under consideration comprise all pairwise comparisons, selected uniformly at random. Hence, the assent-maximizing rule can be thought of as generalizing Kemeny (1959) by allowing arbitrary distributions of choice problems over arbitrary subsets of alternatives.

As Baldiga and Jerry showed, assent-maximizing social welfare functions can lead to outcomes supported by a much larger share of the population than the Kemeny (1959) method. Indeed, the Kemeny (1959) rule selects a Condorcet winner when there is one; yet in contests with a large number of alternatives, it is possible that the Condorcet winner generally does not receive a plurality when more than two alternatives are considered. The assent-maximizing rule fixes this by integrating in the social preference that arise in cases with more than two alternatives – and moreover, it weighs these various social preferences in a way that reflects the true distribution of choice problems that arise.

This reflects the notion, long recognized in decision theory, that the frequency of different choice problems should shape the choice rule. As Baldiga and Jerry remarked, taking this idea seriously implies a broader need for data about the frequency of different choice problems throughout welfare economics.

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