Human Preference Formation and Measurement of Impact in Large Techno-Social Systems

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Abstract

Large techno-social systems refer to complex systems that integrate technology and social structures to deliver services, products and solutions to large populations. Examples include the Internet, social media networks, online marketplaces and e-government systems. This paper addresses two fundamental aspects arising in these systems. First, since human preferences are both an input and an output, these systems may have a significant impact on behavior, for example, by shifting consumer preferences, changing attitudes, reinforcing existing biases, creating new biases or by altering social norms and expectations. This means that to understand this impact it is necessary to have an equilibrium framework for thinking about the endogenous formation of preferences. Second, much research argues that these systems may disrupt traditional business models, create new markets, increase competition, and alter labor markets. As such, they will have an impact on the equilibrium forces in the global economy. But, how strong are these forces and in what direction they operate? These are challenging questions whose answers, intuitively, depend on who are the most important or influential agents. This in turn begs the question: How can we measure the "impact" of different agents in an interdependent, interconnected world? This paper reviews formal frameworks available in the literature that are useful to study both the endogenous formation of preferences and the measurement of impact in these systems.

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"The real problem of humanity is the following: We have Paleolithic emotions, medieval institutions and god-like technology."

– Edward O. Wilson, 2009

1 Introduction

On September 9, 2009, in a sold-out event at Sanders Theatre in Harvard University that coincided with the 150th anniversary of the Harvard Museum of Natural History, National Public Radio correspondent Robert Krulwich moderated a public discussion between Edward O. Wilson and James Watson. He asked: "Will we solve the crises of next hundred years?" "Yes, if we are honest and smart," responded Wilson, who added: "The real problem of humanity is the following: we have Paleolithic emotions, medieval institutions, and god-like technology. And it is terrifically dangerous, and it is now approaching a point of crisis overall." Until we understand ourselves, concluded the Pulitzer-prize winning author of *On Human Nature*, "until we answer those huge questions of philosophy that the philosophers abandoned a couple of generations ago—Where do we come from? Who are we? Where are we going?—rationally, we're on very thin ground."[1]

The development of Large Techno-Social Systems (LTSS) represent a major opportunity to continue the scientific journey that started a few centuries ago to make progress on these questions. The challenge, as we shall see, is that these systems also add new difficulties. Indeed, while the development of LTSS has no impact on the past (where do we come from?), it may definitely have an impact on human preferences (who we are?) and in the directions that we may or may not take (where are we going?).

LTSS refer to complex systems that integrate technology and social structures at a scale not previously observed in history (Galor, 2022). At their most fundamental level, they operate by changing the nature and extent of human communication. Jackson (2019) notes that changes in human communication have already shrunk the world many times in the past in the wake of the printing press, the posting of letters, overseas travel, trains, the telegraph, the telephone, the radio, airplanes, television, and the fax machine. He also quotes Thomas Friedman, interviewed in the magazine *Wire* (May 1, 2005): "In Globalization 1.0, which began around 1492, the world went from size large to size medium. In Globalization 2.0, the era that introduced it to multinational companies, it went from size medium to size small. And then around 2000 came Globalization 3.0, in which the world went from being small

[1] Quoted in *Harvard Magazine* (September 10, 2009).

to tiny."

A tiny world has drastic implications for human interactions, and these in turn for how human preferences may change as a result of changes in these interactions. Some preference parameters may be enduring and stable, but others may shift temporarily or even permanently. Nature vs nurture is a distinction that has always preoccupied social scientists and philosophers.

Understanding both change and stability in preferences because of the advent of LTSS matters for many reasons, for example: (i) for the study of networks, "which are often overlooked when people analyze important political and economic behavior and trends" (Jackson, 2019), (ii) for the study of human institutions, which "are the constraints devised to structure human interactions" (North, 1990), and (iii) for today's firm and production processes (e.g., the frequency of working from home has been rising rapidly in developed countries, and this raises major issues ranging from productivity, profitability and work-life balance). Indeed, much discussion in the media focuses on the potential that LTSS have to bring both benefits and challenges, and how it is crucial to address their negative impacts while leveraging the positive ones.[2]

Clearly, both through positive and negative effects, LTSS are already having an impact on the equilibrium forces in the economy, changing certain traditional business models, creating new markets, increasing competition, and altering labor markets through, for example, the automation of certain jobs and the creation of new ones (Acemoglu and Johnson, 2023). "Creative destruction" is a term well understood at least since Joseph Schumpter. It is quite unfortunate, however, that most philosophers are ill equipped to address broader consequences. Typically, they have abandoned altogether Wilson's "huge questions," offering at most a casual discussion of different issues that is guided by no formal, analytical frameworks.

A problem is that the range of discussions is in fact endless. And it is precisely in this

[2]On the negative side, the problems associated with LTSS include privacy and security (hackers and cybercriminals can gain access to an increasing amount of personal and sensitive information being shared online); addiction and mental health (excessive use of technology and social media may negatively impact mental health); disinformation and fake news (particularly harmful when it comes to politics and elections); an increasing consumption of only information that aligns with existing beliefs leading to increased polarization and a breakdown of civil discourse and greater inequality. On the positive, LTSS improve connectivity and accessibility (allowing people to increasingly communicate and access information from all over the world), may increase innovation and economic growth by providing new opportunities for businesses and entrepreneurs, may improve education and healthcare (delivering educational and healthcare services to remote and underserved populations), generate greater political empowerment (by providing a platform for political activism and increasing the voices of marginalized communities), and may bring more people together across geographical and cultural boundaries.

jungle of noisy discussions that we lose sight of perhaps the most important consequence: the shaping of human preferences by LTSS. This is the first aspect that I want to point out here. The second one is that to address this "shaping," we need a theoretical framework, and that to make empirical progress we need, at a minimum, to have a way to measure the influence or impact of the agents involved in a LTSS. These are focus of my reflections in this article.

2 Endogenous Preference Formation

It seems obvious that the tiny world that LTSS have created can have a significant impact on human preferences. This can occur, for example, when changes in communication or contact systems alter social norms and expectations, change certain attitudes, modify working and leisure times, and reinforce existing biases or create new ones. For instance, the use of social media has led to a decline in face-to-face communication and the development of new norms and expectations around instant gratification and constant connectivity. Many people spend now more time using technology and engaging in virtual activities than engaging in traditional forms of leisure. The availability of new information through LTSS can influence consumer preferences, leading to shifts in demand for certain products and services. Attitudes towards privacy also change, leading to a greater willingness to share personal information in exchange for convenience or other benefits. And an important aspect often discussed is that LTSS algorithms are designed to personalize content and advertisements based on a user's past behavior, which can lead to reinforcing behavior where users are only exposed to and/or choose to be only exposed to information and perspectives that align with their existing beliefs and values.

There are different economic models of preferences that have been developed to help us understand how preferences are influenced by the economic and social environment in which we live. For example, in habit formation models individuals' are influenced by past experiences and behaviors. We develop inertias and our changes in behavior may take a long time or require a significant shock or event. In social learning models individuals develop their preferences by observing the behavior of others and interacting with them in various ways. These models suggest that individuals may be influenced by social norms, and that these norms can shape their preferences. In identity models individuals' preferences are influenced by a sense of social identity or self-image, not just their own narrower self-interest, with a desire to signal identity and values to others.

These and similar models are useful for understanding a range of economic and social phenomena, such as consumer behavior, social norms, and the role of institutions in shaping individual preferences.[3] However, while we have good formal models to study how the economic, social, legal, and cultural environment affect preferences, it turn out that preferences *also shape* these environments. Put differently, although concepts such as habit formation, social norms, cascade effects, conspicuous consumption and snob effects are found under various forms in the literature, mainstream social sciences usually assume preferences as *exogenous* and *stable*. Preferences may evolve dynamically but are still stable. This should not be taken as a criticism. On the contrary, the assumption of stable preferences provides a robust foundation for generating predictions about responses to various changes in the environment. Further, this assumption should also prevent the analyst from succumbing to the temptation of simply postulating the required shift in preferences to "explain" all apparent contradictions to the theory although, unfortunately, we often see philosophers and other social scientists succumbing to this temptation.[4]

What is missing in the literature, though, is a framework that includes feedback from preferences to the environment. Put differently, we still lack a rigorous understanding of the mechanics underlying the *endogenous* relationship between preferences and the social, economic, and institutional environment.

In Palacios-Huerta and Santos (2004) we make some progress by developing a tractable framework for the analysis of the *endogenous* relationship between preferences and the environment where individuals operate. This general equilibrium framework focuses on the extent to which resources and production are allocated on the basis of "prices" generated by voluntary exchanges—called "markets," broadly defined. These exchanges are indeed some of the main "institutions" that determine economic and non-economic outcomes and shape human interaction. They encompass, in a general sense, the extent and form of economic, legal, and social activities, all of which are defined and shaped by LTSS. "Outcomes help form tastes" (Becker, 1996), and tastes in turn determine outcomes. This is the endogenous

[3] See, for example, research by George Akerlof, Jean Tirole, Roland Benabou, Ernst Fehr, Daniel Kahneman, Amos Tversky, Robert Frank, Samuel Bowles, Herbert Gintis, and other economists who have made important contributions to our understanding of preferences.

[4] The last few decades have also witnessed a number of intriguing refinements mainly involving "behavioral anomalies" of various sorts that often postulate almost arbitrary cognitive imperfections in preferences and values when faced with puzzling behavior. But as Becker (1996) notes: "Legal rules, culture, habitual behavior, social norms, available opportunities and information, past acts of investments and consumption, frequently place more far-reaching constraints on choices than do conflicting selves, mistakes and distortions in cognitive perceptions. ... Modern economics has lost a lot by completely abandoning the classical concern with the effects of the economy on preferences and attitudes."

relationship we want to capture.

This framework is one of the few exceptions available in the literature. It is developed in the context of a concrete example where the extent of markets (including public and private institutions) and the risk structure of the economy are endogenously related to individuals' preferences as captured by their attitudes toward risk. Although it concentrates on this example, any other parameter or aspect of individual preferences besides that governing risk attitudes can be readily studied as well.[5] Next, I describe in some detail the framework:[6]

2.1. Preferences

Consider a continuum of ex ante identical individuals in $[0, 1]$ that live for two periods. Their preferences over consumption are given by:

$$x_0 + \tau(s) \sum_{s=1}^{S} \left(x_1(s) - \frac{\overline{\rho}}{2} (x_1(s))^2 \right)$$

where S represents the total number of possible states of nature, $\tau(s)$ the probability associated with state s, x_i the consumption in period i, and $\overline{\rho}$ is the parameter that governs the risk aversion of the individual. Individuals are endowed with w_0 units of the consumption good in the first period and $w_1(s)$ units in the second period in state s. Let V be the variance of the second period endowment.

The endogenous formation of preferences is modeled as a *competitive sorting* of individuals into two classes of preferences that are identical to each other except for one parameter. We choose, without loss of generality, the parameter that represents the attitude towards risk $\overline{\rho}$. This parameter takes two values, $\overline{\rho}_1$ and $\overline{\rho}_2$, with $\overline{\rho}_1 < \overline{\rho}_2$. For instance, we may assume $\overline{\rho}_1 = \rho$ and $\overline{\rho}_2 = \rho(1 + V)$. We study the endogenous formation of preferences in terms of the formation of this specific parameter, which will in turn be a function of the structure of the environment. These attitudes toward risk are formed prior to any trading taking place in markets to open in the first period, and take into account all market and non-market uncertainties to which the individual is exposed. Let π be the proportion of individuals with a risk aversion parameter $\overline{\rho}_1$ in this economy.

2.2. Technology

A lower aversion to risk is assumed to be formed at a cost $\mathbf{C}_1 > 0$, which may be interpreted in terms of time, effort, and other resources. If our agents were families or

[5] Choosing the parameter that governs the curvature of preferences (risk attitudes) is also convenient from the perspective of empirical work. In particular, we find strong empirical support for the hypothesis that risk attitudes are endogenous related to the extent of markets.

[6] In what follows I reproduce the description in Palacios-Huerta and Santos (2004).

other groups, then we could readily think of examples in which individuals invest effort and resources in order to affect the preference parameters of other members of the family or group (e.g., parents investing in their children's preferences). This cost is paid out of first period endowment and is a loss to the economy. Without loss of generality, we may assume that it is an inverse function of the proportion π:

$$\mathbf{C}_1 = \frac{c_1}{f(\pi)},$$

with $f'(\pi) > 0$ and $c_1 > 0$. In other words, the added utility resulting from a lower aversion to risk is partially offset by its cost. Although no specific functional form is necessary, this inverse relationship is quite convenient to interpret the empirical evidence in Palacios-Huerta and Santos (2004). Obviously, specific applications in the context of LTSS may provide valuable guidance and explicit microfoundations (e.g. psychological, biological, or sociological) into other functional forms that may be assumed for the cost process $\mathbf{C}_1$.

The variable V is our proxy for all non-market uncertainty since individuals can redistribute aggregate uncertainty across the population following different optimal rules, but they cannot alter it. We further assume that market and non-market uncertainties enter the decision process of the individuals as a bonus $\mathbf{C}_2 \geq 0$ in the utility of individuals whose attitude towards risk is governed by $\overline{\rho}_1$. This parameter can be expressed, for example, as:

$$\mathbf{C}_2 = c_2 \frac{\gamma V}{h(E) + \gamma V},$$

where c_2 is a non-negative constant, γ is a 'perception' parameter that captures how agents contemplate aggregate uncertainty, and $h(E)$ is a positive function of the exposure to market uncertainties E (defined below), with a positive derivative. Again, as in the case of $\mathbf{C}_1$, it is unnecessary to assume a specific functional form for $\mathbf{C}_2$. Actually, it may even be assumed to be zero (recall that $\mathbf{C}_1$, however, is always strictly positive).

As a summary, we write the utility functions of the two types of individuals ($\overline{\rho}_1$-types and $\overline{\rho}_2$-types) as:

$$u_{\overline{\rho}_1} = x_0 + \tau(s) \sum_{s=1}^{S} \left(x_1(s) - \frac{\rho}{2} \left(x_1(s)\right)^2 \right) + \mathbf{C}_2$$

$$u_{\overline{\rho}_2} = x_0 + \tau(s) \sum_{s=1}^{S} \left(x_1(s) - \frac{\rho(1+V)}{2} \left(x_1(s)\right)^2 \right)$$

2.3. The financial structure

Once preferences (attitudes towards risk) are formed, individuals trade during the first period in a possibly incomplete financial market. Because individuals have two different risk attitudes, trade is feasible in all markets. In particular, it is to be expected that the $\overline{\rho}_1$-types are willing to take on a larger risk than the aggregate. Markets allow for hedging market uncertainties and the fact that they may be incomplete means that the exposure E may be greater than that if no markets were missing.

We call a financial structure F_i a set of available assets in zero net supply, where i represents the number of assets in that set. For simplicity, i is also the dimension of the space spanned by F_i. In order to have a sufficient statistic describing the degree of market completeness of the economy, we assume that a randomization takes place across financial structures, once preferences have been irreversibly formed. This randomization is limited to $[F_S, F_0]$, where F_S is the financial structure associated with complete markets. F_S occurs with probability p and F_0 occurs with probability $(1-p)$. Hence the available ex ante financial structure is:

$$F = pF_S + (1-p)F_0.$$

The greater p is, the closer the economy is to delivering a complete financial structure. This form of parameterizing "market completeness" is quite convenient in that it allows for a smooth and readily computable way of characterizing the equilibrium distribution of individuals and preferences as a function of the existing structure in LTSS.

2.4. Timing of the economy

To summarize, the timing is as follows:

1. Individuals observe the degree of market completeness, p, and have a certain perception γ of the importance of aggregate uncertainty. Given this information, irreversible preferences (attitudes towards risk) are formed.

2. Randomization over financial structures takes place.

3. Payment of the costs of attitudes towards risk and trade take place.

4. Delivery takes place.

2.5. Definition of the equilibrium

The problem of an individual once a certain financial structure F_i has been realized can be written as:

$$\max_{\theta_{F_i}} \left[x_0 + \tau(s) \sum_{s=1}^{S} \left(x_1(s) - \frac{\overline{\rho}}{2} \left(x_1(s)\right)^2 \right) \right]$$

subject to:

$$\overline{w_0} = x_0 + \theta_{F_i} \cdot q_{F_i}$$

$$x_1(s) = \theta_{F_i} \cdot R_{F_i}(s) + w_1(s)$$

where $R_{F_i}(s)$ is the vector of asset payoffs associated with financial structure F_i in state s, θ_{F_i} is the individual's portfolio and q_{F_i} is the vector of asset prices. Here, $\overline{w_0} = w_0 - \mathbf{C}_1$ if the problem is that of a $\overline{\rho}_1$-type individual and $\overline{w_0} = w_0$ if the problem is that of a $\overline{\rho}_2$-type individual. Let $u_{\overline{\rho}_1,F_i}$ be the utility associated with a $\overline{\rho}_1$-type when the realized financial structure is F_i and similarly with $u_{\overline{\rho}_2,F_i}$. Then, the equilibrium is defined as follows:

Definition. An equilibrium in this economy is an array of portfolio positions $\overline{\theta}_{F_i}$, a vector of asset prices $\overline{q}_{F_i}$ associated with the realized financial structure F_i, and a proportion of $\overline{\rho}_1$-type individuals π such that:

(1) Individuals maximize utility given $\overline{q}_{F_i}$.

(2) Markets clear:

$$\pi\overline{\theta}_{\overline{\rho}_1,F_i} + (1-\pi)\,\overline{\theta}_{\overline{\rho}_2,F_i} = 0, \text{ for all } i$$

(3) All individuals enjoy the same utility in equilibrium:

$$p\overline{u}_{\overline{\rho}_1,F_S} + (1-p)\overline{u}_{\overline{\rho}_1,F_0} + \mathbf{C}_2 = p\overline{u}_{\overline{\rho}_2,F_S} + (1-p)\overline{u}_{\overline{\rho}_2,F_0}$$

Note that in this framework, market exposure E is a proxy accounting for the loss of utility associated with the incompleteness of the exchange in the LTSS environment where individuals interact. Clearly, it is a decreasing function of market completeness. Specifically, it may be proven that $E = (1-p)\sum_{s=1}^{S}\tau(s)(w_1(s))^2$, which is the common factor affecting both types of individuals. See Palacios-Huerta and Santos (2004), where we offer a generalization of the model, various calibrations (note that the model can be solved numerically as a function of market completeness), and empirical evidence.

Unfortunately, there are few general equilibrium frameworks in the literature that would seem suitable to study endogenous preference formation. The good news is that this may be changing. Bernheim et al (2021), for example, have recently developed a dynamic theory of endogenous preference formation in which people adopt worldviews that shape their judgments about their experiences. Their framework highlights the role of "mindset flexibility," that determines the weights placed on current and anticipated worldviews when evaluating future outcomes. I believe that Edward O. Wilson would agree that it would be highly desirable to make progress along general equilibrium frameworks.

3 Measuring the Impact of LTSS Agents

In *The Measure of Reality* (1997), historian Alfred W. Cosby makes the case that the "quantification of reality" in Europe from 1250 to 1600 crucially contributed to put the Western world ahead of the rest. Clearly, measurement is central for progress not only in the natural sciences, but in the social sciences as well as data suggest theories and theories are best tested with new data. Not much progress can be made in understanting LTSS and their impact if we lack the tools for measuring.

LTSS are a leading example of complex networks. As such, they relate directly to research on the economics of networks, which is a field that studies the impact of "network effects" on social and economic structures involving firms and individuals. Indeed, research has shown that, even when preferences are taken as fixed and stable, the economics of networks can provide valuable insights into the behavior of LTSS and their impact on the economy. It can help to explain, for example, why dominant platforms, such as Facebook and Google, tend to dominate their respective markets, and why it can be difficult for new entrants to compete. Additionally, it can inform policy decisions around regulation, for example by identifying potential anti-competitive practices and suggesting remedies.

Important LTSS actors include technology companies, government regulators, civil society organizations, academic researchers, and obviously users.[7] Clearly, the influence they have depends on the specific LTSS under consideration, as well as the specific context. To make matters more challenging, the balance of power among these actors can change over time as both the technology and the social, economic, and political contexts evolve. Viewed from this perspective, here again the sad and decidedly unscientific state of affairs is that philosophers have not only abandoned the idea of measurement, but that their typical discussions rarely go beyond a broad *description* of who are, intuitively, the most influential actors within LTSS.

To address these issues, a first natural step would seem to be to relate LTSS to research on the measurement of centrality in networks. Centrality is a concept that measures the

[7] Companies such as Google, Facebook, Amazon, and Apple control vast amounts of data and have significant power over the ways in which technology is developed and used. Regulators also play a crucial role in shaping the rules that govern LTSS e.g., through privacy laws, data protection measures, and other ways that can impact the behavior of technology companies and the users of their platforms. Non-profit organizations and advocacy groups shape public opinion and advocate for changes in the ways in which LTSS are used and regulated. Academic researchers are also important in that they can improve our understanding of the impacts of these systems, and the challenges and opportunities they present. And, obviously, users have a direct influence in the ways in which technology companies develop and market their products, as well as the types of regulations that are enacted to govern their use.

relative importance of a "node" or a node's position within a network. Different measures of centrality can then be used to attempt to identify the "most influential" nodes within a network, understand the overall structure of the network, and measure the ways in which information and influence flow through the network. In the context of LTSS, these measures could then be used to understand the importance of different actors within the network. For example, they can be used to determine which social media platforms or websites have the most influence over public opinion, which media companies have the most control over the flow of information and goods, or which individuals have the most followers.

There is a plethora of questions that involve measuring "impact," "influence" or "importance" using the information contained in the data on the communications between different entities, both within and across LTSS. There are also different measures of centrality, each of which provides a different perspective on the importance of an agent in a network.[8] Interestingly enough, however, the methods typically used are rather primitive. They basically involve "counting" links, contacts, citations, visualizations or any variable that measures "communication." Sometimes these methods "weigh counts" using arbitrary weights. As a result, numerous studies across various disciplines have employed diverse and often arbitrary counting methods, often without adequate justification. In essence, the abundance of potential "ranking methods" makes it challenging to have a preference for one approach over another. Relying on a method merely because it appears "reasonable" or produces intuitively sensible outcomes is, at the very least, a bad practice in terms of scientific rigor. In other words, establishing a meaningful measure of influence within LTSS or other communication frameworks is not possible without a careful examination of the properties of these methods.

In Palacios-Huerta and Volij (2004), we take an entirely different approach: rather than *assuming* arbitrarily a method, we *derive* a methodology. Specifically, we apply the axiomatic approach. This approach has already been successfully used in social choice, game theory, and other areas in economics. We obtain a rather surprising result: there is a *unique* measurement or ranking method that satisfies four simple desirable properties. Put differently, if you like these basic properties, you should also like the unique method that satisfies them to measure an agent's impact in a LTSS.

Consider the context of ranking agents according to their impact within a LTSS network

[8] Economists who have contributed to this field by developing various metrics and models to quantify influence and impact in different types of networks include Matthew O. Jackson, Sanjeev Goyal, and Daron Acemoglu.

of communications. Agents in a LTSS communicate with each other through "publications" that refer to each other, "links," or other measurable "contacts." Let me use the term "links" from now on.

The first property is *invariance to link intensity*. It requires that the absolute number of links that an agent gives to another agent should not affect the ranking as long as the distribution of its links does not change. Put differently, "only the content matters." An example from the academic literature. A citing article awards value to the articles it cites in its reference section. Given the content of the paper, the total value awarded to the articles that it cites cannot be increased or decreased by changing the amount of references. This property seems reasonable. It is like assuming that the value of an academic paper cannot be increased or decreased by leaving intact its content and changing the number of coauthors.

The second property concerns the simplest possible problems: those where there are only two agents in the LTSS. The property *homogeneity in two-agent problems* requires that in two-agent problems, the ratio of the agents' valuations be in a fixed proportion to the ratio of mutual links. Put differently, if there are only two agents communicating with each other in a LTSS, the import-export structure of their links should capture their relative impact.

The third property is *consistency*, which is useful to extend a ranking method from problems with few agents to "large problems" with more agents. The idea behind this property is that if we know how to rank agents in a small problem, we should be able to extend the method to a big problem in a consistent way.

The fourth and last property *invariance to splitting of agents*. It is useful to measure the impact not of a "LTSS agent" but of a "representative LTSS agent" when the agents themselves are heterogeneous in their elements. For example, if our agents are media conglomerates, not all companies within each conglomerate are exactly identical in their communication patterns. Yet, we may be interested in the "representative" agent within the conglomerate.

We show that these four properties characterize a *unique* ranking method. Interestingly, it turns out to be different from the methods regularly used to measure reputation, impact, influence, and prestige in the social sciences, although it is actually at the core of Google's search engine. Next I formalize these properties and give some examples.[9]

Let $\mathcal{J}$ be a countable set of LTSS agents. Let $J \subseteq \mathcal{J}$ be a finite subset of agents. A

[9] In what follows I reproduce the description in Palacios-Huerta and Volij (2004).

communication matrix for J is a $|J| \times |J|$ non-negative matrix (c_{ij}) where for each $i, j \in J$, c_{ij} is the number of links to agent i by or from agent j. For $j \in J$, $\bar{c}_j$ denotes the vector $(c_{ij})_{i \in J}$ of links by or from agent j, and the sum of all links by agent j is denoted by c_j, namely $c_j = \sum_{i \in J} c_{ij}$. All vectors are *column* vectors. For a vector v, $\|v\|$ denotes the 1-norm of v, namely $\|v\| = \sum_{i \in J}^{n} |v_i|$. The diagonal matrix with $d_1, \ldots, d_n$ as its main diagonal entries is denoted by $diag(d_1, \ldots, d_n)$. Given a matrix of links $C = (c_{ij})$, $D = diag(c_j)_{j \in J}$ is defind as the diagonal matrix with the sums of the links by the agents as its main diagonal. Further, CD^{-1} is called the normalized matrix of C. As the entries of each of its columns add up to one, it is a stochastic matrix.

Given a matrix of links C for J, we say that agent i *is linked or cited* by agent j if $c_{ij} > 0$. We say that agent i *impacts* agent j if there is a finite sequence $i_0, \ldots i_n$, with $i_0 = i$ and $i_n = j$, such that for all $t = 1, \ldots, n$, agent i_{t-1}, is linked or cited by agent i_t. Agents i and j *communicate* if either $i = j$ or if they impact each other. It is easy to see that the communication relation is an equivalence relation and, therefore, it partitions the set J of agents into equivalence classes, which are called *communication classes*. A *LTSS system* or just a *system* is a communication class $J' \subseteq J$ such that no agent in $J \setminus J'$ impacts any agent inside J'. If a matrix of links C has two systems, this means that there are two communication classes in J that are disconnected. Note that as long as a system J contains more than one agent, each $\bar{c}_j$ is a non-zero vector of links for each $j \in J$. Since we are interested in measuring impact within a single LTSS, we restrict attention to matrices of links with only one system. This leads to the following definitions:

Definition 1. An *influence ranking problem* is a triple $\langle J, a, C \rangle$ where $J \subseteq \mathcal{J}$ is a set of agents, $a = (a_i)_{i \in J}$ is the vector of *publications* of these agents, and $C = (c_{ij})_{(i,j) \in J \times J}$ is a links matrix for J with only one discipline.

Definition 2. *Isopublication ranking problems* are defined as the class of ranking problems where every agent has the same number of publications.

We are interested in building a *cardinal* ranking of the agents in J, namely a non-zero vector of non-negative valuations $(v_j)_{j \in J}$. Each v_j is to be interpreted as the overall value of agent i. Since only relative values matter, we can normalize the vector of valuations so that they add up to 1. Denote the set of all possible vectors of valuations of J by Δ_J. That is, $\Delta_J = \{(v_j)_{j \in J} : v_j \geq 1, \sum_{j \in J} v_j = 1\}$. Further, $\Delta = \cup_{J \in \mathcal{J}} \Delta_J$.

Definition 3. Let $\mathcal{R}$ be the set of all influence ranking problems. A *ranking method* is a function $\phi : \mathcal{R} \to \Delta$, that assigns to each problem $\langle J, a, C \rangle$ a vector of valuations $v \in \Delta_J$.

Here are some examples of ranking methods:

The *Egalitarian method* is the function that assigns the same value to every agent. Formally, $\phi_E : \mathcal{R} \to \Delta$ is defined by

$$\phi_E(J, a, C) = (1/|J|, \ldots, 1/|J|)^T.$$

The *Counting method* ϕ_C is defined by

$$\phi_C(J, a, C) = (\frac{\sum_{j \in J} c_{ij}/a_i}{\sum_{k \in J} \sum_{j \in J} c_{kj}/a_k})_{i \in J}.$$

The *Modified Counting method* awards each agent the proportion of its non-self-links out of the total number of non-self-links. Formally: $\phi_{MC} : \mathcal{R} \to \Delta$ is defined by

$$\phi_{MC}(J, a, C) = (\frac{\sum_{j \in J \setminus \{i\}} c_{ij}/a_i}{\sum_{k \in J} \sum_{j \in J \setminus \{k\}} c_{kj}/a_i})_{i \in J}.$$

The *Liebowitz-Palmer method* $\phi_{LP} : \mathcal{R} \to \Delta$ assigns to each ranking problem $R = \langle J, a, C \rangle$ the only fixed point of the operator $T : \Delta_J \to \Delta_J$ defined by

$$T(v) = \frac{A^{-1}Cv}{\|A^{-1}Cv\|}.$$

The *Invariant method* ϕ_I assigns to each ranking problem $R = \langle J, a, C \rangle$, the unique member of $v \in \Delta_J$ that satisfies $CD^{-1}Av = Av$.

It can be shown that the Liebowitz-Palmer and the Invariant methods are well-defined, although this is not trivial. Note also that these two methods assign to agent i a value that is a weighted average of some function of the links it receives: $v_i = \sum_{j \in J} \alpha_{ij} v_j$. For the Invariant method, $\alpha_{ij} = \frac{c_{ij}}{a_i} \frac{a_j}{c_j}$, while for the Liebowitz-Palmer method, $\alpha_{ij} = \frac{c_{ij}/a_i}{\|Cv\|}$. According to these measures, not all links have the same value. Being linked at by "important agents" is more valuable than being linked at by "less important agents." But the importance of an agent is determined *endogenously* and *simultaneously* with the importance of all other agents in the LTSS.

It is clear that one can think of an infinite number of ranking methods, the above examples being just a few. Therefore, in order to distinguish among different methods, it is necessary to evaluate the properties that each method satisfies. Consider the following basic, desirable properties:

Property 1. In order to motivate this property, consider a problem $\langle J, a, C \rangle$ where for each agent $j \in J$, agent j's list of links to other agents is given by the vector $\bar{c}_j = (c_{ij})_{i \in J}$.

The vector $\bar{c}_j$ represents agent j's "opinions" about the agents in J. These opinions do not change if agent j were to modify the number of links by multiplying it by a constant $\lambda_j > 0$, thus turning the vector $\bar{c}_j$ into the vector $\lambda_j \bar{c}_j$. The first property requires from the ranking method that it not be affected by such changes.

A ranking function ϕ satisfies *invariance to link intensity* if for every ranking problem $\langle J, a, C \rangle$ and for every non-negative diagonal matrix $\Lambda = diag(\lambda_j)_{j \in J}$ with some positive diagonal entries, $\phi(J, a, C\Lambda) = \phi(J, a, C)$. The following diagram exemplifies this property for isopublication influence ranking problems:

$$\text{if} \quad \begin{matrix} & i & j \\ i & a & b \\ j & c & d \end{matrix} \xrightarrow{\phi} (cv_i v_j) \quad \text{then} \quad \begin{matrix} & i & j \\ i & \lambda_i a & \lambda_j b \\ j & \lambda_i c & \lambda_j d \end{matrix} \xrightarrow{\phi} (cv_i v_j)\,.$$

The idea behind this property is that *only the content* matters: given the content of a publication, that publication has just one vote. Making an analogy again in the academic literature, given the content of a paper, the "value" of a paper is distributed among its references, and this value cannot be modified by leaving intact its content and changing the number of references. Similarly, as noted earlier, it could not be modified by changing the number of authors.

Recall that given a matrix of links C, the matrix D has the total number of links by each of the agents as its main diagonal. Therefore, the matrix $A^{-1}D$ has the agents' ratios of "cited references" per publication, $(c_i/a_i)_{i \in J}$, or "link intensities" ("citation intensities" in the academic literature), as its main diagonal. The above property says that differences in these ratios should not matter. The next two properties will concern ranking problems where all agents have the same link intensity, namely where $A^{-1}D = \lambda I$ for some $\lambda > 0$. Such problems will be called *homogeneous* problems.

PROPERTY 2. This property says that in two-agent problems where both agents have the same link intensity, the relative valuation of an agent should be proportional to the ratio of their mutual links or "citations". Formally, let $R = \{i, j\}, a, C$ be a two-agent problem such that $a_i = a_j$ and $(c_{ii} + c_{ji})/a_i = (c_{ij} + c_{jj})/a_j$. The ranking function ϕ satisfies *homogeneity in two-agent problems* if there is $\alpha > 0$ (that may depend on $\{i, j\}$ but not on a nor C), such that for all such problems, $\phi_i(R)/\phi_j(R) = \alpha c_{ij}/c_{ji}$.

The following diagram exemplifies this property for two-agent isopublication problems:

$$\begin{array}{c} \\ i \\ j \end{array}\!\!\begin{array}{c} \begin{array}{cc} i & j \end{array} \\ \begin{pmatrix} K - c_{ji} & c_{ij} \\ c_{ji} & K - c_{ij} \end{pmatrix} \end{array} \xrightarrow{\phi} (cv_i v_j) = \frac{1}{c_{ji} + \alpha c_{ij}} (c\alpha c_{ij} c_{ji}) .$$

The intuition is straightforward. The value c_{ij} is a measure of i's direct influence on j. Thus, the ratio c_{ij}/c_{ji} represents the direct influence of agent i on agent j relative to the direct influence of agent j on agent i. In general, one would like to take into account not only the direct influence of each agent on another, but also the indirect influences as well (e.g., i also affects h, which in turn affects k, which in turn affects j). This is why these ratios are not in general a perfect index of the agents' total impact. In a two-agent problem, however, the ratio c_{ij} *is* in fact a measure of the *total impact* of agent i on agent j since there are no other agents and hence no indirect effects. We stress that this property only concerns two-agent problems.

PROPERTY 3. The property of *consistency* allows us to relate "large problems" to "small problems." Thanks to this property, if we know how to solve a ranking problem with few agents, we will also know how to solve problems with a greater number of agents.

Let $R = \left\langle J, (a_i)_{i\in J}(c_{ij})_{(i,j)\in J\times J}\right\rangle$ be a ranking problem, and let k be an agent in J. The reduced ranking problem with respect to k is $R^k = \left\langle J \setminus \{k\}, (a_i)_{i\in J\setminus\{k\}}(c^k_{ij})_{(i,j)\in J\setminus\{k\}\times J\setminus\{k\}}\right\rangle$, where:

$$c^k_{ij} = c_{ij} + c_{kj}\frac{c_{ik}}{\sum_{t\in J\setminus\{k\}} c_{tk}} \qquad \text{for all } i, j \in J \setminus \{k\}.$$

Note that since $(c_{ij})_{(i,j)\in J\times J}$ is irreducible, $\sum_{t\in J\setminus\{k\}} c_{tk} > 0$, and hence, R^k is well-defined. Further, $(c^k_{ij})_{(i,j)\in J\times J}$ is itself irreducible.

The reduced problem represents the following situation. Suppose we want to rank the agents in J and our computer cannot deal with $|J| \times |J|$ matrices but only with $(|J| - 1) \times (|J| - 1)$ matrices. Therefore we need to abstract from one agent in our data set, say agent k. Still, we are interested in the relative values of all the remaining agents. If we eliminate agent k, we lose some valuable information. So we are interested in a slighlty modified matrix so that the information of the missing agent k is not lost. In the old matrix, c_{kj} was the number of links to agent k by agent j. We need to redistribute these links among the other agents. Clearly, an intuitive way to do so is in proportion to the links (citations or opinions) by the missing agent k. In other words, agent j gave credit to agent k in the form of c_{kj} links, while agent k gave credit to the agents other than k according to the vector $\bar{c}_k$ of links by k. Therefore, we need to redistribute each of the c_{kj} links, $j \in J \setminus \{k\}$, according to the relative impact of the agents on k, that is in proportion to the values in $\bar{c}_k$. If this is the correct method to recover the information lost, we should expect that our ranking method give, at least in homogeneous problems, the same relative valuations to the agents in $J \setminus \{k\}$, if applied either to the original problem or to the modified, reduced one.

The ranking function ϕ satisfies *consistency* if for all homogeneous problems $R = \langle J, a, C \rangle$ with $|J| > 2$, and for all $k \in J$,

$$\frac{\phi_i(R)}{\phi_j(R)} = \frac{\phi_i(R^k)}{\phi_j(R^k)} \qquad \text{for all } i, j \in J \setminus \{k\}.$$

To sum up, this property requires from a ranking method that the relative valuations of the agents of a homogeneous problem not be affected if we apply the method to the reduced problem with respect to k.

Property 4. Finally, we extend the analysis to study the impact not of a "LTSS agent," but the impact of a "representative LTSS agent." Again, to make an analogy, not all academic papers that a journal publishes are the same, much like not all the websites, newspapers or radios of a given media conglomeate are the same. If we want to turn to the problem of evaluating the influence of, say, media conglomerates according to their "representative" newspaper or tv-station, we need an additional property. The new axiom requires that the splitting of an agent (journal, media group) into several identical but smaller agents does not affect the ranking.

Formally, suppose that an agent $j \in J$ splits into two identical agents. Specifically, j splits into agent $(j,1)$ and agent $(j,2)$, each with $a_j/2$ publications. Further, for these two new agents to be equivalent, the links or citations are also split: the vectors of links by agents $(j,1)$ and $(j,2)$ to the other agents are equal and given by $\bar{c}_j/2$. Also, the links of agent j are equally split: each agent $i \neq j$ is linked at or "cited" $c_{ij}/2$ times by each of the newly born agents. Lastly, the self-links c_{jj} are equally split between the two agents, giving $c_{(j,\alpha),(j,\beta)} = c_j/4$ for $\alpha, \beta = 1, 2$. For a case of a two-agent problem, this split is illustrated as follows:

$$\begin{array}{c} \\ i \\ j \end{array} \begin{array}{c} \begin{array}{cc} i & j \end{array} \\ \begin{pmatrix} c_{ii} & c_{ij} \\ c_{ji} & c_{jj} \end{pmatrix} \end{array} \longrightarrow \begin{array}{c} \\ i \\ (j,1) \\ (j,2) \end{array} \begin{array}{c} \begin{array}{ccc} i & (j,1) & (j,2) \end{array} \\ \begin{pmatrix} c_{ii} & c_{ij}/2 & c_{ij}/2 \\ c_{ji}/2 & c_{jj}/4 & c_{jj}/4 \\ c_{ji}/2 & c_{jj}/4 & c_{jj}/4 \end{pmatrix} \end{array}.$$

We would like this split of agent j not to influence the ranking.

Let $R = \left\langle J, (a_j)_{j\in J}, (c_{ij})_{(i,j)\in J\times J}\right\rangle$ be a ranking problem. Each agent $j \in J$ will be split into $T_j \geq 1$ identical agents, denoted (j,t), for $t = 1,\dots T_j$. Let T_j denote both the number and the set of "types" of agents j. The resulting ranking problem is $R' = \left\langle J', (a_{j,t_j})_{j\in J, t_j\in T_j}, (c'_{(i,t_i)(j,t_j)})_{((i,t_i),(j,t_j))\in J'\times J'}\right\rangle$ where $J' = \{(j,t_j) : j \in J, t_j \in T_j\}$, $a_{j,t_j} = a_j/T_j$ and $c'_{(i,t_i)(j,t_j)} = \frac{c_{ij}}{T_i T_j}$. We call the problem R' a split of R, and we denote its links or "citation" matrix $(c'_{(i,t_i)(j,t_j)})_{((i,t_i),(j,t_j))\in J'\times J'}$ by C'. As mentioned above, we would expect a split of an agent not to affect the relative valuations of the publications. This is the requirement imposed by the following property.

A ranking method ϕ satisfies *invariance to splitting of agents* if for all ranking problems R and for all its splittings R' we have:

$$\phi_i(R)/\phi_j(R) = \phi_{i,t_i}(R')/\phi_{j,t_j}(R') \qquad \forall i,j \in J \text{ and } \forall t_i \in T_i \text{ and } t_j \in T_j.$$

We are now ready to characterize the only ranking method that satisfies all the properties described so far.

Theorem 1. *There is a unique ranking method that satisfies invariance to citation intensity, homogeneity for two-agent isopublication problems, consistency, and invariance to splitting of agents. This is the Invariant method* ϕ_I.

Lastly, I note that ϕ_I is at the core of Google's search engine. In Palacios-Huerta and Volij (2014) we review other results of the axiomatic approach to measuring impact. This is a literature whose main results have been obtained only recently and that it is currently evolving. Here, I have simply attempted to discuss why the axiomatic approach is necessary for general measurement of impact problems within LTSS.

4 Conclusions

Globalization 3.0, in which the world went from small to tiny, may have started around 2000. It is not unreasonable to think that the advent of new LTSS may have moved the world to Globalization 4.0 in only a couple of decades since then. As such, LTSS may have likely enlarged, and perhaps made more complex, the problem of humanity defined by Edward O. Wilson as the intersection between Paleolithic emotions, medieval institutions and god-like technology. For emotions and institutions do not change as fast as technology. I have reflected here on two of the main topics that arise in LTSS and that capture what in my view are among the most important issues associated with that intersection.

I write that the problem may have "perhaps" been made more complex, but this is no more than a conjecture. It could well be that drastic improvements in technology are making the problem *simpler*. For one, contact processes at a scale not know until recently may have made "markets" more complete, improved the informational content of prices (both actual and shadow prices) that guide efficient allocations, improved the amount and use of knowledge in society (Hayek (1945)), and increased the rate of return to new ideas, especially now that are ideas are getting more scarce (Coase (1974), Bloom et al (2020)). Indeed, knowing about the impact of new LTSS on that intersection is no simple matter.

What we do know is that history provides important support for the role *ideas* and the *transformation of culture* as key drivers of human betterment, especially for the less fortunate. Deirdre McCloskey's (2006, 2010, 2016) trilogy, for example, serves as a reminder of the exceptional nature of economic growth. Indeed, at the heart of contemporary economic history lies a profound puzzle: Why did the phenomenon of modern economic growth manifest itself at a specific time and place? Why did it choose England as its incubator, and why did it choose the 18th century as its birth period? In essence, the thesis is that it was the transformation of culture that paved the way for social and economic evolution. The capacity for vast wealth creation on an unprecedented scale emerged when we no longer considered wealth creation as a tainted pursuit (Hirschman (1977)), and when society started to value the principles of the middle class as much as those of the aristocracy. Ideas and culture within early and arguably rudimentary LTSS did show, however, how "the great enrichment" benefited especially the less fortunate. It was the greater equality of "respect" (dignity) and opportunities, the greater equality of rewards for equal merits (which is different from the pursuit of equality in outcomes, a characteristic of socialism and paleo-marxism), and the greater equality before the law.

This in turn leads to the impact of institutions. Here an issue is the inertia of established narratives that run contrary to historical facts. Surely, these inertias are challenging to overcome, especially those that repeatedly appear in educational textbooks and in the media. And this is perhaps more difficult when media and philosophers lack a basic understanding of economics (see, e.g., Tirole (2017) and his analysis of some of Michael Sandel's arguments), and when the "struggle between technology and prosperity" may motivate public sector interventions (e.g., regulations) that are unwarranted, or at least excessively optimistic (see, e.g., McCloskey (2023) on Acemoglu and Johnson (2023)). These and others are powerful reasons why the institutional responses to new LTSS are difficult to predict, need not move in the ideal directions and may in fact well go in the wrong directions. Predictions are always hard, especially about the future as the old Niels Bohr joke says, but equilibrium models that include an interaction between preferences (emotions), institutions (including markets) and technology show promise for enhancing our understanding (see Palacios-Huerta (2013)). The difficulties are hard but not impossible to defy and, frankly, there is no practical alternative.

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