# Applicability of Markets to Global Scheduling in Grids

—Critical Examination of General Equilibrium Theory and Market Folklore—

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NAS Technical Report NAS-03-004

February 2003

**Abstract**

Markets are often considered superior to other global scheduling mechanisms for distributed computing systems. This claim is supported by: a casual observation from our everyday life that markets successfully equilibrate supply and demand, and the features of markets which originate in the general equilibrium theory, e.g., efficiency and the lack of necessity of a central controller. This paper describes why such beliefs in markets are not warranted. It does so by examining the general equilibrium theory, in terms of scope, abstraction, and interpretation. Not only does the general equilibrium theory fail to provide a satisfactory explanation of actual economies, including a computing-resource economy, it also falls short of supplying theoretical foundations for commonly held views of market desirability. This paper also points out that the argument for the desirability of markets involves circular reasoning and that the desirability can be established only vis-à-vis a scheduling goal. Finally, recasting the conclusion of Arrow's Impossibility Theorem as that for global scheduling, we conclude that there exists no market-based scheduler that is rational (in the sense defined in microeconomic theory), takes into account utility of more than one user, and yet yields a Pareto-optimal outcome for arbitrary user utility functions.

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# 1 Introduction

Computational grids (or grids, for short) are collections of resources (CPUs, networks, disks, data acquisition devices, etc.), unified into an infrastructure that supports transparent access by application engineers. They typically span multiple administrative and geographical domains. It is commonly believed that grids are best operated as batch systems, that is, if accessing them takes place through global scheduling of jobs. For the purpose of this discussion a job is considered a collection of finite, known demands on computational resources.

Markets may be employed in computational grids as mechanisms for global scheduling, i.e., for matching jobs to be run and computing resources, and markets are very often deemed superior to other scheduling mechanisms [10, 12, 14, 17, 30, 37, 44, 46, 61, 63, 64, 69, 70, 71]. Efficiency and the lack of necessity of a central controller are usually mentioned as markets' attractions.

The purpose of this paper is to describe why such beliefs in markets are not warranted. That is, we put forth an argument for inadequacy of what is considered the foundation of the beliefs in markets. As our argument makes use of concepts and terms in economics, the important ones (including a term in computer science) appear in bold at the first instance in the paper and are explained in the glossary, which can be found at the end of the main text. The foundation consists of the prevailing perception of actual economies and the **general equilibrium theory** (hereafter abbreviated as the GE theory, see Glossary), including its conclusions, which are known as the **fundamental theorems of welfare economics**. We also discuss the tautological element in the reasoning for the desirability of markets. **Arrow**'s Impossibility Theorem (references include: [45]), which is independent of the theory, also shows that a market-based scheduler cannot be preference-rational[1] and inclusive of all user preferences at the same time. Our argument does not serve as one against markets as mechanisms for global scheduling, however. Markets may well be the best possible mechanism. We argue that the reasons widely prescribed to in believing so are misplaced; there is no *a priori* reason to believe that markets provide the most desirable scheduling function, especially not without specifying the goal of scheduling.

The main part of our problem can be partitioned into three subproblems: the problem of scope, that of abstraction, and that of interpretation. First of all, we touch upon the problem of scope. Some phenomena are considered important, but not explained by the GE theory, such as **market failure** and economically beneficial intervention by **government**s (i.e., central authorities). One of the fundamental theorems in welfare economics (which requires that the economies satisfy the basic premise of the GE theory) supports a **Pareto optimal** outcome (an outcome in which welfare of no individual can be improved without sacrificing that of others) by markets alone, i.e., without any conscious effort by the participants to reach global optimality. However, actual economies do not exactly satisfy the assumptions of the GE theory; economies in the real world are not true **Walrasian** economies, and Pareto optimality of outcomes is not guaranteed.[2] It is impossible, in the vast majority of cases, to verify whether an outcome attained by an actual economy is Pareto optimal or not. Thus, we focus on so-called market failure cases. For the well known examples of market failure, the undesirability of the outcomes and their cause (i.e., violation of the perfect-market assumption) are widely accepted by the economic profession. We conclude that markets for computing resources are subject to market failure.

[1]In microeconomic theory, economic agents are rational when their preferences are complete, transitive, and reflexive. We distinguish rationality in microeconomic theory from rationality in everyday usage, as needed, by referring to the former as preference-rationality.

[2]As it was **Walras** who laid the foundation of the GE theory, an economy described by the theory is often referred to as Walrasian. In accordance with the custom in economics, we take the word, Walrasian, to mean: of general equilibrium theory.

We further argue that what we perceive as the powerful market mechanism in everyday life *cannot* be traced back to the GE theory; there is a problem of abstraction. For this purpose, we turn to the debate on **market socialism**, an attempt to apply the theory to reality. It concerns two manifestations of the theory: one as an economy based on market capitalism and another as one based on market socialism. The debate elucidates the essential components of markets and their functions in practice; it examines which conditions are necessary for a market to operate successfully in the real world, a consideration which is directly relevant to and important in employing the theory as the basis for a global scheduling mechanism. With these points in mind, we provide an analysis of that debate, known as the Socialist Calculation Debate.

The last subproblem is that of interpretation. Not only do we see some difficulty in accepting the GE theory as an ultimate *explanan* of actual economies, but we also see limitations in the theory itself. By theoretical limitations, we mean incompatibilities among desirable aspects and properties of economies, which can be regarded independent of institutional arrangements (such as organizational structures of a government or central authority), for economies that perfectly satisfy the assumptions necessary for the theory's validity. We draw on Leonid Hurwicz's works [31, 32] for describing such limitations. Furthermore, we examine the principal virtues which markets are said to possess, i.e., their ability to fulfill a global goal when the participants in the markets are unaware of the goal [10, 14, 46], and sparsity of communication required [14, 30, 46, 70]. We point out that there is a practical problem associated with price as a perfect information carrier; it may embody all pertinent information, but it is not accompanied by a device that allows **economic agents** to infer the precise condition of the economy. The discussion of the problem of interpretation includes references to market stability and the circular reasoning in the argument in favor of markets.

Market-based global schedulers usually employ artificial agents in lieu of users, hence we discuss the role of artificial agents in relation to the GE theory. Finally, we advance the view that a **preference-rational**, market-based scheduler that accommodates all types of **utility** cannot possibly take all user utility into consideration and still allocate resources in a Pareto-optimal fashion; markets do not have an obvious advantage over other scheduling mechanisms.

## 2 Real-World Markets and General Equilibrium Theory: Problem of Scope

Before we examine whether market mechanisms serve well as global schedulers for computational grids, we ask a more fundamental question: Do markets function well? This is rather an ideological question, more so than its first impression suggests. On one hand, we may say that markets work well, based on our daily experiences of being able to purchase most of the things we require. We may further assert that market-based economies' superiority over command economies was proven by the collapse of the USSR and its satellite countries, one of whose crucial elements is believed to be an economic one. On the other hand, we may also say that markets do *not* work well by citing examples such as high unemployment rates that occasionally persist (as was the case in France during the 1980s and most of the 1990s), the energy crisis of 2001 that stemmed from the deregulation in the energy industry in California, and the necessity of circuit breakers for stockmarkets. Those who believe in markets' superb functionality may argue that undesirable outcomes are caused by inappropriate institutional arrangements which attenuate the market forces. Examples include the Russian economy, which, according to market purists, would be growing fast once market forces would be allowed to work in an unhampered manner, and the emission of sulphur oxides, which can allegedly be curbed only through creation of complete markets for emission rights in the future. Whichever camp may be closer to the truth, what we appear to agree on is that there is some room for improvement in real-world markets; whether too much or too little is left to markets, they are not entirely desirable as they are now. We also seem to agree that there exists neither an economy purely based on markets alone, nor one based on commands from a central authority alone, and that, even if brought into existence, neither would be ideal.

We listed above some real-world cases which can be interpreted as refutation of infallibility of markets. We discuss more of them below, which are collectively named market failure. Their outcomes are not Pareto optimal, due to the violation of a condition which an economy needs to meet if it is to be described by the GE theory. Our argument is that the GE theory does not provide an all-encompassing picture of actual economies and that market failure is a case in point. We conclude that the environment for computing-resource markets is not what the GE theory successfully explains; the environment is likely to fall under the case of market failure. Consequently, reliance on the GE theory as the theoretical foundation for market-based scheduling amounts to application of the theory beyond its scope.

## 2.1 The Premises of the General Equilibrium Theory

Despite its guise of wide applicability, the GE theory is meant as a description of a rather special type of economy. In Hurwicz's terminology [31, 32], the GE theory concerns a specific **environment** and a particular **mechanism**. The environment, as defined by Hurwicz, is a set of resource endowments, the production technology (i.e., the numerical relationship among the amounts of inputs and output), and individual preferences. The theory deals with a specific environment: the **classical environment**. That is, there exists no **externality**, no **indivisibility**, **local nonsatiation**, technology is **convex** with respect to inputs (i.e., **convex technology**), and preferences of economic agents are convex and continuous with respect to goods consumed [31, 32].[3] Additionally, there should be universal price quoting of commodities, or market completeness. Transfer of initial endowments must be permissible [45]. A mechanism is the totality of behavior patterns which allows prediction of economic **state**s, given the environment and the initial state [31]. Its description does not overlap with those of environment and state [31]. Moreover, a set of behavior patterns is **incentive compatible** if it leads to a Nash equilibrium, i.e., no agent wishes to deviate from those patterns, provided that others also do not deviate [32]. **Perfect competition** is the mechanism that drives an economy described by the GE theory. Following Hurwicz further, we employ the concept of Pareto-satisfactoriness for mechanisms, which is a shorthand for the combination of three properties: **Pareto nonwastefulness**, **unbiasedness**, and **essentially-single-valuedness** [31, 32]. A mechanism is nonwasteful over a class of environments when its outcomes are optimal, unbiased over a class of environments when all optima are attainable by allowing redistribution of initial endowments, and essentially-single-valued if equilibria (which are supported by the same mechanism and environment) are indistinguishable in terms of utility for all agents [31, 32]. Subsequently, we see that the GE theory (or more accurately, the set of fundamental welfare theorems) simply says: "the [perfectly] competitive process is Pareto-satisfactory over classical environments" under the condition that markets are complete and redistribution of initial endowments is allowed [32, 45]. We discuss below implications of the theory in this framework.

## 2.2 Market Failure or Imperfect Competition

Market failure literally means malfunction of markets, and intuitively, we may think of market failure as a situation in which markets by themselves do not succeed in providing a good demanded at

[3] We only need the no-local-satiation condition for the first fundamental welfare theorem to hold.

a "reasonable" price. Lack of supply of a good may be considered equivalent to an infinitely high price for that good. Market failure, thus defined, is not uncommon. For example, firms are inclined not to take into account the environmental impact of their production activities, unless consumers actively and explicitly boycott products that are environmentally destructive; the environment is often offered to firms at no cost, i.e., at an "unreasonably low" price, if there is no pertinent regulation. Utility firms tend to charge "unreasonably" high prices in the absence of regulations on pricing, because of their monopolistic nature. During the past few years, many pharmaceutical drugs have become short in supply [3], i.e., available only at an "unreasonably" high price.

We may discuss market failure in a more precise manner by considering cases with little political and institutional effects. In microeconomic theory, market failure is observed whenever a market is not perfectly competitive, hence leading to a result that is Pareto inefficient. Imperfect competition includes absence of markets, as is the case for many environmental "goods," for example, clean air. A market is guaranteed to attain a **Pareto efficient**[4] outcome only if all of the following conditions are met. All market participants are price takers (excepting price-adjusting agents, such as auctioneers, and implying a perfectly competitive market), all relevant goods are exchanged in the market, each of them is associated with one price which is public knowledge, initial redistribution of endowments is permissible, and preferences of the participants are locally nonsatiated [45]. In connection with the loose, intuitive definition of market failure, we may say that a price becomes "unreasonable" when competition is imperfect and there are not enough market participants to make the price responsive to the market condition. Consequently, we see that market failure in the intuitive sense is also market failure in the theoretical sense.

Microeconomic theory has identified four causes which render competition imperfect, leading to market failure. The first is concentration of market power that results in monopoly or oligopoly, i.e., a small number of firms in the market. This may arise from the nature of production technology (e.g., the fixed cost is too high to support more than one profitable producer in the market) or from barriers erected by the firms already in the market to deter entry by other firms (e.g., an increase in production capacity once entry is anticipated [45]). The aircraft manufacturing industry belongs to the technology case, and the PC operating systems industry belongs to the barrier-to-entry case. The second cause is externality. An economic activity of one agent may affect the welfare of another; some activities have external effects. A typical case is environmental pollution caused by firms' productive activities in a community which values the environment. The public nature of some goods constitutes the third cause. Since the provision of a public good by one individual does not exclude others from benefiting from the good, there is usually too little provision of such goods (i.e., Pareto inefficient outcome) if left to the markets. Examples include transportation infrastructure, national defense, and environmental quality. The last major cause of imperfect competition is imperfection in information, or information asymmetry. The GE theory assumes a market for every good distinguished by its characteristics. That, in turn, requires that all economic agents are capable of making such distinctions: perfect information. When some agents know more than others, we have a condition called information asymmetry. In the labor market, for example, prospective employees know more about themselves than employers, and the candidates have an incentive to convey only the information that they think would lead to landing jobs. A similar situation is observed between insurance sellers and buyers, as well as in markets of goods whose quality cannot be assessed until they are in use, such as second-hand cars. In sum, instances of imperfect competition, with their concomitant market failures, are far from unusual or rare.

[4]Efficiency in microeconomic theory specifically means Pareto efficiency, which means no agent's utility can be improved without harming the utility of others. We simply write "efficiency," where the word is to mean a desirable property that is broader than Pareto-efficiency, as is the case in our daily discourse, but without giving a precise definition. For a further discussion, see Section 4.4.

Our observation that there are many cases of market failure, or imperfect competition, in the real world does not reduce the importance of competition [27, 62]. Information on a production method, which may lead to higher sales and lower costs, is obtained by producers as they compete with each other [24, 27, 40, 62] and search for alternatives [24, 40, 48]. However, such competition is different from perfect competition in the GE theory. The producers in real-world economies who engage in competition often have some influence over prices; they are not price-takers as assumed in the theory [27, 62]. In short, the theory does not deal with an economic mechanism that makes most actual economies function. This point will be further discussed below in connection with the Socialist Calculation Debate.

## 2.3 Markets for Computing Resources and Market Failure

As we saw above, the GE theory concerns a competitive process in the classical environment (no externality, no indivisibility, local nonsatiation, convex technology, and convex, continuous preferences). The presence of externality leads to a noncompetitive process, and **demurrage** is an example of externality. Indivisibility is particularly relevant to the problem of computing resource allocation, as many of the resources are measured in integers, i.e., they are indivisible. Roughly speaking, the condition of local nonsatiation translates into sufficient differentiation among various combinations of commodities in terms of utility.[5] Whether this condition is satisfied in commonly encountered situations has not been a topic of active research so far. Most likely, there will be no production of computing resources in the computational grid, hence the question of the nature of technology would not arise. While it is probably impossible to conduct a satisfactory theoretical investigation of an economy as a whole without convex and continuous preferences (at least, with the current state of the art in mathematical analysis), it has been pointed out that preferences of economic agents are not characterized completely by preference-rationality and self-interest [66, 67], which are the most common assumptions that justify their convexity and continuity.[6] Our conclusion is: The environment for a computing-resource market is unlikely to be the classical one, for which the GE theory is meant.

## 2.4 Other Unexplained Phenomena

We discuss below important phenomena for which the GE theory offers little explanation, if any: government policy (or, policy of a central authority) and trust among economic agents. It has been widely acknowledged that government policies played—at least some—role in the rapid industrialization process of the East Asian countries [68, 72]. While not all policies may have been beneficial to these economies, no economist of any ideological stripe has argued that these countries would have been better off if their governments had implemented none of those policies. The American airline industry has been in chaos since its deregulation [62]. Left to the market, the U.S. cell-phone industry has ended up with five incompatible standards; this has significantly diminished the usefulness of the service compared to that in Europe, where there is a single standard agreed upon by the national governments [16]. Clearly, the positive role of the government, or equivalently, the imperfect nature of markets, is acknowledged, but only implicitly.

Market participants' sole interest in attaining the highest utility, which usually consists only of material gains to themselves, is considered the drive behind market processes leading to the most desirable allocation of resources. As Arrow [2], and subsequently Stiglitz [62] and Fukuyama [18] argued, economic transactions require trust that agreements are honored; if cheating is rampant,

[5] When preferences are locally nonsatiated, "thick" **indifference set**s are excluded [45].

[6] Attempts at modeling the preference-nonrational behavior of individuals include the work by Rubenstein [57].

eventually very few transactions will take place, much fewer than the number required for a desirable and attainable allocation of resources. The existence of various industrial standards support this assertion. As Stiglitz [62] put it, firms "create, sometimes deliberately, information problems for consumers." Thus, markets cannot function well if the participants were self-interested in the short term and do not take strategic considerations of their actions into account (e.g., what kind of impact one's own action would have on others' choices of their actions), as is the case with the participants in the Walrasian economy. There is also a gap between perceived and actually realized personal gains (e.g., gains from firm takeovers [62]), which invalidates the simple claim that pursuit of self-interest is desirable.

# 3 Socialist Calculation Debate: Problem of Abstraction

We examine from a different angle the issue of whether the general equilibrium (GE) theory represents what makes a real-world **market economy** function. That is, whether the theory pertains to those features that are deemed desirable in the construction of market-based computing-resource schedulers. We carry out the examination of the problem of abstraction based on an intense debate between the market-socialists on one side, e.g., **Lange**, **Taylor**, and the **Austrian school** of economists on the other, e.g., **von Mises**, **Hayek** (hereafter called the Austrians).

We briefly describe the connection among market economies, market-socialist economies, and the GE theory, including the fundamental welfare theorems. Subsequently, we proceed to examine how relevant the theory is for a market economy and a market-socialist economy. While we focused on the adequacy of the premise of the theory in the previous sections, our attention is now on the elements of real-world economies which are excluded by the theory and how important they are if a system is to operate in the manner displayed by real-world markets.

## 3.1 Two Sides of the Coin: Market and Market-Socialist Economies

Starting from the point of view that the GE theory correctly and sufficiently describes the workings of a market economy and that such workings produce desirable outcomes (i.e., Pareto-optimal allocations, as summarized by the first fundamental welfare theorem), market-socialists strove for establishment of a system based on the theory that leads to outcomes identical to (or better than) those of a market economy, where the means of production is publicly owned, unlike in a market economy. Their hope was to eliminate the waste and inequality which they saw under capitalism [7]. Freedom of choice in consumption and occupation was to be maintained in a market-socialist system [38, 65], as the usefulness of markets and pricing was acknowledged [48]. Their position was that any Pareto-optimal outcome is attainable if redistribution of initial endowment is allowed, as the second fundamental welfare theorem states,[7] and that the process of perfect competition can be recreated by the authority, who assumes the role of auctioneer in the **tâtonnement process** in the GE theory (i.e., the trial-and-error process involving an auctioneer to reach an equilibrium in prices and quantities demanded and supplied).[8] Consumers' needs (which are formulated under budgets insufficient to purchase all they fancy), were to be satisfied by prohibition of rationing and through

[7]As discussed above, the second fundamental welfare theorem is valid only in classical environments. Moreover, redistribution has informational and enforceability problems.

[8]Practicality has been defined differently by the economists engaged in the Debate [6]. In the eyes of market socialists, their system gained practicality through employment of the tâtonnement process [38, 65]. This assertion was considered to have weakened **Barone**'s conclusion that socialism is impractical as a mathematical exercise [40]. Kantorovich [34, 35] also demonstrated mathematically how a planned economy could succeed, which earned him the Nobel Prize in 1975. As will be discussed below, the tâtonnement process does not quite describe a market economy in reality.

price setting by a central authority "as the only method of balancing quantities demanded and quantities supplied" [38]. In describing the price determination mechanism in a market-socialist system, Lange [38] asserted that there would be a unique set of prices (note that the validity of this statement has been proved only under the premises of the GE theory). The market socialists believed that the adjustments required to reach an equilibrium would be small, ignoring the continuous changes faced by the actual economy [40].

The idea that the authority only needs to act as an auctioneer, whose duties do not require any knowledge of firms' technologies, appealed to the market socialists [56]. In other words, for capitalism and for market-socialism, the same economic principles apply, according to Pareto, Barone, and Taylor (as quoted by Lippincott [42]), and the same process will be appropriate, according to Landauer (as quoted by Hayek [21]). The only difference would be how the prices are set (whether by markets or by the authority), who owns the means of production, according to Lange, **Lerner**, and Taylor (as quoted by Stiglitz [62]), and how inputs and outputs of production are determined [7].

Not all economists subscribe to the equivalency. Hayek argued that the problems facing the two types of economic systems are different because the needs of consumers necessarily differ and because we do not have an unambiguous social-welfare goal [21]. Observing the Hungarian economy, Kornai [36] reached the conclusion that a market cannot be simulated by a bureaucracy, unlike Lange had envisioned (e.g., rules can perfectly reproduce the effects obtained by free entry and exit of firms [38]).[9] Kornai also observed that a centrally controlled system without private ownership tends to create chronic shortage by its very nature, and not an equilibrium between supply and demand as Lange had hoped [36].

Lange emphasized that the similarity was only formal and that the socialist system was more preferred; the authority could distribute income so as to maximize social welfare, and prices could be set so as to reflect true social value [38]. In fact, Lange argued that the capitalist system in practice was not exactly as the GE theory implied and that a socialist system can better implement the theory with potentially a shorter time required to reach an equilibrium [39]. Additionally, market socialism was expected to avoid monopolistic or non-price-taking behavior of firms [62], which is the problem of capitalism raised by Karl Marx, albeit phrased slightly differently.[10] Market socialism was thought to be superior thanks to its planning capabilities, which are indispensable for efficient resource allocations, especially with respect to investment [38], but lacking in markets [39, 62].[11] Lange [38] also believed that the central authority would have better knowledge of the economy than any entrepreneur, making the tâtonnement process more suited to a socialist economy (e.g., faster attainment of an equilibrium) and allowing more informed decision making that better matches the social goal. According to Kornai [36], the assumption which underlies the alleged advantages of market socialism—a partly market and partly planned system—is that market and bureaucracy are complementary. However, the Hungarian experience showed that the combination is unlikely to produce the "best of two worlds" and that a practical separation of the two is impossible [36].

We have already argued by pointing out market failure cases that the GE theory does not explain all the possible economic situations in a market economy. Neither were socialist economies in

[9] While maintaining the position that the functions of markets can be perfectly replaced by rules given to the managers, Lange [38] did point out "the real danger of socialism," i.e., "bureaucratization of economic life."

[10] Ironically, many production units in socialist economies operate in a monopolistic or oligopolistic environment. They are subject to many of the trappings of monopolistic or oligopolistic firms in a capitalist economy, including successful lobbying for more resources [36]. The loss of welfare from monopoly is rather small, according to Stiglitz's [62].

[11] Lange [39] goes as far as to say that markets deal with a static problem, turning around the criticism directed at the market socialists by the Austrians.

reality any closer to the state described by the theory [21]. For Stiglitz [62], the problem with market socialists lay in their mistaken belief that the GE theory was a reliable description of a market economy: "[T]he standard analysis underestimated the strength—and weakness—of market economies."[12] In the following subsection, we take up this issue: The general equilibrium fails to describe the essential elements of a market economy in the real world.

### 3.2 What General Equilibrium Theory Leaves Out

The Socialist Calculation Debate is about the validity of the GE theory as a description of economic principles and the theory's applicability to different institutional settings, rather than about determining the superiority of capitalism over socialism or *vice versa*. As a comparison of the two systems, it was a derailed debate; the "preoccupation with concepts of pure economic theory ha[d] seriously misled" the participants in the Debate [24].

We argue below that the GE theory leaves out many important elements that are indispensable for successful operation of actual market economies: quick responses to changes in the environment, communication of information through competition among the producers, and incentives that, at least partly, emanate from private ownership (and entrepreneurship). We regard technology acquisition, innovation efforts, etc., as part of entrepreneurship. We also argue that real-life competition, which requires successful firms to engage in innovative activities, is distinct from perfect competition in the GE theory. Most of these issues were brought to attention by von Mises, Hayek, and Robbins, over several decades, starting in the 1920s, and quickly became the central issue in the Debate. They can be bundled together as problems of dynamics, which the proponents of the GE theory as well as Lange and his followers have taken rather lightly [40]. The focus of the Debate became more diffused when Lange defended market socialism with the reasoning that the tâtonnement process is manageable as a calculation problem, and hence is practical [38, 39]. By advancing such a defense, "[t]he market socialists offered a response to the wrong argument" [40].

To the above list of factors that are crucial but missing from the theory, Stiglitz [62] added: the possibility of an equilibrium when demand is not equal to supply, the infeasibility of decentralization through price, the necessity of strictly positive profits (firms in the GE theory earn zero profit), the nonexclusivity of price in resource allocation, the possibility of coordination failures (which originates from incomplete markets and incomplete information), the existence of nonlinear price systems, and the diversity of capital allocation mechanisms. He also questioned one of the Austrian arguments that private ownership, or assignment of property rights, is at the core of the incentive problem, by citing the fact that shareholders do not have control over all aspects of firms, that non-financial incentives in addition to financial ones play an important role, and that banks exercise influence over firms' decision making [62].

Moreover, the theory does not differentiate the various types of market economies, whereas in reality their outcomes vastly differ from each other. For example, the performances of the German and the U.S. economies have been far from identical, and the difference has been duly noted [1]. Both economies have experienced moments of apparent market malfunction, a phenomenon that remains unexplained by the theory.

Theory is an abstraction from reality. This necessitates adoption of assumptions by a theory as an explanation of reality. Stiglitz [62] argued that the results of the fundamental welfare theorems are sensitive to assumptions, notably that of perfect information (which is necessary for perfect competition as we saw above); the GE theory cannot be said to describe actual economies satis-

[12] The most flagrant problem was the assumption of perfect markets, which cannot be supported once the issue of imperfection of information is taken into account [62].

factorily.[13] Refutation of a theory based solely on the inadequacy of assumptions is not usually accepted in economics.[14] Today the economics profession has come to accept the GE theory as a tool for exploring large-scale economic changes that would be brought about through implementation of policies [45, 56, 58], especially those that macroeconomic models do not cover [58], rather than a theory that explains the precise and essential workings of an economy. It is mostly used in the realm of taxation [58] and international trade [56, 58].

Turning to the socialist economies, we focus on the criticisms that are relevant to the applicability of the GE theory.[15] We note that the failure of socialist economies cannot be taken as evidence for or against the GE theory, as its implementation was only debated and not practiced [36, 40].[16] Put differently, a theoretical model for one system can be compared only with that for another system, and implementation of theory with that of another theory [6, 36], but this rule has been violated very often [6]. Comparing the public-owned sector in Lange's model and the state-owned sector in the post-reform Hungarian economy (which consisted of a public and a private sector), Kornai [36] pointed out that their behaviors did not match. Unlike in Lange's theoretical economy, prices in the Hungarian economy were not Walrasian and production responded to signals other than prices. While Lange's firms simply followed directions given, Hungarian firms had objectives other than following orders [36]. The bureaucracy was involved in many aspects of the economy besides price determination, contrary to Lange's central authority as a Walrasian auctioneer [36].

In reality, the problems faced by market and market-socialist economies are similar, although they may be different from what the GE theory depicts [62]. No manager can be absolutely free of personal motivation, planned and *ad hoc* measures coexist, and neither complete centralization (total government control) nor complete decentralization (no government involvement) is possible or desirable [36, 53, 62]. Nove [53] summarized the model for socialist system as one that assumes omniscience and omnipotence, both of which are nonexistent, and thus make the model prone to failure.

### 3.2.1 Necessity of Economic Adjustments

One problem with the Walrasian tâtonnement process is that it implicitly assumes that an equilibrium is achieved instantly. This premise creates the following problem. It fails to provide insight into how economies behave before an equilibrium is reached, although attainment of an equilibrium will necessarily require time [23, 45]. In other words, although continuous change is the nature of an economy [22, 25, 26, 48] and a different state of the economy may lead to a different equilibrium,

[13] Stiglitz noted that some of the information related costs are fixed; fixed costs are also known to make competition imperfect.

[14] After all, representative-agent models in macroeconomics, if interpreted as models with homogeneous agents, would eliminate any need for trade. Blaug [8] summarized the well-known debate about the validity of a theory in connection with how realistic its assumptions are. Neither of the two heavy-weight participants of the debate, Milton Friedman and Paul Samuelson, advocated rejection of a theory on the grounds that it is based on unrealistic assumptions.

[15] Some practical and important items missing from the debates of socialist economies, which includes the Social Calculation Debate, were pointed out for the case of the Soviet economy by Nove [53]. Incapability of a socialist economy to pursue a social goal, evasion of responsibility, shortage as an inevitable consequence of full employment and rapid growth policies, negligence of consumers and service, distortion of behavior through aggregation of orders, difficulty in planning and defining quality, difficulty in setting well-defined goals, vicious cycle of shortage and hoarding, instability of complex planning, negligence of auxiliary (but nonetheless important) tasks (such as loading, unloading, repairs, materials handling), lack of fiscal discipline (the so-called soft-budget constraint), overinvestment, and incentives for planners to keep prices lower than those implied by supply and demand. To the list, Kornai [36] added distorted prices, which feed each other.

[16] Stiglitz [62] did not see a serious gap between the theory and the socialist economies in practice, and concluded that "if the neoclassical model of the economy were correct, market socialism would have been a success."

the process ignores the issue of adjustment.

Needless to say, a decentralized economy cannot be made to "wait" until an equilibrium is reached [40]. Lavoie [40] argued that economies, in fact, trade at nonequilibrium or "false" prices, thereby deviating from the theory; the force that moves the economy toward an equilibrium, and not the state of an equilibrium, is what makes an actual economy work.[17] Even when an equilibrium is finally reached, that will remain a "solution" for only a limited amount of time, because an economy is always subject to change; rarely is an equilibrium stationary [22, 24, 48]. Moreover, in a scheme of overall utility maximization, what is best for the present depends on what awaits in the future [24], making the calculation of the best solution for a certain period of time impossible at the start of the period in the absence of perfect foresight. Communication is also involved in making changes in the overall plan of the economy, which cannot be carried out instantaneously [22]. Detailed economic planning, which was sought by the market socialists, is difficult, if not impossible. Kornai [36] drew on the case of the Hungarian economy, and listed rigidity as among "the most tormenting properties of the command system." Naturally, rigidity is not a problem, but rather a desirable property, if the economy is static. Technical progress is a form of change, bringing about difficulties in planned economies [53]. Indeed, technical progress, excepting the areas with national prestige (e.g., aerospace and nuclear engineering), was not fast in the Soviet economy.

### 3.2.2 Information and Competition

The market socialists interpreted the GE theory as an embodiment of an ideal economy. Therefore, according to the market socialists, prices were the only necessary piece of information in making economic decisions that would lead to a Pareto efficient outcome, while information not directly related to prices is also important in the real world [62]. True to the theory, they considered it of significant importance that the market-socialist system uses prices which prevail in the markets that are perfectly competitive in the sense defined by the theory: No individual participant has the leverage to affect prices. The Austrians objected that information required for allocations of resources as found in markets could not be obtained by the central authorities, because it is obtainable only through engaging in economic activities, particularly, competition as observed in reality. Their stance was that perfect competition as defined by the GE theory had little to do with competition as we see in reality, which is crucial in a successful economy. They also argued that information (or knowledge) that is relevant to allocation of resources was diffused in the economy and may not be available in a communicable form. We elaborate below the information acquisition mechanism as seen by the Austrians. We also discuss the disciplinary function of competition and the relevance of market socialism to global scheduling.

*Information Acquisition Mechanism*

The Austrians described, without the aid of mathematical models, a mechanism which would make prices carriers of information necessary for economic-decision making, and maintained that such a mechanism could not be found in Walraisan economies. As Hayek reiterated in his similarly themed writings [22, 23, 25, 26, 28], there are serious and inherent problems in economic planning by the central authority with respect to information, if the planning is not an **indicative** one. The authority's drawing of a feasible plan to make the best use of available resource requires that it be in possession of pertinent information. However, such information is dispersed [22, 25, 26, 28] since

[17] In **Walrasian equilibria**, demand is equal to supply. Stiglitz [62] pointed to credit and labor markets, where equilibria are not Walrasian; demand is *not* equal to supply, but there exists no mechanism in the economy to correct this. Taking into account quality of goods and services, the optimal price will not be one that equates supply and demand, according to Stiglitz [62].

“[f]or what purposes and in what way particular resources are used with the greatest advantage can be intelligently decided only by the ‘man on the spot’,” [25] and only such an arrangement would allow changes that are rapid enough to match an ever-changing environment [26], which is the very nature of an economy. The sheer volume of communication required for nonindicative planning may also make the information gathering impractical [22, 28]. Even if the information could be collected and its volume were manageable, personal (or subjective) knowledge may well be quite different from the data economists require (or objective knowledge), while the totality of the former should correspond to the latter [23].

The Austrians asserted that no person is equipped at the outset with objective knowledge, which is utilized in comparing the outcomes of various economic decisions, as Lange implicitly assumed [40]. In more general terms, Hayek [26] accused the market socialists of “discard[ing] everything that is important and significant in the real world[,]” in addition to arguing that neither Pareto nor Barone tackled the issue of knowledge acquisition [28]. Information for economic-decision making is not available all at the same time, but acquired through the desire to maximize utility (in case of producers, profits [48] in a competitive environment [22, 24, 25, 28], both within single and among different industries [22]). The process of communication or knowledge acquisition was critical to Hayek, who thought the equilibrium attained among possible equilibria is much more dependent on the stationarity of the knowledge possessed by the agents than on the stationarity of the environment [23].

Unfortunately, the behavior of economic agents remains unknown unless they engage in the process; we do not know how producers would behave (including how they gather and process information) until they actually compete with each other [27]. This partly stems from the fact that economic agents usually strive to fulfill “specific, temporary[,]” and individual purposes, hence, economic behavior is not as predictable as scientific phenomena are [27].[18] We may also say that there is a problem of so-called tacit knowledge, whose existence manifests itself only when a situation arises which requires that knowledge [22, 50, 54]. It follows that cost curves, etc., that are used for setting rules for managers in a market-socialist system, are obtainable only on an on-the-fly basis; economic information is discovered, and discovery is made almost daily [24]. For the purpose of information discovery, prices should not be fixed because their role is to signal the cheapest possible method of production and encourage production by even cheaper methods [24]. In other words, perfect competition in which all producers take the price as given “leaves no room whatever for the *activity* called competition” [27].

*Competition as Discipline*

We add to the above argument that the mechanism with which a competitive environment in actual economies disciplines entrepreneurial activities is missing from the GE theory. Competition functions by rewarding those that provide the good that is most desired by the buyers, and not necessarily all who engage in the same activity. However, the producers under the theory are profit maximizers, who are indistinguishable from each other and always earn zero profits, due to perfect competition. As Lange [38] noted, perfect competition is peculiar in the sense that it requires participants to maximize profits, although they are destined to end up with zero profits. Moreover, zero profits do not allow any investment; the GE theory precludes innovation and technological progress. Stiglitz [62] pointed out that in actual economies some loss-making firms do survive for years and that severe competition may not be best in a changing environment, just as survival-of-the-fittest in the biological world is not.[19] We conclude that perfect competition as defined in

[18] Hayek [27] named the order created by a market *spontaneous order*. He wrote that such an order is not made for any purpose, but may serve individual needs well.

[19] He also added that profit maximization under imperfect competition may not necessarily lead to production of better

the GE theory not only fails to describe the information acquisition process in reality, but also the disciplinary process of entrepreneurial activities.

*Market Socialism and Global Scheduling*

Other information-related problems in a planned economy, such as one under market socialism, include: overall complexity and accompanying necessity of aggregation, which hinder practical implementation (including correction in response to changes in the economic environment) [7, 22, 24, 25, 53, 62], dependency of plans (which necessitates coordination and creates spillover effects [53]), and difficulty in setting appropriate goals and rules for control [53]. Although application of the GE theory is certainly not equivalent to economic planning, the two share a critical task of collecting information dispersed in the system. If we are to employ a global scheduling mechanism with the tâtonnement process, as has been proposed by most market solutions to the global scheduling problem, information with respect to utility needs to be conveyed to the so-called auctioneer. Utility is almost never known explicitly in reality; it is only revealed through economic actions. Therefore, application of the theory to global scheduling is also subject to the problem of collecting dispersed information that does not exist in a communicable form.

### 3.2.3 Incentives and Private Ownership

By envisioning a successful economic system with publicly owned means of production, the market socialists declared private ownership unimportant [62]. The actions that would be taken in order to enhance the value of private property in a market economy were to be replaced appropriately by directives given by a central authority; they did not see any difference between "the self-directed action of profit seeking and the other-directed action of rule obedience" [40]. In a counterargument, the Austrians pointed out that the functions of a market cannot be divorced from private means of production [48]. This was because only market-established prices, which are based on private property, can give correct guidance as to the best way of producing the goods needed [48]. In other words, without private property, the value of exchange does not have meaning [21], and thus fails to give economic incentives.

We may say that there are two types of incentives related to the issue. One is whether the economic agents have the incentive to follow the directives given by the central authority. We call such incentives *obedience incentives*. The other is whether they have the incentive to make economic-value enhancing decisions, which may or may not coincide with the imposed directives. We call the second type *property-value enhancement incentives*. The market socialists thought that obedience incentives can be put into place that match with property-value enhancement incentives, without involving private property. The Austrians' take on the issue was that the two can match only if private property exists and if the directives are to enhance the value of private property.

Property-value enhancement incentives necessitate some decentralization in a planned economy, as they involve properties that belong to individuals.[20] Partial decentralization, in turn, makes an economy's responsibility structure unclear, especially if there is no private property, because there would be no financial consequences from economic decisions taken [22]. The remedy proposed by the market socialists, namely, provision of bonuses, would not solve the problem, since there would be too little risk-taking if one's own fortune is not directly at stake [22].[21] The Soviet

products at lower prices, unlike under perfect competition [62].

[20] As Hayek [22] put: "The question, then, is not whether all problems of production and distribution can be rationally decided by one central authority but whether decisions and responsibility can be successfully left to competing individuals who are not owners or ... otherwise directly interested in the means of production under their charge."

[21] Risk taking is smaller without private property. This is because risk is taken only if potential reward from doing

experience has shown that although material incentives are indeed required, "the desirable income relativities are hard to define and harder to enforce" [53]. Nove [53] reported that this point was proven for farming. Hayek [22] argued that the authority cannot replace the economic calculation which every entrepreneur would conduct in order to improve the value of his/her private property, because the authority cannot possibly examine all the options the entrepreneur has before making a final decision. Information required for economic-decision making is created by the entrepreneurs as they engage in economic activities [48], as we argued above. In sum, competition, which originates from entrepreneurship and, in most cases, from private ownership, is important for resource allocation which is economic-value enhancing.[22] No mechanism which ensures the functionality provided by entrepreneurs has been proposed for market-based global schedulers.

### 3.3 Parametric Prices, Market Prices, and Money Prices

*Parametric Prices*

Lange's view on prices in a Walrasian economy (or Walrasian prices), which he called parametric prices [38], was that they constituted an "objective price structure[,]" thereby resulting in a unique set of prices that equate supply and demand.[23] It was claimed that parametric prices, which are quoted in competitive markets, could be attained *without* such markets: starting from a set of random prices, by using the tâtonnement process and a certain accounting rule [38]. The accounting rule was to treat the prices as fixed [38], or as parameters, just as the participants in a perfectly competitive market would do.

While the parametric function of prices is what made the prices in competitive markets "objective[,]" they were distinguished from "exchange ratios on a market[.]" Lange's logic structure encountered two problems when he proceeded to assert that parametric prices are more general than the exchange ratios on a market, that they are the "terms on which alternatives are offered," that such prices are not arbitrary, and that these prices (and not the prices according to the narrow definition) were "indispensable for allocation of resources." The first problem is that parametric prices are those found in competitive markets, but Lange argued that they are not supposed to be prices in a narrow sense, i.e., exchange ratios on a market. One way to make sense out of this contradiction is to assume that Lange had markets in mind that are ideal, but do not exist in the real world, when he referred to "competitive markets," and a market in the real world when he simply wrote "market." The characterization of a definition being broad implies that anything that fits under the narrow definition also be accommodated by the broad definition. Thus, Lange's statement, "[i]t is only prices in the generalized sense which are indispensable to solving the problem of *choice* between alternatives" [38], is another contradiction.

Von Mises objected that parametric prices would be arbitrary [42]; by that he meant that they lacked economic meaning, that they were not based on economic motivation [51]. Lange [38] replied that they would not be arbitrary since the tâtonnement process ensured equality between supply and demand, which meant for Lange the attainment of the unique, objective set of prices. This exchange illustrates the third flaw in Lange's framework. If there were a unique equilibrium and trade occurred only at equilibrium prices, as Lange assumed, the narrow and the broad

so is large enough, and reward, material and non-material, is larger with private property than without. Technological progress relies on innovations, and innovations, in turn, depend upon risk taking. Hence, technological progress would be slower in a system with publicly owned means of production than in one with privately owned means of production. Nove [53] observed that in the Soviet economy, risk aversion, rather than risk taking, is unintentionally rewarded.

[22]Stiglitz [62] further questioned whether ownership is important for incentives.

[23]Lange does not provide explanation as to what an objective price structure is or why a unique equilibrium is guaranteed.

definitions of price should coincide at an equilibrium, rendering Lange's taxonomy meaningless. Moreover, von Mises's thoughts were about trade in a real-world setting, that is, in disequilibrium. In sum, Lange's definition of parametric price and its defense are fraught with inconsistencies. The GE theory as interpreted by Lange does not provide the framework to accommodate a consistent resource allocation mechanism, such as global scheduling.

*Market Prices and Money Prices*

Although the Austrians appeared to be highlighting the important bits of actual economies which the GE theory, and subsequently, the market socialists chose to ignore, they, too, were confined to a world which missed some critical elements of reality. For example, Hayek [26] wrote about "[t]he mere fact that there is one price of any commodity[,]" but we know from our simple grocery-shopping experience that this statement is false. What Hayek had in mind is the premise of the GE theory, where any difference in commodity is distinguishable to all economic agents, and all units of the good that are recognized as the same are priced the same. By defining the price system as "a mechanism for communicating ... only the most essential information" [26], Hayek strongly contributed to establishing the belief that is firmly held among economists and laymen alike that prices (or, more precisely, prices determined by markets, as argued below) are the only information an economic agent needs for making the best economic decision. In reality, however, prices constitute a necessary piece of information, but they are not sufficient [53, 62]; economic decisions based on prices alone are rare. Hayek [26] gave an impression that he had taken into account all that was ignored by the market socialists and the GE theory, but was important in the real world by adding to the above definition of a price system the following: "Of course, these adjustments are probably never 'perfect' in the sense which the economist conceives of them in his equilibrium analysis."

Based on the belief that market prices contain all useful information, the Austrians concluded that no economic system is superior to a market economy, although Hayek conceded that the proposition could be only inferred and not proved [27]. Without market prices, "rational allocation of resources" was impossible, according to Hayek [28]. For such a price system, every commodity had to be priced [21], and pricing should not be limited to consumer goods as the market socialists envisioned. Not any kind of prices, but market prices alone, condensed vital economic information, because they were the result of competition among various production methods [22] and voluntary exchange among buyers and sellers [24], both motivated by economic agents' wish to enhance the value of their own properties [47] and based on "the special circumstances of time, place, and quality" [24]. The Austrians asserted that competition, one of the important workings of markets, cannot be effectively replaced by law [24, 27]. That was due to the fact that markets give room to individuals to do what they think is best [27], which laws cannot take into account because of markets' dispersed, temporary, and possibly tacit nature. That is, they argued that we cannot have market prices without markets, contrary to what market socialists expected. The market socialists responded to this simply, and without elaboration, that prices in their system would have economic significance [42].

Soviet politicians recognized the great importance of prices that reflect consumers' needs, i.e., market prices, long before the demise of the Soviet system [53]. Based on the Soviet experience, Nove [53] reached the conclusion that market prices are "the necessary accompaniment of relative scarcity, opportunity-cost, choice, the need to calculate cost and to relate effort to result, to have an economic link between demand and supply, criteria for decentralized decision-making." Only such prices can influence economic decisions in a way that encourages economic-value enhancing resource allocation [53]. If prices do not equate demand and supply (as was often the case in a planned economy) and if it is in the power of the central authority to decide on priority activities in case of supply shortage (which was done crudely in the case of the Soviet economy), prices do not convey any information that is useful in the determination of which production process is most efficient and what consumers want [53]. If prices are fixed for a relatively long period of time, as happens by necessity in a planned economy, the gap between the latest economic condition and the information embodied by prices may be quite large.[24]

Some economists who were engaged in construction of a non-capitalist economic system proposed doing away with any type of price. For example, Soviet economists made numerous attempts to do so on the grounds that price was a tool for capitalism and not based on Marx's labor theory of value [53]. However, they never succeeded in replacing money, whose fungibility has the power to integrate the various markets in the economy [36], and money prices, whose practicality far exceeds that of calculating the necessary amount of labor for each productive activity [53].

We conclude that for a successful operation of an economy, be it market-based or otherwise, money prices are necessary. In particular, of all price-determination mechanisms known, markets yield prices that aid attaining the goal of economic-value maximization through competition among entrepreneurs and accompanying adjustments of prices. We see below that market prices are not, however, sufficient for making the best economic decisions as commonly believed. Put differently, market prices for computing resources alone do not lead to the best solution when allocation of resources is seen as an economic problem.

# 4 Virtues of Markets: Problem of Interpretation

Many share the view that it is markets, and only markets, that have the capability to allocate resources in an economically desirable manner. In the area of computing, this view has found the strongest supporters among the architects of global schedulers for computational grids. They put aside the fact that the GE theory has been the theory not only for market economies but also for market-socialist economies, and seek the theoretical underpinnings of their view in the GE theory and the fundamental theorems of welfare, which assert Pareto-efficient outcomes for certain economies. First, we elucidate some of the important results of the general equilibrium theory that are usually ignored. Additionally, we discuss the common, but misguided, perception of markets, whose origin appears to be the theory: the interpretation of markets as a decentralized system with prices which convey all the information necessary for an efficient allocation of resources. Finally, we touch upon the stability of markets and the tautology contained in the often expressed desirability of markets.

## 4.1 Theoretical Limitations in General Equilibrium Theory

We have seen above how the setting for an economy described by the general equilibrium theory may deviate from actual economies. We now turn to the limitations of the economies that are free of real-world complications, under the condition that the participants are not **atomistic** (or too numerous for any individual agent to have a global effect) and the economy is of the pure exchange type. Our environment is the classical one, unless stated otherwise.

### 4.1.1 Incompatibility of Desirable Properties

Even abstract economies, which are in a sense idealized, cannot exhibit all of the following desirable properties simultaneously: Pareto optimality of outcomes, incentive compatibility of the behavioral rules for the participants, and decentralized nature of communication required for the process to

[24] Nove [53] noted that Marx himself never argued for fixed prices.

reach an equilibrium (Hurwicz defined processes whose informational requirements are no greater than those of the perfectly competitive process and whose participants have direct information only about themselves, as informationally decentralized) [31, 32, 45].[25] The intuition behind this result is as follows. When information is decentralized as defined by Hurwicz, participating agents are not equipped with the faculty to detect false information [31, 32]. Thus, agents may display overt behavior that hides their true preferences, since that can result in higher individual utility levels from the final resource allocation. However, the allocations attained through such actions would most likely not be a Pareto optimal result, which belongs to the set of equilibria attained based on true preferences. That is, there are informational and enforceability limitations to achieving a Pareto optimal outcome through a perfectly competitive process in a nonatomistic case [45]. Furthermore, no process is incentive-compatible if the participants' initial endowments cannot be redistributed by coercion [31, 32]. We may simply wish to allow redistribution in order to obtain all of the three desirable properties of the resource allocation problem. However, there are many requirements for carrying out a redistribution, apart from the necessity that participants agree to it. For example, the authority must have the capability to correctly assess each agent's endowment and preferences, but "[s]uch information is extremely unlikely to be available in practice" [45]. When information is imperfect, redistribution does not attain a Pareto-nonwasteful outcome [62].

Hurwicz surveyed and investigated the possible extension of the GE theory to non-classical environments and/or non-competitive processes [32, 55]. There can be an informationally decentralized process with **Pareto satisfactory** outcomes for non-classical environments, if externalities do not exist [55]. Reformulation of an economy with externalities as one without may lead to loss of convexity in technology and preferences; casting of an economic problem with imperfect competition (which may be due to externalities, as we saw above) as one with perfect competition transforms the environment into a non-classical one. Hence, there is a tradeoff between a deviation from a competitive process and that from the classical environment. Moreover, it is likely that externalities increase the amount of information required for achieving a Pareto satisfactory equilibrium [55].[26] Finally, there does not exist an informationally decentralized process in all **nonconvex environment**s which yields nonwasteful results [55].

In conclusion, the GE theory and the fundamental welfare theorems, concern: not any environment, but the classical one; not any goal, but Pareto-nonwastefulness; not any communication mechanism, but an informationally decentralized one. The theory cannot be extended to nonclassical economies without giving up Pareto-nonwastefulness or informational decentralization. More generally, Pareto-nonwastefulness, informational decentralization, and incentive compatibility cannot all be fulfilled at the same time, not even for classical economies when economic agents are nonatomistic. That is, the results of the fundamental welfare theorems are not incentive compatible, as they imply Pareto optimal outcomes for perfectly competitive processes (which are informationally decentralized).

### 4.1.2 Attainment of an Optimal Allocation

An inherent problem with Pareto optimality is that economic theory is not equipped with a criterion that permits us to choose the best Pareto optimum among several, although the existence of multiple Pareto optimal allocations is very common. When there are multiple Pareto optima, they

[25]Reiter [55] noted that the basis of Hurwicz's definition of informational decentralization was that "the messages an agent may send correspond to specifying net trades for himself vis à vis the rest of the economy in the aggregate."

[26]This is in accordance with Hurwicz's result for classical environments and **Euclidean message spaces**; there is no mechanism with a message space of lower dimension than that of perfect competition, achieving nonwasteful outcomes in the same environment [55].

all differ in terms of resource allocation, and hence in final utility attained by individual agents; Pareto optimality, simply put, means one agent cannot be made better off without making another worse off. If the GE theory is to be applied to real-world situations, the system in question is required to have one Pareto optimal equilibrium, and preferably only one, to avoid the knotty issue of choosing among "equals." For practical purposes, the system needs to converge to that single optimal point from any initial condition. Under the assumption that preferences of the agents are continuous, strictly convex, and strictly monotone in the amounts of goods, it is sufficient for the existence and uniqueness of an equilibrium and convergence to that point from any initial condition that the system satisfy the **weak axiom of revealed preference** in the aggregate (i.e., "wealth effects do not cancel in the aggregate the positive influence of the substitution effects" [45]) and the **gross substitutability** (i.e., "there are no strong **complementarities** among the goods in the economy" [45]). The gross-substitution property of aggregate excess-demand (demand over endowment, summed over agents) alone is sufficient for uniqueness of the equilibrium if production is absent from the economy, which is the likely case for computing resources in grids. Whether these conditions would be satisfied by a computing-resource economy is yet unknown.

### 4.1.3 Dynamics of Demand and Supply

A casual observation of the economy tells us that the core dynamics of an economy is at work both at the aggregate and the local levels; prices fall when supply exceeds demand and they rise when demand exceeds supply. We are also aware that the local economies that constitute the whole are not all identical. For example, the price of coffee beans differs across the economy, but the prices do follow a general trend. That is, the prices of coffee beans in San Francisco and New York are not exactly the same, but at the same time, we do not see the price hitting rock bottom in San Francisco when it is sky high in New York. The GE theory treats the aggregate as a homogeneous entity, i.e., as if it were no different from a local economy, except in scale. While this approach greatly simplifies the logical structure of the theory, it introduces another problem: the necessity of an economic rationale for the postulation that any interaction that takes place among the local economies is instantaneous and complete in propagating a local change. Mas-Colell *et al.* [45] phrase the problem as follows (where $t$ and $p$ denote time and price, respectively):

> Certainly there are intuitive dynamic principles: if demand is larger than supply then the price will increase, if price is larger than marginal cost then production will expand, if industry profits are positive and there are no barriers to entry, then new firms will enter, and so on. The difficulty is in translating these informal principles into precise dynamic laws. ... Which economic agent is in charge of prices? For that matter, why must the "law of one price" hold out of equilibrium (i.e., why must identical goods have identical prices out of equilibrium)? What sort of time does "$t$" represent? It cannot possibly be *real* time because, as the model stands, a disequilibrium $p$ is not compatible with feasibility (i.e., not all consumption plans can be simultaneously realized).

It follows that the adjustment processes toward an equilibrium for the entire economy that have been proposed for the GE theory, including the most popular, the tâtonnement process, do not have real-world counterparts. In other words, while it may be possible to construct an artificial economy based on the GE theory, such an economy would not make use of the economic dynamics we experience in everyday life. The GE theory may give an impression that it has succeeded in formalizing economic dynamics, but it has not done so in a satisfactory manner.

### 4.1.4 Uncertainty

In applying the GE theory to a real-world economy, we must take into account the fact that we do not live in a world of certainty. We do not know for sure how the environment will change, and we often have to devise strategies to cope with various environments we may encounter. Uncertainty can be accommodated by the GE theory through considering the state of the world and **state-contingent** commodities, i.e., commodities whose complete description includes the nature of the state. According to the theory, the economy under uncertainty is one with a market for every state-contingent commodity. In a pure exchange economy, which is the most natural type for a computing-resource economy, a single commodity available at different times can be considered distinct commodities. For the economy under uncertainty to fit the basic framework of the theory, all relevant markets must exist before the realization of a state, and all trades must take place before then. If there is no date at which all trades must cease, this means that we need "futures markets extending infinitely far into the future[,]" but this fact has been "simply ignored" [62].

We may consider a less restrictive trading scheme, sequential trade, in which trade takes place as events unfold. However, for sequential trading to achieve the same equilibria as all-at-the-start trading, it is necessary that the agents have the correct expectations of the prices in the future [45]. In addition, if the number of elements in the price vector at the start is smaller than that of all possible states, which we take to be finite, we have incomplete markets, and the results of two alternative tradings, all-at-the-start and sequential, will not coincide. In sum, if we accept that markets are much more likely to be incomplete than complete, the conclusion is that real-world uncertainty prevents us from attaining without failure a Pareto optimal equilibrium. Simply put, "modern capitalism is a system very much different from a perfectly competitive atomistic Walrasian world" [36].

## 4.2 Commonly Perceived Advantages of Markets

**Market efficiency** is attributed to: the equivalence of pursuit of a global goal and that of individual goals, which is in turn due to the decentralized nature of markets, and the perfect-information condition, which is attained through prices. However, as Stiglitz [62] argued, the GE theory and the fundamental theorems of welfare do not provide the proof of markets' desirability over all other possible resource allocation mechanisms. We advance below our argument against exclusivity of the market as the universally most useful economic arrangement by examining its most touted features: its decentralized nature, and its posession of a perfect information carrier in the form of prices.

### 4.2.1 Decentralization

One of the reasons given for the desirability of markets is their allegedly decentralized nature. A decentralized system is usually thought to be more functional than a centralized system [46]. Reasons often cited for favoring decentralized systems are as follows. They are better suited for large systems [17, 46, 64], easy to design and implement [14, 17, 64, 71], scalable [63] (or extensible [61]), devoid of a single point of failure [37, 44, 63], speedy [61], reliable [61], and capable of meeting the global objective (when market participants pursue their own local goals) [10, 14, 46]. Apart from the alleged superiority, some consider control of a distributed system to be best done using a decentralized method, and hence desirable for computational grids [30, 37, 44, 61, 69, 70, 71]. We assert that none of the above can be fully supported by theory or by observations of actual economies.

The most commonly held interpretation of markets is that the pursuit of economic self-interest or independent local goals is the path to meeting a global goal, the most efficient allocation of resources.[27] In other words, markets are thought to be capable of achieving a global objective without global directives; complete decentralization is not only feasible, but also desirable, especially for systems with a large number of agents for which central control would be more cumbersome. This view often seeks its support in the second fundamental theorem of welfare, which states that any Pareto optimal outcome is achievable through perfect competition, provided that certain conditions are met. There are assumptions which are crucial in establishing the second fundamental theorem of welfare as theoretical evidence for the desirability of decentralized systems over centralized ones, including perfect information (or existence of a mechanism that makes the sum of locally held information equivalent to information that could be gathered by a central authority). If information is imperfect, coordination of economic activities would be required for ensuring a Pareto efficient outcome. As we argued in connection with market failure, imperfect information is very common. If the system has a goal other than obtaining a Pareto efficient outcome, incentives of local agents must be perfectly aligned with that goal.

If the market socialists' claim that the GE theory depicts a market economy as well as a planned economy is valid, there is no support in the theory for favoring decentralization over centralization [9]. Moreover, a large number of economic agents may not necessarily confer an advantage upon a decentralized system, especially not when their characteristics belong to a certain distribution. This is because the central authority can gather information by sampling a small proportion [9]. In fact, centralization and decentralization have different strengths, and naturally, work better in different circumstances. The former has the capacity to collect local information, process the gathered information, and disseminate the processed, i.e., global, information [9, 41, 62]. It is also considered to be more amenable to large changes in the environment [9]. The imperfection of a centralized mechanism in reality translates into usefulness of decentralized systems [9, 62]. When the local information that cannot be collected by a central authority is significant, decentralized systems become more attractive [9]. If local agents do not have a complete set of information, some kind of communication among them is necessary to reach a globally optimal outcome [9, 15, 49, 62], which has been corroborated through the Soviet experience [53]. The imperfection of links among privately held pieces of information is considered a reason behind the potentially advantageous role of coordination when a complete set of information is unavailable to economic agents [9]. The necessity of coordination [9, 62] and the time required for market screening (i.e., sorting between more demanded and less demanded goods) to take place [9] make the market process slow. In other words, in case of an emergency, a centralized system is preferred, as witnessed by mobilization efforts during wartime in many countries [9, 60]. On the other hand, central control with considerable consultation and information gathering is considered a process slower than markets under imperfect information [9]. Decentralization may be favored over centralization for reasons other than efficiency; it allows competition and direct participation of individuals, both of which are believed to be desirable by themselves [62].

We may agree on the conditional desirability of a decentralized system, but its realization in a pure form, i.e., without any central control, is most likely infeasible. Not only are markets incomplete in terms of decentralization in reality, but theoretical investigation also indicates that decentralization requires prices that are nonlinear in quantity of goods demanded, which is difficult to implement [62]. There is nothing inherent in markets that guarantees that local optimization is equivalent to global optimization. Markets are subject to the same restrictions as any other system if they are to exhibit such equivalency; the global objective must be an increasing function of local objective functions with no other arguments, and the global objective function must not depend on the identities of local agents. Jaffe [33] has shown for flow control of data communication net-

[27] For a further discussion of efficiency, see Section 4.4 below.

works that when users calculate their own message rate, using only local information conveniently available, there exists no algorithm that optimizes any of the several measures of network performance which were chosen for the analysis. A study of temperature control of several rooms, using a market-based multi-agent system, concluded that "market communication" allows a system with locally held information to achieve a goal no worse than that of a system with global control [73]. However, this is a mislabeled conclusion, since their market involves a Walrasian auctioneer, which has a decidedly centralized character and has no counterpart in real-world markets. Alternatively, we may say that if a global goal is to be fulfilled, global information is probably indispensable. If we take the position that global information cannot become available without some kind of central control, including coordination, then our conclusion is that complete decentralization would not lead to a globally optimal outcome. We take up below the question of price as a global information carrier.

### 4.2.2 Prices as Perfect Information Carriers

Besides for their decentralized nature, markets are often favored for features whose origins can be traced back to the widespread perception of price as a perfect information carrier. Some researchers in the field of market-based global scheduling have claimed the following items as the attraction of markets, in addition to those related to decentralization: simplicity [17, 30, 37], flexibility [14, 46, 63], efficiency [46] (or the ability to achieve Pareto-optimal allocations under certain conditions [71]), dynamic adjustability [30, 63], scalability [10], sparsity of required communication (which stems from the existence of price) [14, 30, 46, 70]. We assert that neither theory nor reality supports these claims.

Market prices have been hailed as the sole pieces of information that are required for agents in the economy to base their economic decisions on. Prices—**spot market** prices, to be more precise—are thought to be perfect in gathering, synthesizing, and disseminating information for economic-decision making. This is certainly the case in the ideal economy under the general equilibrium theory, where prices reflect the agents' preferences, production technology, and the amounts of resources available [62], thanks to competition [21] and market-clearing in the economy [62].[28] However, the parts of the GE theory that are often referred to deal with static situations, where perfect information on the state of the world is possessed by the economic agents, i.e., situations under certainty. In such situations, it is difficult to argue for the importance of price as an information carrier [62]; the function provided by price is superfluous. Examining a temperature control system, Ygge and Akkermans [73] concluded that price is not required if global information is made available to local agents before any transaction takes place, that is, if information is perfect. Moreover, should there be uncertainties other than those of price, they may be better coordinated through organizational procedures [60]; for example, in emergency situations, such as during a war, quantity goals are often employed [60].

If prices are indeed embodiments of all relevant information in the economy, there must be a mechanism for yielding such parameters from information dispersed throughout the economy. Such a mechanism would involve collection and synthesis of information, which may be carried out consciously or unconsciously, making it unclear whether the information requirement for the entire system is lighter in a decentralized system with prices than in a centralized system when the same resource allocation is to be achieved. A simple example shows that indeed the amount of

[28] Hayek appears to go back and forth between the economy as in reality and that as in the GE theory. On one hand, he wrote: "[P]rice expectations and even the knowledge of current prices are only a very small section of the problem of knowledge as I see it" [23]. On the other hand, his earlier writing stated: "[N]o other process was conceivable which would take in the same way account of all the relevant facts as did the pricing process of the competitive market" [21].

required information may not be smaller in a centralized system. Consider a system with $n$ agents, where $n$ is an integer larger than unity. Each agent reports local information to the central authority, the authority summarizes the information, which is then reported to the agents. We exclude the efforts involved in calculating the information package to be sent back to the agents. We assume that the communication effort required between the local agents and the central agents is the same regardless of the amount of information and that communication cost is entirely determined by the amount of effort required to relay information to another agent. Consequently, we see that the communication cost is $2nc$, where $c$, a strictly positive number, is communication cost per agent per information package. Suppose, instead, that all agents send each other the information they happen to possess. Under the assumption that the communication cost per agent per package is $c$, we see that the total communication cost amounts to $(n-1) \cdot n \cdot c$ if every agent is to obtain all other agents' information. As in the centralized case, we ignore the efforts for computation after all agents are given all the information. Comparing the two costs, we see that the cost for the decentralized system is larger for all $n$ larger than three. It does not provide a justification for a decentralized system when the size of the system is large, as has been argued [17, 46, 64].

Hurwicz [31, 32] has shown that even a simplified theoretical economy cannot exhibit Pareto-nonwastefulness, informational decentralization, and incentive compatibility at the same time. If no agent has the entire set of information related to the economy at any time, and if the information is initially scattered throughout the economy (i.e., if the system is informationally decentralized), it cannot be Pareto-nonwasteful *and* incentive compatible. Prices may be perfect in the sense that they are commonly believed to be, but then, the outcome of the economy is Pareto-wasteful, incentive incompatible, or both.[29]

Rather little attention has been paid to the question of whether price, as a single number, is as useful as a set of distinct and distinguishable pieces of information. We assert that each price must represent a different state and the relationship between price and state needs to be fully known by the economic agents, if price as a single number is equivalent to a set of all pieces of economic information available and related to that good; there must be one-to-one correspondence between price, or any other alternative signal, and the state of the world with respect to the good concerned. Stockmarkets are considered to be the most efficient markets, but even they do not differentiate various economic decisions taken by firms; stock prices are too "coarse" in that sense [62]. If there is limitation to the ability of economic agents to observe the properties of commodities and actions taken by firms so that the agents may properly distinguish them, the price system would necessarily be imperfect and be based on perceptions, including reputations [62], which may or may not coincide with the true economic situation.

Prices in the real world, therefore, do not embody all information in the economy in a form that can be readily used to learn the state of the economy. Often in theory, only two variables are required to describe a good, namely, price and quantity, but much more information is used in reality, as witnessed by the contents of contracts [60]; the necessity of contracts arises because not everything is priced, or markets are incomplete [62]. Although prices may not be perfect, they constitute information necessary for making economic decisions [53, 60, 62]. Prices may not be the only means to collect and disseminate information [9], but no practical substitute for prices in competitive markets is thought to exist, for the reason that competitive price is the only conceivable device to reflect all economic agents' values [40]. Moreover, as they are borne from "subjective and strictly contextual" information [40], it is difficult to envision a rule for aggregation of information

[29] Rational expectations equilibrium prices, which include Pareto optimal prices as a subset, result when equilibrium prices are formed from *pooled* information (i.e., signals such as price and the interpretation of the signals by every individual, which are known to each other) and are *fully revealing* [45].

in the manner of prices [9], or to replace competition by rules for setting a price, as was argued by the economists of the Austrian school in connection with the feasibility of market socialism. On the other hand, prices may reflect more than scarcity, such as quality [62]. We conclude that, contrary to widely held beliefs, real-world prices need to be supplemented by other information for desired allocation of resources; they do provide useful information which other economic variables do not, if they are formed through competition, but some information is necessarily missing.

### 4.3 Market Stability

While linear systems are the preferred modeling tools due to their ease of exposition, many economic phenomena are known to be best represented as nonlinear systems, frequently encountering chaos [5]. Systems with the functionality of a market are unstable [30], even without external shocks to the system [11]. Instability of a system may not be undesirable in itself, but it is undoubtedly so if economic agents cannot benefit from the frequent changes. That is certainly the case with stockmarkets, where market crashes leave most participants worse off. To the extent that computing jobs cannot be rewritten to take advantage of changing availability and prices of computing resources, market flexibility is useless and even harmful for computing-resource markets [52]. We conclude that markets by themselves do not provide an ideal environment for allocation of computing resources, without implying that there exists a better mechanism.

### 4.4 Tautology

As a concluding note on the desirability of markets, we touch upon some fundamental issues that unfortunately have been sidelined. We have earlier argued against the equivalency between utility maximization by individuals and that by a society or a system. The underlying assumption was that both have well defined utilities, which guide their actions, as is assumed by market proponents who cite the equivalency as one of the advantages of markets. Instead, if we take the stance that societies and systems are utility maximizers and their utilities are only revealed through outcomes, as they are for individual economic agents, utility maximization by individuals and by systems would be observed at any time, although it is not the former which leads to the latter. We adopt this stance, noting the fact that market values are formed through market processes. Based on the above definition of utilities and values, we assert that societies and systems are all rational and efficient and that the consequences of efficiency are value dependent. Furthermore, the desirability of markets holds by definition if we are to achieve market efficiency or to maximize market values. We also argue that reliance on market values as our beacon is useful, but only to a certain extent.

Firstly, economic agents maximize utility by definition. In other words, an economic agent's utility, or value, is maximized at all times. Values are formed through complex processes, and hence, we obtain an impression of observing suboptimal behavior of economic agents in terms of utility maximization when we do not know their true utility functions; we observe irrationality and inefficiency when our knowledge of the pertinent system of thought and behavior is incomplete. All economic agents maximize utility, and thus, are rational and efficient by definition. The precise consequences of concepts such as rationality [29] and efficiency can be revealed only with the knowledge of value, or a system of thought and behavior, as they simply mean maximization of value.

We now turn to the problem of value maximization of a system. On one hand, as noted in Section 4.2, utility maximization by individuals in a society (or a system) is not equivalent to that of the whole. On the other hand, every society requires people "not to waste" [19]; societies encourage their members to act rationally and efficiently from the point of view of the entire society, or to follow the rules as determined by each society. It is very often the case that goals of societies are not known explicitly, or even when they are, they do not unambiguously imply a certain code of conduct. Social rules are aimed at regulating agents' behavior, in view of attaining an implicit social goal. Hence, we may look at a society or a system as a utility maximizer as we do individual economic agents; every society and system is rational and efficient by definition, where its goal and value are revealed through outcomes. In other words, if the utilities of utility maximizers can only be deduced from the outcomes, utility maximization of individuals and that of the system should be observed concurrently. The two maximization processes are not equivalent, but by determining their utilities or values *ex post*, we may say that individuals and societies maximize value at the same time.

History and culture shape the rules of societies and systems [19, 43], engendering a variety in rules which reflects that in history and culture. The Crown Jewels possessed by the British monarchy as well as the seashells that are passed along as valuables by some societies in the Pacific provide illustrative examples; both have no practical use, but are considered of high value simply because of their respective history and convention [43]. Put differently, what rationality and efficiency exactly entail is dependent on the society or the system.[30]

An important set of conclusions emerge from the above argument. As it is only markets that yield market values and as the values come into being through market processes (i.e., our knowledge of market values is obtained only through deduction from market outcomes), the claim that a market is the most efficient resource allocation mechanism is equivalent to stating that market values are the most important. The pursuit of market efficiency is nothing but the prioritization of values, in which those of markets are at the top of the list. While more desirable outcomes can be reached, for example, by improving the communication among economic agents, market efficiency is a goal always achieved by the process called market, given market structure at each moment. The goal of any economic system is to allocate scarce resources to maximize value, and as long as that value is set to be that determined by markets, markets are the best system conceivable.

As with any other value-maximizing system, markets allocate resources to higher-valued uses. The values in markets are determined by what sells, or by the values of the buyers who are willing to pay most as a group, and they are not necessarily the most well informed, the most altruistic, nor necessarily capable of assessing and controlling the effects of their consumption on the society. Only to the extent that the values of the above group coincide with those of the society in general do markets serve as a mechanism that enhances the welfare of the entire society. In conclusion, with respect to allocation of computing resources, we need to decide above all what is the goal to be achieved, without relying on the term "efficient," so that we can examine whether markets are the best mechanism.

## 5 General Equilibrium Theory and Markets for Computing Resources

We have argued above that the GE theory does not offer a satisfactory picture of how an economy functions, in terms of scope of the problem that can be dealt with and abstraction from reality. We also saw that certain interpretations of the theory, which are commonly subscribed to, and the view of real-world economies based on the theory, are erroneous. We now turn to the issue of whether multi-agent systems are amenable to application of the theory. Subsequently, we argue that markets cannot meet an arbitrary scheduling goal.

[30]Nove [53] brushed past this issue when he asked without further examination: "[H]ow is one to judge whether a decision is arbitrary or irrational save by reference to some objective criteria?"

## 5.1 Applicability of Theory and Usefulness of Artificial Agents

As we discussed earlier, the indivisibility of many computing resources—CPUs, memory, etc., are available only in integer-numbered units—is a recipe for market failure. Demurrage is a kind of externality, also leading to market failure. Moreover, a transparent and fair pricing system is difficult to construct under demurrage, if not impossible [51].

Almost all proposed global-scheduling mechanisms based on markets are multi-agent systems, or implicitly have such systems in mind, involving an artificial agent for each user [10, 12, 30, 44, 46, 61, 69, 70, 71]. There appears to be an assumption that multi-agent systems do not have the complexity of real-world economies, and thus are much closer to the economies envisioned under the GE theory. One of the problems with this assumption is that there are limitations to the economy that is ideal under the theory, as we argued earlier in the paper. An economy that precisely fits the model would not exhibit all the major desirable properties (Pareto-nonwastefulness, incentive compatibility, and decentralization), all at the same time. Another problem is that the economics profession has come to see the theory without real-world complications inappropriate as an explanation of detailed working of the economies in reality, just as the Austrians have argued in the Socialist Calculation Debate. An economy that is ideal according to the GE theory would not behave as actual economies do, whose functionality is sought after by believers in the desirability of markets.

Moreover, as long as the problem remains that of scheduling the jobs submitted by users, their preferences should be taken into account and they should be represented as agents in the scheme. That is, the preferences of the users should be made completely explicit, and artificial agents be constructed based on them so that the agents can usefully replace the users. Questions as to which resource is most preferred over others in a set of resources must be posed over numerous sets so that utility functions can be constructed. Not only is such a task difficult and time consuming, but also prone to inaccuracy since there is usually no device present to detect changes in preferences. The difficulty of determining user preferences makes it also impossible to engage in the task frequently. Ideally, users should be able to choose different agents or alter agents so as to accommodate their needs, which may differ from job to job. This is certainly impractical with a system with one artificial agent per user (which is the most feasible arrangement), if not impossible, because of the difficulty in constructing and modifying utility functions. In addition, lack of autonomy may be felt among the users, as a result of their inability to change agents in accordance with the changes in their preferences. Without autonomy of local participants, a scheduling mechanism is unlikely to be embraced by the computing community [13, 59].

If a system could be operated satisfactorily with artificial agents, that fact would greatly diminish the attraction of its decentralized feature. This is because the success of artificial agents means that all information about the users is explicitly expressed. Explicit preferences could be more easily communicated to the central authority than the preferences which human users possess, since the latter are implicit in their natural state. There would be no point in collecting information about users' preferences through a trial and error method, as in the tâtonnement process, because the system has complete knowledge of the agents. Finally, human beings are much more perceptive to abnormality of market behavior, allowing them to take into account the degree of deviation from the mean, whereas a system of artificial agents usually takes a much longer time to do so [30].

## 5.2 Scheduling Goals and Markets

What is lacking from the arguments for markets as a scheduling mechanism is a consideration as to what markets are capable of achieving and whether that may match with scheduling goals. Pricing of computing resources affects the pattern of resource usage, including the nature and the timing of jobs submitted. Pricing forces utility-maximizing users with a finite budget to take personal preferences into account, which are private information.

Adoption of markets makes sense if it brings about improvement over what conventional schedulers can achieve; conventional scheduling is assumed incapable of practically optimizing in terms of the metric concerned, and pricing should alter job contents and submission pattern so that the resultant scheduling is closer to optimal and/or more practical. That is, we cannot discuss the desirability of markets without specifying the goals of scheduling and the mechanism of pricing. Unfortunately, neither is mentioned in works arguing for markets as the global scheduler [10, 12, 30, 44, 46, 61, 69, 70, 71], leaving us with no concrete justification for adoption of markets in distributed computing systems.

What markets are equipped to do is to encourage economic agents to maximize their value (or utility), which necessitates agents'use of privately held information without explicitly revealing it. Markets do not guarantee anything about the desirability of resultant resource allocations. The best that markets are capable of attaining is an outcome that maximizes market value, as argued above. The question of whether markets provide the best mechanism for meeting a certain scheduling goal can be answered by turning to Arrow's Impossibility Theorem, which is independent of the GE theory. Following the definition of rational preferences in microeconomic theory [45], we define a *rational* scheduling mechanism as one which ranks any given two choices with respect to job scheduling in a manner that is complete and transitive [45].[31] Then, applying Arrow's theorem to the context of global scheduling, we see that a scheduling mechanism, which ranks the order of job execution in a Pareto optimal fashion, whatever user utilities may be, and whose preference between two orders is based only on the user preferences of the same orders, is either non-preference-rational, or follows the exact preference of one user.[32] Accepting Pareto optimality as the implicit goal of markets, we conclude that a market-based mechanism is non-preference-rational, or it follows the preference of one user. We see that either it does not have a clear scheduling policy, or it achieves preference-rationality in policy by neglecting the needs of all users but one. As Mas-Colell *et al.* [45] put: "[W]e should not expect a collectivity of individuals to behave with the kind of coherence that we may hope from an individual." The fact that a scheduler is market based by itself does not imply its desirability over others.

## 6 Conclusion

The general equilibrium theory is inadequate as a detailed description of the mechanism that allows an economy to function in the manner we observe daily. Thus, a global scheduler for grids whose mechanism is based on the theory would not behave like the markets we casually encounter. For the purpose of advancing our argument, we discussed three problems: problems of scope, of abstraction, and of interpretation.

Market failure cases, for which the theory does not provide any explanation, are common: the problem of scope. Markets for computing resources do not satisfy the assumptions of the theory, hence market failure is very much a possibility. Other significant phenomena left unexplained by the theory are: the positive role of government policy (i.e., policy adopted by a central authority), the necessity of trust among economic agents, and the discrepancy between perceived and realized

[31] If not preference-rational, a scheduling mechanism may appear arbitrary to users and may not be supported by the user community.

[32] In the usual context of economics, the agent whose preferences match exactly with those of the society as a whole is termed a "dictator."

events.

The Socialist Calculation Debate was, on the surface, about the viability of an economy implied by the general equilibrium theory with publicly owned means of production. It shed more light on what made the actual market-economies operate successfully but was excluded from the theory: the problem of abstraction. The theory ignores the dynamic nature of successful economies, such as their capacity to adjust to changes in the environment, the process of information creation and dissemination, and incentives of the economic agents, all of which are relevant to markets for computing resources.

Although the Austrian school argued against the market-socialists' belief in the general equilibrium theory as the theory for an ideal and successful economy, they, too, resorted to the theory and firmly established the idea that market prices alone carry all the information necessary for economic decision making. In real-world decision making, market prices constitute information that is necessary, but not sufficient. We note the circular reasoning in the argument for the desirability of markets. Markets maximize value, which is determined by the markets, and hence, always attain market efficiency given the structures of the markets at each point in time. There exists no agreed upon goal of global scheduling that is more specific than market efficiency: an outcome that would be achieved by any market.

The problem of interpretation is serious because the idealized economies under the theory themselves do not always exhibit favorable features, such as Pareto-optimality, information decentralizability, incentive compatibility, and uniqueness of optima. Economists have not succeeded in providing a model that meaningfully describes the behavior under price adjustment process or uncertainty in the framework of the GE theory. Other alleged attractions of the markets are: perfect alignment of local and global goals, smaller amount of information required in a decentralized system, and price as the embodiment of all information required for economic decision making. None of these hold unconditionally. Moreover, the economic conditions which make prices perfect information carriers result in redundancy of the very role provided by prices. We pointed out that there exists no known mechanism which reveals the precise state-of-the-world through prices.

We questioned the assertions that markets are omnipotent and that the general equilibrium theory embodies what constitutes that omnipotence. We argued that markets do not always lead to desirable outcomes, the theory explains only restricted types of markets, does not deal with the most attractive aspects of real-world markets, and is erroneously identified as the theoretical support for some other properties of markets. Some alleged desirable properties, such as decentralized nature, are not desirable under all circumstances. Moreover, the desirability of markets follows automatically if market values are to be maximized, since the values are formed by the market processes—markets maximize market values by definition.

Nearly all proposed market-based global schedulers employ artificial agents. However, satisfactory representation of user utilities by artificial agents means that information necessary for the purpose of scheduling is available to the central authority. This in turn makes artificial agents redundant.

If markets are to be favored over other mechanisms, this should be based on their comparison with respect to attainment of a scheduling goal. Regrettably, what that goal should be is a discussion that is missing from the current argument for computing-resource markets. We applied Arrow's Impossibility Theorem to computing-resource economies and reached the conclusion that it also fails to buttress the claim that markets are better than other scheduling mechanisms.

## 7 Glossary

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| Arrow: | Kenneth Arrow (1921- ). American economist known best for his Impossibility Theorem and contribution to the GE theory. The impossibility theorem shows that under certain assumptions about people's preferences between options, it is impossible to find a voting rule under which one option emerges as the most preferred. Arrow was also one of the first economists to note the existence of a learning curve. His basic idea was that as producers increase output of a product, they gain experience and become more efficient. He has also worked on the economics of uncertainty, which is still a standard source for economists today. In 1972 Arrow, jointly with Sir John Hicks, won the Nobel Prize in economics. It was awarded for "pioneering contributions to GE theory and welfare theory." (Adapted from *The Concise Encyclopedia of Economics*.) |
| Atomistic: | Condition of an economy in which the number of agents in the economy is too numerous for any individual agent to have a global effect. |
| Austrian school: | Tradition of economic thought originating in the work of Menger, Professor of Economics at Vienna until 1903. Menger's principal achievement was the construction of a marginal utility theory of value. He was succeeded by von Wieser, who not only further developed the work of Menger, but also clarified the concept of opportunity cost. They were followed by Böhm-Bawerk, who contributed to the fields of capital and interest-rate theory, as well as by von Mises and von Hayek, proponents of markets as opposed to socialism. (Adapted from *The Penguin Dictionary of Economics*.) |
| Barone: | Enrico Barone (1859-1924). Italian economist and dedicated follower of Walras and Pareto. Barone's most notable contribution was in getting the Socialist Calculation Debate started with his famous 1908 article ([4]). His position, later taken up by Taylor and Lange, was that it was indeed possible in a collectivist state for a planning agency to calculate prices to achieve maximum efficiency. However, he did not think it could do "better" than a capitalist economy. (Adapted from *The History of Economic Thought Website*.) |
| Classical environment: | As defined by Hurwicz for the GE theory: Environment without externality, indivisibility, and with local nonsatiation, and in which technology is convex with respect to inputs, and preferences of economic agents are convex and continuous with respect to goods consumed [31, 32]. |
| Complementarity: | Relationship among goods such that decrease in demand for one good induces decrease in demand for others, given any price level of the other goods. |
| Convexity (of a function): | Let $S$ be a nonempty convex set on $\mathcal{R}^n$. Then the function $f : S \to R$ is said to be convex on $S$ if its value at the midpoint of every interval in $S$ does not exceed the average of its values at the ends of the interval. |
| Convex technology: | Technology whose magnitude of output is convex-valued with respect to the magnitude of inputs. |

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| Demurrage: | Unavailability of resources for use, which is caused simply by the use of other resources in the same system. |
| Economic agent: | Agent whose concern is to solve the economic problem given in the best way possible; an economic agent is a utility maximizer. Since an economic agent is a utility maximizer, it follows that it is also rational, in the sense that it fulfills its goal (i.e., utility maximization), and efficient. |
| Environment: | As defined by Hurwicz for the GE theory: Set of resource endowments, the (production) technology, and individual preferences [31, 32]. |
| Essentially-single-valuedness: | A mechanism is essentially-single-valued if equilibria (which are supported by the same mechanism and environment) are indistinguishable in terms of utility for all agents [31, 32]. |
| Euclidean message space: | Abstract, multi-dimensional space of vectors whose informational content is communicated among economic agents. |
| Externality: | Consequences for welfare or utility not fully accounted for in the price and market system. (Adapted from *The Penguin Dictionary of Economics*.) |
| Fundamental theorems of welfare economics: | Two theorems provided by the GE theory. They state that any general equilibrium attained through perfect competition (i.e., competitive equilibrium) is Pareto optimal and that any Pareto optimal allocation can be supported as competitive equilibrium with appropriate lump-sum redistribution among economic agents, provided that certain conditions are met[58]. |
| General Equilibrium (GE) theory: | The theory which deals with a model of an economy with markets for each commodity, and in which consistent optimization occurs as part of equilibrium. Consumers maximize utility subject to their budget constraint, leading to demand-side specification of the model under the theory. Producers maximize profits, leading to the production-side specification. In equilibrium, market prices are such that the required equilibrium conditions hold. Demand equals supply for all commodities, and in the constant-returns-to-scale case zero-profit conditions are satisfied for each industry. In a pure exchange economy, consumers are endowed with goods and their demand functions are usually derived from utility maximization [58]. |
| Government: | Equivalent to a central authority of a system. |
| Gross substitutability: | Relationship among the goods in the economy which implies absence of strong complementarities [45]. |
| Hayek: | Friedrich August von Hayek (1899-1992). Economist noted for his conservative views and criticisms of the Keynesian welfare state. In 1974 he shared the Nobel Prize for Economics with the Swedish economic liberal Gunnar Myrdal. Hayek's conservative thesis was that governmental control of or intervention in a free market only forestalls such economic ailments as inflation, unemployment, recession, or depression. In 1944 he suggested in *The Road to Serfdom* that mild piecemeal reforms and governmental manipulations inevitably lead to ultimate domestic disaster of the kind that paves the way for totalitarian takeover—such as the one by Hitler. (Adapted from *Encyclopædia Britannica Online*.) |

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| Incentive compatibility: | Set of behavior patterns is incentive compatible if it leads to a Nash equilibrium, i.e., no agent wishes to deviate from those patterns, provided that others also do not deviate [32]. |
| Indicative planning: | Long-term economic planning by a state which is without explicit enforcement and merely indicates goals of the economy as a guide, serving as a coordination mechanism. |
| Indifference set: | Set of combinations of various amounts of specific goods over which an economic agent would be indifferent. |
| Indivisibility: | Feature of a good which indicates that it retains its identity as that good only in a certain, predetermined number of units. |
| Lange: | Oskar Ryszard Lange (1904-1965). Polish economist best known for his contributions to the economics of socialism. He outlined, with coauthor Marek Breit, a version of socialism in which the government owned all plants and in which each industry, called a public trust, was organized as a monopoly. Workers would have a large say in running each industry. Subsequently, he entered the debate with Hayek about the feasibility of socialism. He presented "market socialism," in which the government would own major industries and a central planning board would set prices for those industries. (Adapted from *The Concise Encyclopedia of Economics*.) |
| Lerner: | Abba Ptachya Lerner (1905-1982). Described the full Pareto-optimality conditions in a general equilibrium economy. In particular, he introduced the Paretian rule for efficiency, i.e. that price equal marginal cost, $P = MC$. Partly as a result of this major contribution to the general equilibrium theory, he joined Oskar Lange in the Socialist Calculation Debate. Lerner stressed the importance of achieving efficiency by the $P = MC$ rule, and that this could be achieved by socialism or free markets. He stressed that as a result, only the initial distribution of income is at the discretion of the social planner, the resulting allocation can only be as efficient as in a perfectly competitive market economy. Lerner was convinced of the efficiency of the general equilibrium system. At the same time, Lerner believed in the importance of consumer choice, and argued that private enterprise should take over any particular industry in a socialist economy if it proved to be more efficient. (Adapted from *The History of Economic Thought Website*.) |
| Local nonsatiation: | Preferences are such that utility can be increased through infinitesimal (i.e., mathematically local) changes in the amounts of goods consumed. |
| Market economy: | Economic system in which the allocation of resources is determined mainly by supply and demand in markets. The values maximized by markets are called market values. |
| Market efficiency: | Efficient resource allocation and process of production, which only markets are capable of achieving. |
| Market failure: | Phenomenon that is observed whenever a market is not perfectly competitive, hence leading to a result that is Pareto inefficient. |

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| Mechanism: | As defined by Hurwicz for the GE theory: The totality of behavior patterns which allows prediction of economic states, given the environment and the initial state [31]. |
| Market socialism: | Refers to an economic system which features: (1) state ownership of the means of production and control over investment throughout the economy; (2) a more equal distribution of income and wealth than typically found in capitalism; (3) democratic election of government officials responsible for economic decisions; and, (4) state control over investment, combined with a reliance upon the market for almost everything other than investment. The economists Oskar Lange and Fred M. Taylor were early proponents of such an approach. (Adapted from *The Oxford Companion to Philosophy*.) |
| von Mises: | Ludwig Edler von Mises (1881-1973). Economist known for his contribution to liberalism in economic theory and his belief in the power of the consumer. Von Mises argued in favor of the price system as the most efficient basis of resource allocation. His works include those on marginal utility, purchasing-power parity, and business cycles. (Adapted from *Encyclopædia Britannica Online* and *The Penguin Dictionary of Economics*.) |
| Nonconvex environment: | As defined by Hurwicz for the GE theory: Environment in which technology is not convex with respect to inputs and/or preferences of economic agents are not convex with respect to goods consumed. |
| Pareto efficiency: | Condition attained when resource allocation is such that it is impossible to augment any economic agent's utility without lowering the utility of other agents. Also called Pareto optimality. For the purpose of differentiating efficiency in microeconomic theory (which is Pareto efficiency) from that in everyday use, we call the former Pareto efficiency and the latter simply efficiency. Pareto efficiency was first discussed by Vilfredo Pareto (1848-1923), who is best known for two eponymous concepts. The first and most familiar is that of Pareto optimality. The second is Pareto's law of income distribution. Derived from British data on income, it showed a power-law relationship between each income level and the number of people who received more than that income. (Adapted from *The History of Economic Thought Website*.) |
| Pareto nonwastefulness: | A process is Pareto nonwasteful over a class of environments when its outcomes are Pareto optimal [31, 32]. |
| Pareto optimality: | See Pareto efficiency. |
| Pareto satisfactoriness: | Shorthand for the combination of three properties of a mechanism, Pareto nonwastefulness, unbiasedness, and essentially-single-valuedness [31, 32]. |
| Perfect competition: | Competition among economic agents such that any action of one agent does not have effect on the whole system, owing to the large number of agents in the system. |

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| Preference-rational: | In microeconomic theory, economic agents are rational when their preferences are complete, transitive, and reflexive. For the purpose of differentiating rationality as in microeconomic theory from that as in everyday use, we call the former preference-rationality and the latter simply rationality. |
| Spot Market: | Market in which goods are bought and sold on the spot (i.e., sooner than an agreement for the future is deemed necessary). |
| State: | Condition which an economic system faces. Note that Hurwicz [31, 32] uses the word "environment" for features of technology and preferences of economic agents, such as convexity and indivisibility, separating these elements of state from others. |
| State contingency: | Description of a good which is dependent on the nature of state. |
| Tˆatonnement process: | The trial-and-error process involving an auctioneer to reach an equilibrium in prices and quantities demanded and supplied. |
| Taylor: | Fred M. Taylor (1855-1932). American economist who argued for market socialism in the 1920s and 1930s and also for the marginalist theory. (Adapted from *The History of Economic Thought Website*) |
| Unbiasedness: | A mechanism is unbiased over a class of environments when all optima are attainable by allowing redistribution of initial endowments [31, 32]. |
| Utility: | Mathematical representation of an individual's preferences over alternative bundles of goods. (Adapted from *SonderForschungs Bereich 504 Glossary*) |
| Walras: | Léon Walras (1834-1920). Remembered for two major contributions to economics. The first is his development of the marginal utility approach to the theory of value. His second and greater claim to fame lies in his development of the theory of general equilibrium, in which all the markets in an economy are examined, and in which all prices of goods and factors along with their amounts are simultaneously determined. (Adapted from *The MIT Dictionary of Modern Economics* (Fourth edition, Cambridge, Massachusetts: MIT Press, 1992).) |
| Walrasian equilibrium: | Condition achieved when: (i) firms are maximizing their profits given equilibrium prices; (ii) consumers are maximizing their well-being given, first, the equilibrium prices and, second, the wealth derived from their holdings of commodities and from their shares of profits; and, (iii) markets clear at an equilibrium (that is, at a Walrasian equilibrium, all consumers and firms must be able to achieve their desired trades at the going market prices) [45]. |
| Walrasian: | Of general equilibrium theory. |
| Weak axiom of revealed preference: | Axiom which states that wealth effects (i.e., changes in consumption decisions due to those in wealth) do not cancel the positive influence of the substitution effects (i.e., changes in consumption decisions due to those in relative prices of goods concerned) [45]. |

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