PLENARY SESSION 3

Invited paper 13

Markets for privately produced public goods

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13.1 The new global markets

Markets are a dominant institution in the global economy. As the century turns, however, the market itself is evolving. Two major trends are markets for knowledge and environmental markets. Markets for knowledge hold the key to the dynamics of the world economy: telecommunications and electronics, biotechnology and financial products, all involve trading products that use knowledge rather than resources as the most important input. Environmental markets are starting to emerge. The Chicago Board of Trade started trading emissions of sulphur dioxide (SO_2) following the Clean Air Act, and water markets are contemplated in California. The first global environmental market has been created: following our earlier proposal (Chichilnisky 1995, 1996) the 166 nations who are parties to the Framework Convention for Climate Change (FCCC) agreed in Kyoto, December 1997, to create an international framework to trade carbon emission credits among industrial nations.[1]

Markets for knowledge and environmental markets are different because they trade a different type of good, privately produced public goods (PPP goods), rather than the private goods that characterize traditional markets. With private goods — such as apples or machines — traders can choose what they wish to consume independently of each other. Knowledge and environmental goods are different: the planet's atmosphere is the same for all, and knowledge can be shared without losing it. As explained below, knowledge and environmental

[1] These are the so called Annex I countries, see Article 6, paragraphs 1 and 5 of the Kyoto Protocol. I advanced the proposal for the creation of an international framework for trading emissions permits at an international OECD conference in Paris, in 1993, and in 1994 at a workshop of "Joint Implementation and Beyond" organized under the auspices of the Global Environment Facility (GEF) with the participation of the members of Bureau of the International Negotiating Committee of the Framework Convention on Climate Change (FCCC) at Columbia Business School in May 1994. In December 1995 the proposal for the creation of an International Bank for Environmental Settlements (IBES) that would organize and regulate emissions trading was presented officially at a keynote address to the Annual Meetings of the World Bank, Washington D.C. and in various publications proposing blueprints for this trading regime, see Chichilnisky (1996a,b). In November 1997 The Rockefeller Foundation and the Global Environment Facility organized a workshop to discuss the creation of the IBES in Bellagio, Italy. In December 1997, Article 6 of the Kyoto Protocol, paragraphs 1 and 5, formalized the creation of such an international framework. The actual modalities, regulation and monitoring of the trading of emissions will be decided at the next Conference of the Parties (COP4) of the FCCC, to take place in Buenos Aires, November 1998. Columbia Earth Institute is organizing a follow up conference for the FCCC in April 1998.

assets are privately produced public goods, PPPs. Markets trading PPPs may be important in the future, because knowledge and environmental resources are key trends in the world economy, trends that lead the transformation that I call the knowledge revolution.

Focusing on these new markets, I analyze here the introduction of new institutions and the policies that can lead the transformation of industrial society into a sustainable society through the knowledge revolution. I focus on a new type of economic organization, involving markets that trade a mixture of private and public goods. These new markets require new regimes of property rights, also proposed here, and carry with them the seed of a society which encourages the creation of knowledge, and could lead to a better use and distribution of knowledge and of the world's natural resources.

13.2 Ecology and the knowledge revolution

Today the world faces a major challenge: to find practical paths for sustainable development. This means finding ways to reorient consumption patterns and use of natural resources in ways that improves the quality of human life, while living within the carrying capacity of supporting ecosystems.[2] This requires building a future in which humans live in harmony with nature. We are far from this goal, indeed in many ways the world economy is moving in the opposite direction.

However, just as the environmental problems generated by industrial society are becoming a threat to human welfare, industrial society is in the process of transforming itself. The rapid pace of this change has led me to call it a revolution. The change is centered in the use of knowledge and for this reason I call it the "knowledge revolution". What characterizes this so-called knowledge revolution?

The question is best answered in a historical context, by contrasting the current situation with the agricultural and the industrial revolutions, two landmarks in social evolution. Neither of the two previous revolutions is complete. Across the world we find today pre-agricultural societies populated by nomadic hunters and gatherers, and most of the developing world is still within agrarian societies. While the two previous revolutions are still working their way

[2] This is the definition of sustainability adopted by the Bruntland Report, and is anchored in the concept of development based on the satisfaction of "basic needs", a concept that was introduced and developed empirically in Chichilnisky, 1997a and b. Sustainable development is explored also in Caring for the Earth, a joint publication of IUCN, UNEP and WWF.

through human societies, knowledge is becoming a leading indicator of change. Knowledge means the ability to choose wisely what to produce, and how to do it. This ability is becoming the most important input of production, and the most important determinant of wealth and economic progress. It resides mostly in human brains rather than in physical entities such as machines or land. It is worth pointing out that the important input is *knowledge* rather than information. This is the difference between the computer industry, which is based on information technology, and other sectors such as telecommunication, biotechnology and financial sectors, which involve knowledge. The value of biodiversity resides on its knowledge content, according to ecologists such as E. Wilson and T. Lovejoy. *In an nutshell: knowledge is the content, information is the medium.*

The content (knowledge) is driving change, and this is facilitated by the medium (information). Information technology is the *fuel* for knowledge. Its abundance and inexpensive supply fuels the growth of sectors such as communications, biotechnology and global finance. Information technology fuels knowledge sectors because it performs the important role of allowing the human brain to expand its limits in the production, organization and communication of knowledge. The most important input of production today is not information technology itself: it is knowledge.

13.3 Characterizing the knowledge revolution

We may characterize the knowledge revolution as a period of rapid transition at the end of which *knowledge* itself becomes the most important input of production, the most important factor of economic progress and wealth. For example, today the knowledge content of biodiversity for improving public health and human welfare, is identified as a crucial source of economic value. By contrast, in prior revolutions the most important inputs were land (in the agricultural revolution) and machines (in the industrial revolution), that became better utilized because of new knowledge. Knowledge differs fundamentally from land and machines in that it is not rival in consumption. More on this below.

The process of change that I call the knowledge revolution is underway. Some indications include the fact that the value of corporations in the stock exchanges of the world is increasingly measured from their knowledge assets, such as discoveries, patents, brand names and innovative products, rather than from their capital base or physical assets. This means that knowledge-type assets (such as patents) are increasingly regarded as the most important source of economic progress in the corporation, and of its value. At the level of the

economy as a whole, knowledge of mathematics and sciences has become a good predictor of national economic progress across the world, see table 1 and figure 3 below.[3] In this period of change the USA leads the pack. Today more Americans make semiconductors than construction machinery. The telecommunications industry in North America (USA and Canada) employs more people than the auto and the auto parts industries combined. The US health and medical industry alone have become larger than defence, and also larger than oil refining, aircraft, autos, auto parts, logging, steel and shipping put together. More Americans work in biotechnology than in the entire machine tools industry. Most US jobs in the last twenty years were generated in smaller, knowledge intensive firms driven by risk capital. In the US, one third of the nation's growth is accounted for by the knowledge sectors, see figure below,[4] so that knowledge is an increasingly important determinant of economic progress. The knowledge sectors of the US economy already grow much faster than the rest of the economy, and therefore account for most of the dynamics of economic growth, see figure 4 below.[5]

Knowledge sectors consume less resources and have less ecological impact than the rest; thus they could decrease environmental damage once they become dominant in the economy. The question is whether the pace and scope of this process of change will foster a sustainable society in a timescale that matters. Encouraging and accelerating this transition is key. The economic transformation depends among other things on the evolution of the new markets for knowledge and for environmental assets. These require special analysis since, as already mentioned, knowledge and environmental assets are privately produced public goods, leading to new types of markets with new challenges and new opportunities for action.

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3 Data from TIMSS: Third Mathematical and Science Study, American Federation of Teachers, American Department of Education.

4 See also *Business Week*, "The New Economy: What it really means" by Stephen Shepard, Editor-in-Chief, November 17, 1997, p. 40, last paragraph.

5 This is despite the fact that current systems of accounting undervalue the contribution of electronics, which are extraordinarily productive and offer rapidly lowering costs for their products, so their weighting factor in GDP (market prices) decreases with time. In a nutshell: in the US knowledge products are rapidly becoming the most important input of production, source of value and economic progress. Similar statistics hold in most of the OECD nations. Development of knowledge sectors is slower in Europe than in the US because their financial markets and property rights systems are not so flexible and well developed and regulated. This is discussed further below.

13.4 A service economy?

It is important to differentiate the knowledge revolution from a service economy which used to be thought to be the latest stage of the industrial society. A service economy is characterized by the production of services more than goods, and it is similar to a knowledge economy in that knowledge sectors often involve services (such as finance). It is true that services now make up the largest part of advanced industrial economies. However the analogy ends there. The inevitable concern about the service economy is that it could lead mostly to service-oriented labor, such as the labor employed in the food services or in bank processing, requiring little skill and achieving lower wages. The radical difference between the service economy and the knowledge society is that in the latter the typical worker is highly skilled and generally well paid. Furthermore the worker's knowledge resides in her/himself and her/his brain and life experience, rather than in the machines that complement labor. Therefore the knowledge economy could result, with proper institutions, in a society that is more human oriented than the industrial or the service society.

13.5 Knowledge as a privately produced public good

As *knowledge itself* becomes the most important input to production, economic behaviour changes because knowledge is a rather special type of good. It is called a *public good* by economists, not because it is produced by governments but because it is not "rival" in consumption. This means that we can share knowledge without losing it. This is a *physical* property of knowledge, not an economic property, and as such it is quite independent from the organization of society. Nevertheless the economic rules governing the use knowledge — for example whether patents can be used to restrict its use — can have a major impact on human welfare and organization. More on this below.

Knowledge is also different from conventional public goods of the type that economists have studied for many years, such as law and order or defence, which are supplied by governments, in a centralized fashion.[6] What is unique about knowledge among other public goods is that, although it is a public good at the level of consumption, it is supplied by *private* individuals who are its creators. At the level of production, therefore knowledge is like any other private good: costly to produce, and the resources used to produce knowledge

[6] Classic work in the area of public goods by Lindahl, Bowen and Samuelson, as well as modern work on the subject, analyze public goods in the context of a government policy rather than in the context of competitive markets.

often cannot be used for other purposes. Producing knowledge requires economic incentives similar to those for producing any other private good.

13.6 A vision of the knowledge society

A distinct possibility is that in the next century a new society will develop, a society that is centered in human creativity and diversity, and which uses information technology rather than fossil fuels to power economic growth. The vision is a human-centered society which is deeply innovative in terms of knowledge and at the same time very conservative in the use of natural resources. The patterns of consumption and resource may not be as voracious as those in the industrial society, and may be better distributed across each society and across the globe. The knowledge society may achieve economic progress that is harmonious with nature.

This vision is only a possibility at present. Without developing the right institutions and incentives this possibility may never come to pass, and a historical opportunity may be lost; we need institutions to bridge the gap between a grim present and a bright and positive future. The rest of this paper will address this issue, for which an economic analysis of knowledge is required.

13.7 The paradox of knowledge

To produce new knowledge creators need economic incentives. This could involve restricting the use of the knowledge by others: patents on new discoveries work in this fashion: by restricting others' use of knowledge. This creates a problem because any restriction in the sharing of knowledge is inefficient, since knowledge could be shared at no cost and by doing so it can make others better off. So restrictions on the use of knowledge are inefficient after knowledge is created. However, without some restrictions there may be no incentive to create *new* knowledge. I call this the paradox of knowledge. This paradox is at the heart of the success of the knowledge society, of its ability to bring human development for many and not only wealth for a few.

13.8 New property rights regimes

New property rights regimes are needed to deal simultaneously with the need to share the use of knowledge for efficiency, while at the same time preserving

private incentives for production. The appendix contains a technical summary of how this would work in practice within competitive markets.

I propose substituting patents by a system of *compulsory licences* which are allocated in a specific way that ensures optimal use of knowledge in society, and which are then traded, in a *competitive* fashion, along with all other goods in the economy. In this new scheme, the right to use knowledge is unrestricted and by law everyone has access to it; however users must pay the creator each time they use this knowledge. Since the licences are traded in competitive markets, they ensure that the creators of knowledge are compensated for their labor in a way that reflects the demand for their products and therefore their usefulness for society. Prices are uniform and determined by competitive markets. Since licences are compulsory, they make knowledge available to all. In this sense this regime differs fundamentally from patents because, in principle, patents can restrict the use of knowledge.[7] No restriction in the use of knowledge is allowed in the system I propose. However a key issue is the distribution, use and applicability of the licences, to which we now turn.

It is clear that a system of licences on knowledge products (e.g. operating systems for software, biological information, how-to-do-it systems) could preserve or even worsen today's uneven distribution of wealth in the economy. This is because the knowledge economy has a built-in incentive for the creation of monopolies. Indeed, any knowledge based corporation is a "natural monopoly" a technical term used to indicate that the cost of duplicating knowledge products (such as software products) is very small, and therefore the larger the firm the lower are its costs. This is an extreme case of "increasing returns to scale" where larger firms have an advantage over their competitors, and therefore can prevent entry by newer and smaller competitors. Such natural monopolies are characteristic of the knowledge society. How to avoid their effects in concentrating welfare in the hands of very few?

The system of property rights proposed here takes into account these possibilities. It establishes how the distribution of licences is a crucial element in achieving efficient solutions. It shows that markets with knowledge operate differently than the standard markets, because knowledge is a public good that is privately produced. The solution is to achieve a distribution of property rights on licences that is negatively correlated with the property rights on private goods, and beyond this to ensure that markets for knowledge act competitively.

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[7] Patents *can* be negotiated, but they do not *have* to be. Owners of patents are legally entitled not to negotiate them, effectively creating a "monopoly" during the period of the patent's life. Compulsory licences do not have this feature.

The results in Appendix I make this proposal rigorous within a standard model of a market economy.

How can such a system of property rights become accepted? This concern parallels that proceeding the introduction of laws to ensure fair trade, a matter on which natural monopolies have offered and continue to offer much resistance and which is eventually overcome by society as a whole.

In reality there are substantial economic incentives for corporations to accept fair trading and the systems of property rights that we propose, although it is clear that more economic thinking and business education is needed before the acceptance becomes widespread. For example, even those producers that benefit in principle from increasing returns to scale could support a system of licences in which the lower income segments of the population are given proportionately more rights to use knowledge than the rest. Consider as an example the case of worker training schemes, school subsidies, etc. Because knowledge is so important for the productivity of society as a whole, and produces positive "externalities" on all producers, there is an incentive to develop a skilled pool of workers. Corporations know that skilled workers are essential to the success of knowledge industries.

All this is formally established in a proposition presented in the appendix, establishing that for an efficient market solution, one that cannot be improved so as to make everyone better off, lower income traders (individuals or in the case of international trade, nations) should be assigned a larger endowment of property rights in the use of knowledge.

In practice, this means a larger amount of licences to use knowledge are assigned to such lower income countries or groups. The scheme I propose is new but realistic. In fact, similar systems are already in place in most industrial societies within the educational system. Examples are school subsidies, that offer subsidized access to education to lower income groups. Another example is the auctioning of use of airwaves by the US Federal Government: in Washington D.C. minorities and women are given substantial discounts when they participate in auctions for the purchasing of property rights on the airwaves. In certain cases this involves a 40% discount of the auction prices.

13.9 Licences: we make it, we take it back

The system of property rights proposed here, while unique in its economic formulation, is reminiscent to a development that is already taking place in the US corporate world, a development that is also connected with environmental issues that have a public good aspect: the disposal of materials involved in

heavy industrial products, such as vehicles and electronic equipment. Leasing vehicles and electronic equipment is now a thriving business that hardly existed twenty years ago. One of the largest packaging companies in the world, Sonoco Products Co., started taking its used products off customers' hands after its CEO Charles Coker made a pledge in 1990: "we make it, we take it back." The policy has already been adopted by the car industry in Germany, where car manufacturers are responsible for disposing of the vehicles that the customers return at the end of their useful life, due to environmental concerns. Another example arises in the floor covering industry. Ray Anderson, CEO of Atlanta-based corporation Interface, the largest maker of commercial carpeting, has set up as a goal to create zero waste while making a healthy profit, and takes back the used products that it sells to recycle them. The mission of their businesses, all these business people say, is to sell *services*, not products. In other words: rather than selling TVs, selling viewing services; rather than selling vehicles, selling transportation services, rather than selling carpets, selling the comfort and visual services that carpets provide. Licencing has the advantage that the producers have an incentive to minimize waste and environmental damage — for example, the waste produced by wrapping or by defunct car bodies — as they will be responsible for it. These business people see licencing services as the way to the future, particularly when consumers are confronted with paying for the disposal of industrial waste.

Implicit in this a new system of property rights is an idea that we share: *licencing the use of services* rather than *owning the products that deliver those services*. The products in the corporate examples just described share another common characteristic with our economic approach: they have some of the characteristics of public goods in that they produce negative environmental "externalities". Knowledge, as we saw, also produces externalities, although positive.

Knowledge, as we saw above, has much in common with environmental assets: it is a privately produced public good. Knowledge products have been licenced for many years, although this has been done in a case-by-case manner, without securing the competitiveness of the market for licences, and without securing the distribution of property rights that would ensure efficient outcomes. In this sense, the new developments in industry reported here move in the same direction as the system of property rights, involving licences, proposed in Appendix I and discussed above. *These new systems of property rights that I propose can be thought of as an improvement, an institutionalization and an economic formalization of licencing and leasing systems that have recently emerged in advanced industrial economies*

13.10 Human impacts of property rights on knowledge

The rules that govern the use of knowledge in society are all important because they can lead to threats and opportunities for human development, both directly and through the possible changes in the patterns of consumption of goods and services. They can determine the impact of human societies on the environment and on resource use, as well as determine inequalities across the world economy. The way we use and distribute knowledge casts a very long shadow on human societies. How does this occur?

A historical comparison helps to explain this process. In agricultural societies the way humans regulated the ownership of land, which was then the most important input to production, led to social systems such as feudalism. Ownership of land had therefore a major impact on human welfare and on economic progress. Similarly in industrial societies the way humans organize the use of capital, which is its most important input of production, leads to very different social systems such as socialism and capitalism. Indeed, these two systems are defined by the rules on ownership of capital. In socialism ownership is in the hand of the governments or other public institutions, and in capitalistic systems capital is in private hands. Property rights on capital have mattered a great deal, and have even led to global strife in most of this century.

Since capital is the most important input of production in industrial society, it is clear that property rights on capital had an enormous impact on the organization of society, on economic progress and on peoples' welfare. Similarly in the knowledge society the way humans organize the use of knowledge, which is the most important input to production, will determine human welfare and economic progress across the world. This means that human institutions that regulate the use of knowledge, such as property rights and markets for knowledge, will become increasingly important. However as we saw knowledge is a different type of commodity than land or capital: it is a public good. Markets with public goods, and other economic institutions such as property rights on public goods, are still open to definition and require much economic analysis. Markets themselves will operate differently in the knowledge economy, because of the nature of the goods traded is different. There will be new challenges and new opportunities.

13.11 The ecological impact of knowledge-intensive vs. resource-intensive growth

In order to focus the analysis it is useful to distinguish two patterns of economic growth, two extreme cases of which is a spectrum of possibilities: economic

development that is *knowledge-intensive*, and that which is *resource-intensive*. The former simply means achieving more human welfare with less material input. The latter means achieving more production by means of more material use. These two categories were introduced in Chichilnisky (1995a, 1994b).

There are excellent historical examples of the two patterns of development, and of the differences they induce on economic growth. East Asian nations fit the knowledge intensive paradigm, while Latin American countries and those in Africa, fit well the pattern or resource-intensive growth. On the whole knowledge intensive development strategies succeeded, while resource intensive development patterns lost ground. Chichilnisky (1997) studies the historical patterns focusing on East Asian nations that are now called the Asian Tigers, including Japan, Korea and Taiwan, and later those called the Small Tigers, such as Singapore, Philippines, Hong Kong and Malaysia. These focused on exports of technology-intensive products such as consumer electronics and technologically advanced vehicles, and overturned the traditional economic theory of "comparative advantages". In contrast with East Asian nations, Latin America and Africa followed a resource intensive pattern of development and lost ground.

13.12 Difference scenarios of development in the North and the South

The most dynamic sectors in the world economy today are not resource-intensive; they are, rather, knowledge-intensive, such as software and hardware, biotechnology, communications and financial markets (Chichilnisky 1994b, 1995a). These sectors are relatively friendly to the environment. They use fewer resources and emit relatively little CO_2 Figure 8 shows this for the US economy. Knowledge sectors are the high-growth sectors in most industrialized countries.

Some of the most dynamic developing countries are making a swift transition from traditional societies to knowledge-intensive societies. Mexico produces computer chips, India is rapidly becoming a large exporter of software, and Barbados has recently unveiled a plan to become an information society within a generation, (Fidler 1995). These policies are an extension of the strategies adopted earlier by the Asian Tigers, Hong Kong, Republic of Korea, Singapore, and Taiwan (Province of China), who have achieved extraordinarily successful performance over the last twenty years by relying not on resource exports but rather on knowledge intensive products such as consumer electronics. By contrast, Africa and Latin America emphasized resource exports and lost ground (Chichilnisky 1994b, 1995a, 1995-1996).

The lessons of history are clear: not to rely on resource exports as the foundation of economic development. Africa and Latin America must update their economic focus. Indeed, the whole world must shift away from resource-intensive economic processes and products. In so doing, fewer minerals and other environmental resources will be extracted, and their price will rise. This is as it should be because today's low resource prices are a symptom of overproduction and inevitably lead to overconsumption.

Not surprisingly, from an environmental perspective one arrives at exactly the same answer: higher resource prices are needed to curtail consumption.

Producers will sell less, but at higher prices. This is not to say that all will gain in the process. If the world's demand for petroleum drops, most petroleum producers will lose unless they have diversified into other products that involve fewer resources and higher value. Most international oil companies are investigating this strategy. Indeed British Petroleum and Shell are already following such policies.

The main point is that nations do not develop on the basis of resource exports, and at the end of the day development can make all better off. As the trend is inevitable, the sooner one makes the transition to the Knowledge Revolution, the better.

The data and a conceptual understanding of how markets operate leads to the same conclusion. Economic development cannot mean, as in the industrial society, doing more with more. It means achieving more progress with fewer resources.

13.13 People centered development: opportunities and threats

The knowledge revolution could develop in different ways, depending on the way our institutions and policies unfold. As already explained, knowledge has the capacity of amplifying current discrepancies in wealth, because knowledge sectors can lead to natural monopolies such as those that arise due to the adoption of operating systems[8] or other standards. In the North-South context, knowledge sectors could amplify the differences in wealth between the North and the South. If this occurs, then the low resource prices from developing countries will persist, since they are caused in part by the necessity to survive at low income levels within a difficult international market climate. It has been shown that with current institutions of property rights, anything that leads to

[8] Microsoft *Windows* operating system is a case in point.

more poverty will lead to increased resource exports from developing countries, (Chichilnisky 1994a).

On the other hand, knowledge sectors will flourish in those nations that have skilled labor. Several developing nations are, or could be soon, in that position. For example, the Caribbean and Southeast Asia are a case in point, as are many areas in Latin America, (Harris 1994).

The main issues here are

- to abandon the resource intensive development patterns that these nations have followed for the last fifty years, with the support and encouragement of the Bretton Woods institutions such as the World Bank and the IMF, and
- to seek to establish the institutions (property rights, financial structures) that could lead them to overcome the "comparative advantages" mirage and thus avoid the heavy stages of industrialization, moving directly to the knowledge society.

Heavy accumulation of capital (financial or physical) is not needed for most knowledge sectors. What is needed is highly skilled labor, of the type that does not require expensive machinery or heavy capital investment in plants, and good managerial ability, all knowledge inputs that rely on a pool of abundant skilled labor. A good example is Bangalore's software industry.

Appendix I

Markets with knowledge

This section presents a general equilibrium model of a market with knowledge.[9] As explained above, knowledge is a privately produced public good. In this sense the model presented below is a model of a market that trades private goods as well as a privately produced public good, in this case, knowledge.

A general equilibrium model with knowledge

There are two traders, North and South, denoted by the index i=1,2 respectively, each producing two goods: one private good (x) and another a privately produced public good (a) representing *knowledge*. Each trader h has finite resources (24 hours a day) which are allocated to produce either private goods or knowledge. For each trader i=1,2 there is a trade-off between producing more private goods and producing more knowledge. However, more knowledge leads to higher productivity. Formally for i=1,2:

$x_i = g_i(a_i, a)$, with $g_i / a_i \rangle 0$, and $g_i / a \rangle 0$

where

$$a = \sum_{i=1,2} a_i, \text{ or } a = \sup_{i=1,2}(a_i)$$

Each trader or region has property rights $\Omega_i \in R^2$ on private goods and own licences that allow them to use knowledge, $\overline{a_i} \in R^2$. Traders derive utility from the use of private goods x,

$$u_i(x_i),$$

Through compulsory negotiable licences, knowledge is available to *all*. Traders may use their licences to access knowledge or may sell their licences in the market. If they wish to use more knowledge than their licences allow, they buy more licences in the market.

Markets for licences are competitive: everyone pays the same price for the same licence; prices are determined by equating supply and demand, and no trader can influence market prices.

[9] The OECD model is called GREEN.

Market equilibrium with knowledge

The equilibrium of the market is defined as follows. It consists of

- A price π^*, the relative price between private goods and licences to use knowledge,
- For each trader $i = 1, 2$ a level of initial allocation of property rights on licences to use knowledge in the economy $\overline{a_1}, \overline{a_2}$,
- For each trader i a level of consumption of private goods x,
- For each trader i knowledge production a_i^*,

so that:

- Each trader i allocates time optimally between the production of knowledge and the production of private goods,
- Each trader maximizes welfare within a budget defined by prices and property rights:

$$Max\ u_i(x_i)$$
$$s.t.\ x_i = g_i(a_i^*, a^*) + {}^*(\overline{a_i} - a_i^*)$$

  i.e. the value of consumption equals the value of production plus the value of licences bought or sold, and

- Markets clear

$$\overline{a_1} + \overline{a_2} = a_1^* + a_2^*$$

A competitive equilibrium determines endogenously a number of prices and quantities:

- the initial allocation of property rights on knowledge in each trader or region;
- the level of production and of consumption of private goods and of knowledge by each trader or region,
- the level of trade of private and knowledge between the parties, as well as
- the terms of trade between the private good and knowledge, *, which is the market price of the licences.

The price * can be thought of as a market determined licence fee on using knowledge, since it is a monetary value that must be paid for using knowledge above the level allowed by the initial allocation of property rights.

Equity and efficiency in markets for knowledge

The most attractive feature of competitive markets is the efficiency with which they allocate resources, requiring minimal intervention once an appropriate legal infrastructure is in place. This was Adam Smith's vision of the "invisible hand," and was formalized in the neoclassical theory of competitive markets that has prevailed in the Anglo-Saxon world since the 1950's. The efficiency of markets is summarized in *the first welfare theorem of economics*. This theorem establishes that the prices and the allocation of goods and services that arises in a competitive market equilibrium are efficient, in the sense that there is no other allocation that can make everyone better off. The first welfare theorem has practical importance. It had a major impact in the functioning of economies such as the US, which are market oriented. It underlies much of its *anti-trust legislation*, as well as its *insider trading laws*, the laws that restrict *price discrimination*, and other forms of *market discrimination* including gender and age discrimination. The rationale is simple and compelling. Since, according to this theorem, competitive markets ensure an efficient allocation for society, it follows that competitive markets are a "public service." Economic actions that undermine the ability of the market to act competitively therefore detract from the public good.

The first welfare theorem is no longer valid in markets in which in addition to traditional goods (private goods such as apples or machinery) one trader's public goods, such as the rights to use the planet's atmosphere, or knowledge. There is however a new first welfare theorem, reported below as the *first welfare theorem for privately produced public goods,* that establishes that the market reaches efficiency, but only for certain allocations of the rights to use knowledge, or licences. The results are quite general, and apply to any competitive market in which, in addition to private goods, trading involves privately produced public goods. Therefore they apply to environmental markets as well as markets with knowledge. In the case of environmental markets, in the special case considered in those works, the licences involved permits for the use of the atmosphere of the planet as a sink for the emission of greenhouse gases.

Theorem 1

(Chichilnisky, Heal and Starrett). Given a total global level of emissions $\bar{a}$, there exist a finite number of ways to allocate property rights on emissions among the two regions, i.e. there is a finite way of distributing emissions rights (or permits to emit) $a_1, \overline{a_2}$, with $\sum_{i=1}^{2} \overline{a_i} = \bar{a}$, so that at the resulting competitive equilibrium, the allocation of resources in the world economy, a_1, a_2, x_1, x_2, is

Pareto efficient. For distributions of permits other than these, the competitive market equilibrium is inefficient. When both traders have the same preferences, then the region with more private goods should be given fewer property rights on the public good.[10]

This theorem is illustrated in figure 9, provided below. The figure shows a starting distribution of permits that gives proportionately more rights to emit to the North, and computes the corresponding competitive market equilibrium allocation. In a second step, by redistributing the permits in favour of the South and at the same time tightening the emission targets on the whole world, the competitive market achieves a new equilibrium allocation which increases the welfare of the North and the South. This means that the first distribution was not Pareto efficient, and illustrates the potential efficiency gains obtained by redistributing permits in favour of the poorer countries.

Theorem 2

By allowing world emissions $\bar{a}$ to vary, one obtains a one-dimensional manifold of property rights from which the competitive market with permits trading achieves a Pareto efficient allocation of the world's resources. For allocations of property rights different from these, the competitive market does not achieve Pareto efficient solutions.

Proof

See Chichilnisky (1996f and 1997c).

The following result applies to the model presented above, which is different from the model of environmental markets in that the privately produced public good is *knowledge*. The mode with knowledge is different from the model of emission markets, because knowledge does not enter in the utility function (as the environmental asset does), but does enter into the production function to improve productivity (as the environmental asset does not).

[10] For environmental markets rather than markets with knowledge see also Chichilnisky 1993a, Chichilnisky and Heal 1994 and Chichilnisky, Heal and Starrett 1993.

Theorem 3

First welfare theorem of economics for markets with knowledge. There exists a one-dimensional manifold of property rights allocations from where the market with knowledge achieves an efficient allocation of resources. For allocations of property rights other than these, the competitive market does not achieve Pareto efficient equilibria.

Proof.

See Chichilnisky (Chichilnisky 1996f) and (Chichilnisky 1997c)

Theorems 2 and 3 identify the set of all "efficient" allocations of property rights on the use of knowledge, i.e. all allocations of licences to use the available knowledge products in society from which the competitive market achieves efficient allocations of resources as in the case of private goods. It turns out that the allocations that yield efficient solutions provide more property rights to those traders who have fewer property of private goods. As an example, this would involve providing those on a low income free access to a number of software programs, a number that is larger than for someone with a larger income.

The intuition behind these results is simple. Competitive markets in which public goods are traded have more stringent criteria for efficiency than markets for private goods. In addition to the standard marginal conditions (i.e. marginal rates of substitution must equal the marginal rates of transformation) the allocations must also satisfy the Lindahl-Bowen-Samuelson conditions for efficient levels of the public good, requiring that the sum of the marginal rates of substitution equals the (common) marginal rate of transformation between the private and the public good. Since more conditions are needed, the standard competitive allocations are not generally "first best", i.e. they are not generally Pareto efficient. In addition it can be shown that they are not "second best" efficient as well, where second best means that they are Pareto efficient conditional on a total level of world emissions which does not exceed the given target. Generally the total amount of the public good is lower in competitive markets than the "first best" or Pareto efficient level.

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