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Environmental Economics

– Lecture Notes –

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to Huib Jansen and David Pearce

Preface

These lecture notes accompany the international second edition (2011) of the textbook *Intermediate Environmental Economics* by Charles D. Kolstad.

The audience are third year undergraduate students of economics in an English university. These students have seen calculus and two terms of micro- and macroeconomics.

Barcombe, June 2020 *Richard Tol*

Acknowledgements

These lecture notes are based on *Intermediate Environmental Economics* by Charles D. Kolstad. I learned a lot from Charlie since we first met 25 years or so ago.

I used to teach environmental economics based on *Natural Resource and Environmental Economics* by Roger Perman, Yu Ma, Michael Common, David J. Maddison and James McGilvray. George MacKerron taught the same course using *Environmental and Natural Resource Economics—A Contemporary Approach* by Jonathan M. Harris and Brian Roach. Where I deviate most from Kolstad, I probably follow Perman or, less often, Harris.

George MacKerron helped in many ways, small and big. Sarah Jacobsen challenged me to look deeper into Malthus and the Romanticists. Michael Munger helped clarify what Robert Carlyle wrote, Marcel Severijnen pointed me to Tacitus. Paul Kelleher has a cameo in a footnote.

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Origins

1.1 Proto-economics

Trigger warning: Many of the quotes in this section are rather racist.

Economics conventionally starts with the publication of Adam Smith's *The Wealth of Nations* in 1776. Before that, however, many anticipated what later became elements of economics.

In those early days, agriculture was the dominant sector in the economy. Production was production of food, trade was trade in food, consumption was consumption of food. These proto-economists, like all farmers, were keenly aware of the importance of climate and geography. Cato (c160 BCE), Varro (37 BCE), Columella (41-68) and Palladius (c400) all wrote handbooks on farm management.

In those days, teleology was common: Things were as they should be. Cicero (44 BCE, On Duties, I 42 151) argues that

> of all the occupations by which gain is secured, none is better than agriculture, none more profitable, none more delightful, none more becoming to a free man

Cicero was writing about large landowners, not about farmhands or peasants. He argued that the landowning elite, which dominated Rome politically and economically, was morally superior. Those on top deserved to be on top.

1.1.1 Environmental determinism

Ancient scholars did not just think that the natural environment was important. They thought it was predominant. For instance, Hippocrates (400 BCE, On Airs, Waters, Places, 23) wrote

> The other races in Europe differ from one another, both as to stature and shape, owing to the changes of the seasons, which are very great and frequent, and because the heat is strong, the winters severe, and there are frequent rains, and again protracted droughts, and winds,

> from which many and diversified changes are induced. These changes are likely to have an effect upon generation in the coagulation of the semen, as this process cannot be the same in summer as in winter, nor in rainy as in dry weather; wherefore, I think, that the figures of Europeans differ more than those of Asiatics; and they differ very much from one another as to stature in the same city; for vitiations of the semen occur in its coagulation more frequently during frequent changes of the seasons, than where they are alike and equable. And the same may be said of their dispositions, for the wild, and unsociable, and the passionate occur in such a constitution; for frequent excitement of the mind induces wildness, and extinguishes sociableness and mildness of disposition, and therefore I think the inhabitants of Europe more courageous than those of Asia; for a climate which is always the same induces indolence, but a changeable climate, laborious exertions both of body and mind; and from rest and indolence cowardice is engendered, and from laborious exertions and pains, courage. On this account the inhabitants of Europe are than the Asiatics, and also owing to their institutions, because they are not governed by kings like the latter, for where men are governed by kings there they must be very cowardly, as I have stated before; for their souls are enslaved, and they will not willingly, or readily undergo dangers in order to promote the power of another; but those that are free undertake dangers on their own account, and not for the sake of others; they court hazard and go out to meet it, for they themselves bear off the rewards of victory, and thus their institutions contribute not a little to their courage.

Hippocrates' prediction that Europeans can never have absolute monarchs is wrong in retrospect. Note that he argues that there are all sorts of things wrong with non-Greek Europeans and Asiatics—because of where they live—implying that the climate in Greece is responsible for the superiority of him and his countrymen.

Aristotle (350 BCE, Politics, 7 VII) wrote

> Those who live in a cold climate and in Europe are full of spirit, but wanting in intelligence and skill; and therefore they retain comparative freedom, but have no political organization, and are incapable of ruling over others. Whereas the natives of Asia are intelligent and inventive, but they are wanting in spirit, and therefore they are always in a state of subjection and slavery. But the Hellenic race, which is situated between them, is likewise intermediate in character, being high-spirited and also intelligent. Hence it continues free, and is the best-governed of any nation, and, if it could be formed into one state, would be able to rule the world.

Aristotle predicted that Europeans could never rule over others. While he foresaw the empire of Alexander the Great, he missed the empires founded by Romans, Franks, Spaniards, Portuguese, Dutch, English, French, and Russians. Like Hippocrates, he argued that his own people were superior by virtue of their climate.

The ancient Greeks were not alone. In an important, early Chinese text, Zhong Guan (780 BCE, Guanzi, XIV 39) writes

> What is water? It is the root of all things and the ancestral hall of all life. It is that from which beauty and ugliness, worthiness and unworthiness, stupidity and giftedness are produced.
>
> How do we know this to be so? Now the water of Qi is forceful, swift and twisting. Therefore its people are greedy, uncouth and warlike. The water of Chu is gentle, yielding, and pure. Therefore its people are lighthearted, resolute, and sure of themselves. The water of Yue is turbid, sluggish, and soaks the land. Therefore its people are stupid, disease ridden, and filthy. The water of Qin is thick like gruel and stagnant. It is obstructed, choked with silt, and wanders in confusion free of its banks. Therefore its people are greedy, violent, and deceptive, and they like to meddle in affairs. The water of Jin is bitter, harsh, and polluted. Therefore its people are flattering and deceitful, cunning and profit seeking. The water of

> Yan collects in low places and is weak. It sinks into the ground, is clogged, and wanders in confusion free of its banks. Therefore its people are stupid, idiotic, and given to divination. They treat disease lightly and die readily. The water of Song is light, strong, and pure. Therefore its people are simple and at ease with themselves, and they like things to be done in the correct way. For this reason, the sages' transformation in the world lay in understanding water.
>
> Now, when the water is unadulterated, people's hearts will be correct, they have no desire to be corrupt. When people's hearts are at easy, their conduct will never be depraved. For this reason, the sages' bringing good order to the world did not lie in preaching to every person or persuading every household, but in taking water as their central concern.

The idea that you are what river shore you dwell on, seems odd to us. But note that Zhong Guan argues that you should not appeal to people's innate goodness. Instead, a wise ruler improves water courses. He so justifies the elite in a hydraulic society, whose main role was to provide public goods in water management.

The idea of environmental determinism lingered. Ibn Khaldun (1377, Muqaddimah 1 4)

> We have seen that Negroes are in general characterized by levity, excitability, and great emotionalism. They are found eager to dance whenever they hear a melody. They are everywhere described as stupid. The real reason for these (opinions) is that, as has been shown by philosophers in the proper place, joy and gladness are due to expansion and diffusion of the animal spirit. Sadness is due to the opposite, namely, contraction and concentration of the animal spirit. It has been shown that heat expands and rarefies air and vapors and increases their quantity. [...]
>
> Now, Negroes live in the hot zone (of the earth). Heat dominates their temperament and formation. Therefore, they have in their spirits an amount of heat corresponding to that in their bodies and that of the zone in which they live. In comparison with the spirits of the inhabitants of the fourth zone,[1] theirs are hotter and, consequently, more expanded. As a result, they are more quickly moved to joy and gladness, and they are merrier. Excitability is the direct consequence.
>
> In the same way, the inhabitants of coastal regions are somewhat similar to the inhabitants of the south. The air in which they live is very much hotter because of the reflection of the light and the rays of (the sun from) the surface of the sea. Therefore, their share in the qualities resulting from heat, that is, joy and levity, is larger than that of the (inhabitants of) cold and hilly or mountainous countries. To a degree, this may be observed in the inhabitants of the Jarid in the third zone. The heat is abundant in it and in the air there, since it lies south of the coastal plains and hills. Another example is furnished by the Egyptians. Egypt lies at about the same latitude as the Jarid. The Egyptians are dominated by joyfulness, levity, and disregard for the future. They store no provisions of food, neither for a month nor a year ahead, but purchase most of it (daily) in the market. Fez in the Maghrib, on the other hand, lies inland (and is) surrounded by cold hills. Its inhabitants can be observed to look sad and gloomy and to be too much concerned for the future. Although a man in Fez might have provisions of wheat stored, sufficient to last him for years, he always goes to the market early to buy his food for the day, because he is afraid to consume any of his hoarded food.
>
> If one pays attention to this sort of thing in the various zones and countries, the influence of the varying quality of the air upon the character (of the inhabitants) will become apparent. God is the Creator, the Knowing One. Al-Masudi undertook to investigate the reason for the levity, excitability, and emotionalism in Negroes, and attempted to explain it. However, he

[1] Ibn Khaldun split the world into seven climate zones. The fourth zone, the middle one, had the optimal climate. Other zones were too hot or too cold. Ibn Khaldun lived in the optimal climate.

> did no better than to report, on the authority of Galen and Ya'qub b. Ishaq al Kind!, that the reason is a weakness of their brains which results in a weakness of their intellect. This is an inconclusive and unproven statement. God guides whomever He wants to guide.

Like Hippocrates and Aristotle, Ibn Khaldun argued that his climate was the best. He adds Cicero's teleology. Arabs were superior because Allah had bestowed them with the optimal climate. The dominant position of Arabs was not by happenstance, but God's will.

Ibn Khaldun's sentiment is reflected in the expression *God's own country*, which has been used to describe, amongst others, Kerala, Yorkshire, and Rhodesia. Robert Rankin mockingly places the Garden of Eden in Brentford.

Montesquieu (1748, The Spirit of Laws, 1 XIV) argues that the climate of France is best. He writes that

> [...] the temper of the mind and the passions of the heart are extremely different in different climates [...]
>
> People are therefore more vigorous in cold climates. [...] In cold countries they have very little sensibility for pleasure; in temperate countries they have more; in warm countries their sensibility is exquisite. [...]
>
> In northern climates, scarcely has the animal part of love a power of making itself felt. In temperate climates, love, attended by a thousand appendages, endeavours to please by things that have, at first, the appearance, though not the reality, of this passion. In warmer climates, it is liked for its own sake, it is the only cause of happiness, it is life itself.

In other words, only the French have the right mix of strength and purpose.

More than 200 years later, Huntington (1915, Civilization and Climate) wrote

> Today a certain peculiar type of climate prevails wherever civilization is high. IN the past, the same type seems to have prevailed wherever a great civilization arose.

Huntington's main innovation on earlier environmental determinists was that he argued that climate is not static. Instead, climate changes. Huntington argued that climate changes people:

> In tropical countries weakness of will is unfortunately a quality displayed not only by the natives, but by a large proportion of the northerner sojourners. If manifests itself in many ways. Four of these, namely, lack of industry, an irascible temper, drunkenness, and sexual indulgence are particularly prominent, and may be taken as typical.

At the same time, he argued that

> the effect of a diverse inheritance would last indefinitely

in a thought experiment about "Teutons" and "negroes" moving to an empty country much like Egypt.

It was only in 1922 that Lucien Febvre started the intellectual push back against environmental determinism. It is now an uncommon position in the social sciences. Indeed, the racist and self-serving reasoning of the early environmental determinists render it disreputable in the eyes of many of our contemporaries.

That said, environmental determinism has not disappeared. Jared Diamond (a physiologist by training) is probably the most prominent of current environmental determinists.

1.1.2 Early concerns about pollution

Early scholars wrote about the natural environment and its effect on society. Environmental pollution and resource degradation recognized too. Ancient Greece and Turkey, for instance, suffered from deforestation and soil erosion. Of his native Atticam Plato (Critias, 360 BCE) wrote

> its mountains were high hills covered with soil, and the plains [...] were full of rich earth, and there was abundance of wood in the mountains.

but

> now losing the water which flows off the bare earth into the sea

That is, Plato understood the relationship between deforestation, soil erosion, and water run-off. Visitors to modern Greece may wonder how such a barren landscape could have supported such a rich civilisation. It did not. Greece was not barren then.

Rome and its empire suffered from lead poisoning in water and air, but they themselves were not aware of this. Air pollution was more easily detected. Seneca (61) wrote about

> the heavy air of Rome, from the stink of the chimneys and the pestilence, vapors and soot of the air.

Environmental policy also goes way back. As the price of fuel wood rose in London, people switched to sea coal, bituminous coal mined on the northeast coast of England. King Edward I of England banned sea coal in 1307. Nonetheless, smog continued to plague London. In December 1952, some 4,000 people were killed by air pollution and maybe 8,000 more in the following months. The Clean Air Act of 1956 marks the beginning of the transition away from coal as the prime fuel for heating in the cities of the UK.

Marquis de Condorcet (1776), remembered in economics for his work on voting, wrote of stubble burning that

> by corrupting the air, causes illnesses in neighboring homes.

This may be the first formulation of an externality, the unintended and uncompensated impact of an economic activity on a third party. Stubble burning is still a big problem, regularly causing major air pollution on the Indian subcontinent.

1.2 Classical economics

1.2.1 Adam Smith on public goods

Adam Smith's 1776 book *An Inquiry into the Nature and Causes of the Wealth of Nations* is often seen as the starting point of economics as a separate discipline.

Smith is seen as a proponent of laissez-faire, the idea that the government should not intervene much in the economy, particularly through the doctrine of the invisible hand, in which the market coordinates selfish interests to deliver the social good.[2] We now call this the First Fundamental Welfare Theorem. We recognize that it only holds under rather stringent conditions, and that Smith's social good is a Pareto optimum.

Smith (Wealth of Nations, 1776 V 1) did argue, though, that

> The third and last duty of the sovereign or commonwealth is that of erecting and maintaining those public institutions and those public works, which, though they may be in the highest degree advantageous to a great society, are, however, of such a nature that the profit could never repay the expense to any individual or small number of individuals, and which it therefore cannot be expected that any individual or small number of individuals should erect or maintain. [...] The performance of this duty requires, too, very different degrees of expense in the different periods of society.
>
> After the public institutions and public works necessary for the defence of the society, and for the administration of justice, both of which have already been mentioned, the other works and institutions of this kind are chiefly those for facilitating the commerce of the society [such as good roads, bridges, navigable canals, harbours], and those for promoting the instruction of the people.

Smith realized that the market underprovides public goods, and called for government intervention.

1.2.2 Malthus, Ricardo and Mill on resource limits

Thomas Robert Malthus (1798, An Essay on the Principle of Population) wrote

> Population, when unchecked, increases in a geometrical ratio. Subsistence increases only in an arithmetical ratio.

Figure 1.1 illustrates this. The supply of food increases linearly or arithmetically. The number of people, and so the demand for food increases exponentially or geometrically. Exponential growth is faster than linear growth. We will therefore run out of food at some point in the future, the *Malthusian Catastrophe*.[3]

Malthus had a solution too: Abstinence. At that time, you could not have babies without sex.

Malthus' argument that food production grows only linearly hinges on decreasing returns to scale in agriculture. If you double the number of farmhands, on a piece of land, you will increase but not double the harvest.

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[2] You have one chance to make a first impression. Lay people typically think that Smith's views on economic policy are shared by all economists. This is peculiar, because Karl Marx was an eminent economist too. After World War II, many economists advocated central planning.

[3] Thomas Carlyle (1839, Chartism) referred to Malthus' work as "[d]reary, stolid, dismal, without hope for this world or the next". Carlyle (1849, The Negro Question) coined the term *the dismal science* in 1849, dismal in "find[ing] the secret of this Universe in 'supply and demand', and reducing the duty of human governors to that of letting men alone". Carlyle argued for slavery. Carlyle's suggestion was resisted by, among others, John Stuart Mill.

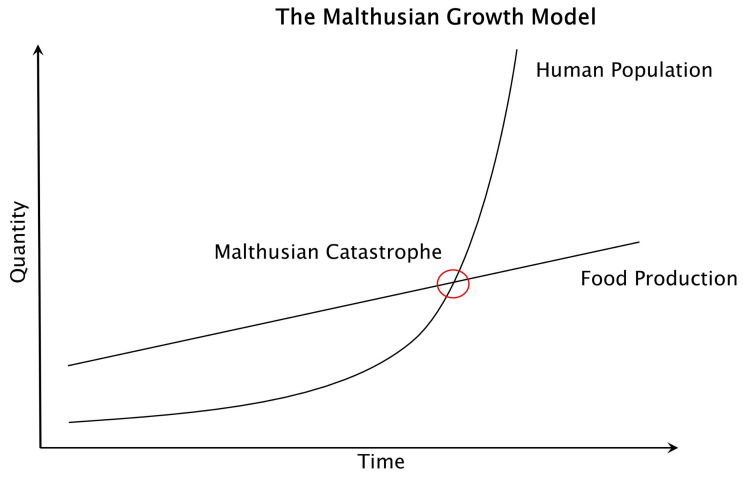

Fig. 1.1 Supply and demand for food over time.

David Ricardo refined the argument. He distinguished between the *internal margin* and the *external margin*. You can increase food production at the internal margin by working crop lands harder. As Malthus noted, this is subject to decreasing returns to scale. At the external margin, you can take virgin lands into crop production. Malthus ignored this. Ricardo did not. Ricardo argued, however, that the external margin would not get around the Malthusian Catastrophe because our ancestors cultivated the best lands first. Expansion on the external margin is thus subject to decreasing quality.

John Stuart Mills further refined the Malthusian argument, nothing that the Catastrophe can be postponed by input substitution. Fertilizers make up for a shortage of soil nutrients, irrigation for a shortfall of rain. However, like Malthus and Ricardo and indeed all Classical Economists, Mills was convinced that economic growth must come to a halt because of resource constraints.

1.2.3 Romanticism

The Classical economists were sons of the *Enlightenment*. A central part of the Enlightenment was that arguments should be based on observations rather than authority and that decisions should be rational. Economics at the time was typically called *political economy*, a reference to rational, scientifically informed government.

Romanticism was a countermovement to the Enlightenment. It was concentrated in the arts, mostly literature (Brontë sisters, François-René de Chateaubriand, Johann Wolfgang von Goethe, Friedrich Schilling, Hendry David Thoreau, William Wordsworth) and to a lesser extent painting (e.g., Caspar David Friedrich) and music

(e.g., Johann Sebastian Bach). Romanticists shared three traits. They drew on the older school of Sentimentalism, arguing that emotions are a valid basis for decisions. They harked back to a simpler, better past. And they believed that nature was beautiful and to be enjoyed, rather than dangerous and to be subjugated.

Romanticism had three major offshoots: Communism, Nazism/Fascism, and Environmentalism.

Mao Zedong and Pol Pot took the harking for the past to the extreme, forcing city dwellers to move to the countryside and take up farming. The longing for the past extended to the mighty kings of yore, and the fascists' desire for a strong leader. In that mythical past, everyone was blond with blue eyes. The racial purity of *Blut und Boden* is a key part of Nazism.

Environmentalists tend to argue that things used to be better, and often believe in the myth of the noble savage.[4] There is a famous quote

> Only when the last tree has been cut down, the last fish been caught, and the last stream poisoned, will we realize we cannot eat money.

This is often presented as a Cree Indian proverb, exemplifying the wisdom and environmental stewardship of pre-modern people.[5] In fact, whenever *homo sapiens* introduced itself to a new ecosystem, it wreaked great havoc, including mass extinction.

Environmentalism shares its roots with odious ideologies, but few environmentalists would support them.[6] That said, environmentalists tend to be to the political left, but the watermelon epithet—green on the outside, red on the inside—is an exaggeration. Some environmentalists argue that democracy is not suited for solving the crisis in the environment. Although the term *eco-fascist* is used with abandon in some circles, there are environmentalists who do not tolerate dissent and pursue their green goals through violent means.

In older literature, danger lurked in the deep dark wood. Romanticists were the first to describe nature as something to be enjoyed rather than feared. This is a reflection of the times. Large predators had mostly disappeared from Western Europe, and you were never far from people. Nature had been tamed and could be enjoyed. People even started swimming in the sea. The oldest environmental organizations began as nature conservation,[7] and emphasized that nature made you a morally better person.

Many people care about the environment but not about Romanticism. The *Ecomodernist* movement explicitly embraces the Enlightenment. It takes positions that are often controversial to environmentalists, arguing for instance that nuclear power is a valid strategy to reduce carbon dioxide emissions and that intensive agriculture

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[4] The noble savage was introduced into modern thought by Michel de Montaigne in 1580. Earlier, in 98, Tacitus had described the Germans as noble savages.

[5] It is actually a modern quote of an Abenaki activist who left the reservation at age 7. The quote was popularized by Greenpeace.

[6] Many fascists love nature, Hitler prime amongst them, Communists less so. Guilt by association is a logical fallacy.

[7] The World Wide Fund for Nature was started to protect the hunting grounds of nobility and royalty.

is better for nature than the organic sort. Environmental economists are probably more comfortable with ecomodernism while ecological economists tend to associate more with environmentalism.

1.2.4 Mill on amenity values

John Stuart Mill (1848, Principles of Political Economy) brought some Romantic elements into economics,[8] writing

> There is room in world, no doubt, for a great increase in population, supposing the arts of life to go on improving, and capital to increase. [...] The density of population necessary to obtain all of the advantages both of cooperation and of social intercourse [...] has been attained. A population may be too crowded, though all be amply supplied with food and raiment. [...] Nor is there much satisfaction in contemplating the world with nothing left to the spontaneous activity of nature.

and adding, for good measure,

> it is only in backward countries of the world that increased production is still an important object[ive]

That is, Mill argued against equating well-being with *material* well-being. This foreshadows Kuznets' admonishment that GDP is a measure of economic activity, not welfare. Mills noted the importance of social intercourse (which we would now rather call interaction) and emphasized the amenity value of nature.

1.3 Neo-classical economics

The neo-classical revolution, led by William Stanley Jevons, Carl Menger and Leon Walras, radically changed economics. The now common tools of partial and general equilibrium and marginal analysis go back to this period.

Although Jevons (1865, The Coal Question) worried that

> I must point out the painful fact that such a rate of growth will before long render our consumption of coal comparable with the total supply. In the increasing depth and difficulty of coal mining we shall meet that vague, but inevitable boundary that will stop our progress.

a Malthusian position with coal replacing food—by and large the neo-classical revolutionaries were hardly interested in issues of environment and resources. This is partly because analysis had moved to the margin, and partly a reflection of the time: Technological progress and industrialization were rapid, and land seemed boundless, with the push into the American west, the Siberian east and the African interior.

[8] Romanticists were fond of Malthus' work, but he was not a Romantic. Malthus was a numbers man, striving for a better future rather than pining for misremembered past and, as all Classical economists, rather wary of a strong government.

Harold Hotelling was one of the few others neo-classical economists to work on resource problems, developing the rule that the price of an exhaustible resource should rise at the rate of interest. Despite Hotelling's prominence, this work was largely ignored until Robert Solow's 1974 paper and the book by Partha Dasgupta and Geoff Heal of the same year.

Although neo-classical economists paid little attention to the environment, they did lay the foundations for the economic analysis of environmental problems and environmental policy. In 1906, Vilfredo Pareto formulated *Pareto superiority*—situation A is better than situation B if at least one person is better off and no one is worse off—*Pareto improvement*—moving from B to A—and *Pareto optimality*—a situation is Pareto optimal if there are no Pareto improvements. Abba Lerner leaned on this and Adam Smith's invisible hand to state the *First Fundamental Welfare Theorem*—the equilibrium in a perfectly competitive market is a Pareto optimum—and the *Second Fundamental Welfare Theorem*—any Pareto optimum can be reached in a perfectly competitive market with the appropriate redistribution of initial endowments. Lerner showed this graphically, the first mathematical proof is due to Hotelling.

Although much of neo-classical analysis was centred on perfectly competitive markets, these economists were not blind to the limitations of this assumption. They just did not know what to do about it. Alfred Marshall, whose 1890 textbook *Principles of Economics* dominated university education, worked on open-access resources.

Marshall also noted that markets were imperfect because of externalities—an externality is an unintended and uncompensated effect of an economic activity on a third party. It was Alfred Pigou who, in 1920, found the first solution to the problem that externalities pose to the efficiency of the market. Pigou 1920, Economics of Welfare, II.XI.11 wrote

> If the amount of investment in any industry was carried exactly to the point at which the value of the marginal social net product there is equal to the central value of marginal social net products, the national dividend, so far as that industry is concerned, would be maximised. Disregarding the possibility of multiple maximum positions, I propose, for convenience, to call the investment that would then be made in the industry the ideal investment and the output that would be obtained the ideal output.
>
> Under conditions of simple competition, if in any industry the value of the marginal social net product of investment is greater than the value of the marginal private net product, this implies that the output obtained is less than the ideal output: if the value of the marginal social net product is less than the value of the marginal private net product, this implies that the output obtained is greater than the ideal output.
>
> It follows that, under conditions of simple competition, for every industry in which the value of the marginal social net product is greater than that of the marginal private net product, there will be certain rates of bounty, the granting of which by the State would modify output in such a way as to make the value of the marginal social net product there more nearly equal to the value of the marginal social net product of resources in general, thus—provided that the funds for the bounty can be raised by a mere transfer that does not inflict any indirect injury on production—increasing the size of the national dividend and the sum of economic welfare; and there will be one rate of bounty, the granting of which would have the optimum effect in this respect.

> In like manner, for every industry in which the value of the marginal social net product is less than that of the marginal private net product, there will be certain rates of tax, the imposition of which by the State would increase the size of the national dividend and increase economic welfare; and one rate of tax, which would have the optimum effect in this respect.
>
> These conclusions, taken in conjunction with what has been said in the preceding paragraphs, create a presumption in favour of State bounties to industries in which conditions of decreasing supply price *simpliciter* are operating, and of State taxes upon industries in which conditions of increasing supply price from the standpoint of the community are operating.

Pigou argues for the State to intervene to internalize externalities, by imposing taxes on negative ones and subsidies ("bounties") on positive ones.[9]

1.4 Keynes and the modern synthesis

For all the methodological advances in economics, the Great Depression caught the discipline empty-handed. The policy, if you can call it that, of laissez faire had failed. Economics was micro, but the problems of the economy were macro. John Maynard Keynes single-handedly created macroeconomics, focusing on the business cycle and countercyclical government policy.

After World War II, the discipline of economics worked on the *Modern Synthesis* of the recent Keynesian macroeconomics with the older neo-classical microeconomics. One product were the growth models of Harrod and Domar, of Solow, and of Ramsey, Cass and Koopmans. At the core of these models lies the Cobb-Douglas production function, which has that economic output depends on three factors, labour, capital and technology. Natural resources are not there. A one-sector growth model can be interpret as a multi-sector dynamic general equilibrium model if markets are perfect.

In other words, from the start of the neo-classical revolution in 1870 to the end of the modern synthesis in 1970, natural resources and the environment were not part of economics.

1.5 Environmental economics

Things changed in 1970s. As before, economics changed not because of internal pressures but because society changed. After World War II, economic growth was rapid. People could afford cars, and ended up in traffic jams. Those cars emitted gases and particles into the atmosphere. Electricity demand grew rapidly with the use of appliances, and coal-fired power plants added to the pollution of the air. New products were invented, new chemicals developed. The waste of the rapid industrialization was dumped. Rachel Carson published *Silent Spring* in 1962, a book that noted

[9] Some students complain about the use of mathematics in economics. Compare and contrast Pigou's definition of the Pigou tax to the one you find in any textbook.

that pesticides weaken egg shells, harming bird reproduction; she predicted a future without birdsong. In 1969, the Cuyahoga River was so polluted it caught fire. In 1972, the Club of Rome published its report of the *Limits to Growth*, a Malthusian tract that predicted society's collapse because of resource constraints well before the average reader of these lecture notes were born. (Hint: It did not happen.) In the same year, the crew of Apollo 17 took the first photo with Earth in full view. Although people had known *intellectually* that our planet is a globe, this was the first *sensory* perception that the Earth is round and finite and we're all in this together. The first oil crises struck in 1973.

After all that, no one could plausibly deny that

- natural resources are scarce;
- environmental externalities are substantial; and
- environmental services are valuable.

Environmental economics was born out of that realization. Its aim is to bring the tools of economic analysis to bear on environmental problems and environmental policy.

Kenneth E. Boulding reportedly said

> anyone who believes exponential growth can go on forever in a finite world is either a madman or an economist.

Boulding was a prominent economist, author of a well-read textbook and president of the American Economic Association. He set out his Malthusian views in a 1966 book *The Economics of the Coming Spaceship Earth*.

Nicholas Georgescu-Roegen (1971, The Entropy Law and the Economic Process) wrote

> economics gives no signs of acknowledging the role of natural resources in the economic process . . . the product of the economic process is waste, waste is an inevitable result of that process and ceteris paribus increases in greater proportion than the intensity of economic activity

Georgescu-Roegen argued that economies are bound by nature (like Boulding), and that models of the economy too should reflect the laws of nature.

Environmental economics took a different route, however. The *Limits to Growth* report had drawn fiery criticism of economists like Graciela Chichilnisky and Bill Nordhaus. In 1980, Julian Simon, a business professor, challenged Paul Ehrlich, a prominent member of the Club of Rome, to a wager. Ehrlich predicted that resource scarcity would drive up the prices of copper, chromium, nickel, tin, and tungsten between 1980 and 1990. Simon predicted a price fall. Simon won.

A common interpretation of the Simon-Ehrlich wager is that human ingenuity is the ultimate resource. We are so clever that we can overcome any challenge that nature might throw of us. This has been true until now. Whether it will be true in the future remains to be seen.

Environmental economics has adopted the position that the tool of economic analysis can be used to analyze environmental problems and that these problems can be solved by changing incentives at the margin.

Ecological economics, on the other hand, takes the position that environmental problems require an overhaul of society and the tools of economics are inadequate.

I am an environmental economist.

Chapter 2
Social choice

2.1 Alternative views on ethics

Social science is about three questions: what if; so what; and what to do.[1] What would happen to eutrophication if fertilizer is taxed based on its nitrogen content? Do the costs of restricting nitrogen application to farmers and consumers matter more than the impacts of eutrophication on nature and recreation? Is it better to tax fertilizer or to forbid certain applications?

The first question, what if, is positive. It requires an as-accurate-as-possible, as-objective-as-feasible description of the relevant parts of the world as it is. The third question, what to do, is normative. You cannot rank options without a clear idea of what is better and worse. The second question is a mix of normative and positive—the measurement of costs and benefits is positive, but the decision what to include and exclude is normative.

The idea of what is better and worse is key to answering normative questions. Normative questions are rife in public policy advice and evaluation, including all aspects of environmental policy.

Environmental economics, when informing public policy, has a more profound normative problem than other branches of applied public economics. The economic analysis of education, health care or labour markets is invariably confronted with making trade-offs between people. In environmental economics, we often make trade-offs between people too, but also between humans and non-humans.

It is therefore important to discuss what we mean by better and worse. Economics is by and large based on a utilitarian ethics. Alternative views are rarely discussed. Yet, utilitarianism is a minority view among moral philosophers.

I discuss three major strands in moral philosophy, naturalist ethics and two strands of humanist ethics, libertarianism and utilitarianism. I particularly focus on utilitar-

[1] Natural science is only about what if questions. The incomplete education of natural scientists leads to endless confusion and discussion when they leave the ivory tower to partake in policy debates.

ianism, because economics is based on that. There are other, less relevant strands of ethics, but these are not discussed here.

2.2 Universality

Immanuel Kant is one of the most important philosophers in history. Although he died more than two centuries ago, young philosophers still study his work, only to discover what a singularly obscure writer he was. Among other innovations, Kant introduced the *moral agent* and the *universal law*.

A moral agent is the unit of analysis in ethics. Rights and duties can be bestowed on moral agents and on moral agents only.

Kant's universal law holds that, if a rule applies to one moral agent, it applies to all moral agents. For instance, assume that you and I are both moral agents. If I argue that you cannot chop off my arm, then I cannot chop off your arm either.

2.3 Naturalism

Naturalist moral philosophy is centred on the question who is a moral agent. This is perhaps best illustrated with a review of political rights.

It used to be that only the views of rich white male Protestants mattered. Rich white male Protestants argued that only they mattered because only they were worthy and capable.

Then along came Jeremy Bentham, a rich white male Protestant, who wrote that government should strive for the greatest good for the greatest number. This was a radical proposition. Poor lives matter. The government should serve not just the elite, but the less fortunate too. Bentham had no truck with Catholics, non-whites or women, but he did argue in favour of people less wealthy than he was.

This intervention set off a cascade. If you cannot argue that someone else is worthy only if she is just like you, then you need a different criterion to delineate moral agents from other entities.

Catholics were emancipated first. You cannot maintain that someone is less worthy because he reads a different translation of the same book. Women were next. The notion that women are too hysterical to own property or vote was shown to be a self-serving lie than men like to tell each other. Skin colour was last. A physiological adaptation to the intensity of sunlight has nothing to do with other human capabilities.

However, if as a rich white male Protestant you cannot argue that only rich white male Protestant matter, then as a human you cannot argue that only humans matter. It is a self-serving argument.

Some people argue that the right delineation is a sense of self. If you put a parakeet in front of a mirror, it will sing to its mirror image—and will continue to do so even if the mirror does not answer back. A parakeet does not have a concept of self and no

concept of other. A moral rule that constrains the self as it treats others is therefore meaningless to a parakeet. That said, other primates, dolphins and elephants do recognize themselves in the mirror. Some human rights would therefore also apply to other higher animals. In 2015, a judge in Argentina ruled that, since Sandra had broken no laws, it was illegal to hold her captive. Sandra is an orangutan.

Utilitarianism is about minimizing pain and maximising pleasure. If that is the ethical starting point, then what sets a moral agent apart is not her ability to self-identify, but rather her ability to experience pain and pleasure. Cats may not recognize themselves in the mirror—there are countless videos on YouTube that prove this point[2]—but cats sure are able to experience pain and pleasure. Many people oppose torture of animals as they oppose torture of humans, and many countries have laws against cruelty to animals.

The human ability to experience pain and pleasure derives from our central nervous system, with nerves throughout the body and a brain to coordinate it all. Worms do not have a central nervous system. If you chop a human in two, you have two halves of a dead human. If you chop a worm in two, you have two worms. But if you cannot argue that someone is unworthy because they have a different skin tone—a physical characteristic—you cannot argue that something is unworthy because it lacks a central nervous system. Octopuses have nine brains. They are smart and have complex personalities. Extending human rights to all animals may seem extreme to people who grew up in a society influenced by Christianity or Islam, but it is a common position in Hinduism.

Trees too signal distress in a way that is alien to humans but clearly recognizable nonetheless. Fruitarians extend the well-accepted rule against cannibalism to all living beings.

The cascade does not stop there. The occasional media flurry on the discovery of life on Mars is rooted in our inability to distinguish organic material from dead material. At the macroscopic scale, it is easy to tell a bear from a tree from a rock. At the microscopic scale, such distinctions are blurred. Viruses, for instance, are somewhere between alive and not. Deep ecologists like Aldo Leopold and Arne Naess argue that non-living entities indeed have a right to integrity of body just like humans do. Certain religions recognize abiotic entities, such as rivers or mountains, as spiritual beings worthy of respect and protection.

2.4 Libertarianism

Libertarianism is one of the schools of humanist moral philosophy. It grants rights and duties to humans only, although some of the reasoning can readily be extended to other species.

As the name suggests, libertarianism is about individual rights and liberties. John Locke argued property is just if it is acquired through labour. That is, if someone

[2] Here is an exception.

goes into the forest, cuts down the trees and starts cultivating the land, then that land is theirs. When Locke wrote this, King James VII and II was trying to establish an absolute monarchy in England and Scotland, including the notion that all land belongs to the crown. Locke disagreed. This thinking is reflected in the US Homestead Act of 1862, and it reflects Germanic traditions of property law.

Locke's idea of just property is impractical. Robert Nozick added that property is just if acquired through labour or obtained through free consent. Just property remains just after voluntary exchange.

Libertarianism is thus only concerned with procedural justice. What matters is how you get there, not where you end up. An unequal distribution of resources is of no concern to a libertarian provided that the rich got rich by legal means.

The role of the state is rather limited in libertarianism. The government should guard against unjust holdings, such as theft. The government should also guard against negative externalities, which are involuntary impositions on the liberties and properties of others. That is all.

Libertarians argue that taxation is theft. Governments can therefore not distribute resources from the rich to the poor. The government may provide public goods, but contributions to that should be strictly voluntary.

2.5 Utilitarianism

Utilitarianism is the polar opposite of libertarianism. Utilitarianism is consequential justice. What matters is where you end up, not how you got there.

At the individual level, utilitarianism is about pain and pleasure. At the social level, utilitarianism is about the greatest good for the greatest number. In narrow definitions of utilitarianism, this means the sum total of the utility of people. In broad definitions of utilitarianism, this means some aggregate of the utility of people and perhaps animals.[3]

The government should deliver the greatest good for the greatest number. It does not matter how. An autocratic government that brings material welfare to its citizens is better, according to utilitarians, than a democratic government of a poor country.

Broad interpretations of utilitarianism can be captured with a Bergson-Samuelson-Atkinson welfare function

$$W = W(U_1, U_2, ..., U_n) = \frac{1}{1-\gamma} \sum_{i=1}^{n} U_i^{1-\gamma} \tag{2.1}$$

where W denotes social welfare and U_i the utility of individual $i = 1, 2, ..., n$. The right-hand side is due to Anthony Atkinson, the middle part was independently suggested by Abram Bergson and Paul Samuelson. The parameter γ is relative inequity aversion.

[3] Some philosophers argue that broad utilitarianism is not utilitarianism at all, but I have yet to see a cogent argument why not.

At the margin, individuals i and j contribute to social welfare as follows

$$\frac{\frac{\partial W}{\partial U_i}}{\frac{\partial W}{\partial U_j}} = \left(\frac{U_j}{U_i}\right)^{\gamma} \tag{2.2}$$

If $\gamma = 0$, the social planner is inequity neutral. $W = \sum_{i=1}^{n} U_i$. It does not matter whether the utility of i or j goes up, because the ratio of their marginal contributions to welfare is always equal to one.

For $\gamma > 0$, the social planner is inequity averse. If i is happier than j, $U_i > U_j$, then $\left(\frac{U_j}{U_i}\right)^{\gamma} < 1$. That is, a utility gain for happy i is less important than a utility gain for miserable i.

There is another way to see the same thing:

$$W = \begin{cases} \min_i U_i & \text{if } \gamma \uparrow \inf \text{ (Rawls)} \\ \prod_i U_i & \text{if } \gamma = 1 \text{ (Bernoulli-Nash)} \\ \sum_i U_i & \text{if } \gamma = 0 \text{ (Bentham)} \\ \max_i U_i & \text{if } \gamma \downarrow -\inf \text{ (Nietzsche)} \end{cases} \tag{2.3}$$

As γ grows, more and more emphasis is placed on the plight of the worst-off in society.

Arrow's Impossibility Theorem shows that a welfare function cannot be an aggregate of individual preferences. That does not mean that you should not use social welfare functions. It does mean that you should be aware of their limitations.

2.6 Critiques of utilitarianism

Utilitarianism is unpopular outside economics. Besides the alternative schools of moral philosophy, I highlight the work of two criticasters.

John Rawls is seen as one of the key ethicists of the 20th centry. Rawls thought and wrote about what a just society would look like. He argued that a just society would be one that everyone in that society would agree on, if they were free to decide, rational, and impartial. For impartiality, Rawls introduced his *veil of ignorance*: You can be impartial only if you do not know what position you hold in society, if you do not know how skilled or talented you are, and if you do not know your attitudes towards risk, inequality and such things.

On that basis, Rawls argued that a just society would be as free as possible. Anyone should be who they like to be and do what they want to do, as long as it does not infringe on other people's liberties. Rawls also argued that a just society minimises resource difference. Incomes should only deviate if that income difference makes everyone better off, and if that income difference is attached to position. For example, doctors and firefighters have to be on standby for 24/7, so it stands to reason that they are compensated for their sacrifice lest no one wants to take that job. Doctors

are trained for a longer period than nurses so it is reasonable to compensate them for that—but not for the fact they were born into a different class or have a greater aptitude for academic study. Rawls' just society is nothing like ours.

As shown in Equation (2.3, a Rawlsian income distribution can be captured in a social welfare function. Other aspects of Rawlsian justice, such as maximum freedom, cannot.

Amartya Sen is an economist and Nobel laureate. A utilitarian would applaud the government of Singapore which is fairly authoritarian but has made its people rich. The governments of South Korea and Taiwan were similarly down on freedom but up on economic growth, and were removed by its people. Not everyone agrees that material wealth is all that matters. Sen noted a deeper problem. An aggregate of individual utilities, cannot reflect properties of society, such as democratic freedoms: A Bergson-Samuelson function has that $W = W(U_1, U_2, ..., U_n)$, $W \neq W(U_1, U_2, ..., U_n, F)$, where F stands for freedom. Nor is it easy to add freedom as an attribute to a utility function: Freedom is not consumed or produced in any conventional meaning of those words, and it is property of society rather than an individual.

Sen also highlighted altruism. At first sight, altruism is compatible with utilitarianism. If person i cares about person j, $U_i = U(C_i, U_j)$. That is, besides on her own consumption C_i, utility is a function of the other person's happiness (or perhaps perceived happiness or consumption). There are two problems with this. First, the construction of the aggregate demand curve assumes that individual demand curves are independent of each other. The vertical aggregation of demand curves allows for the kind of altruism that affects our well-being but not our behaviour. You can work your way around this (not in an undergraduate class though) but then a different problem emerges. A social welfare function is meant to give policy advice. A social welfare function that includes altruism has a fundamental inequity build-in. If your utility depends on your well-being and the well-being of the people you care about, then a social welfare function that reflects your utility double-counts the utility of those you care about. That would not be a problem if care were equally distribution. If not, such a social welfare function is biased towards popular people and biased against unpopular ones.

Sen further wrote about agency. People behave differently in different roles. You are different around your family then when you are with friends or colleagues. This is first and foremost a positive problem, an issue with describing and predicting what economic agents do. It is hard to construct a utility function and budget constraints, that manifests itself in first-order condition that solve differently depending on who else is in the room. But this also affects the social evaluation of individual behaviour, which is after all what a welfare function is about. A middle-aged man chatting up a young woman in a bar is met with pity, a middle-aged male professor chatting up a female student after class stands accused of harassment and abuse of power. A business man giving preferential treatment to an old friend is giving away his own money, a politician gives away public funds. Different roles come with different expectations and responsibilities, so that a transaction can be legitimate and welfare-improving in one circumstance but not in another.

Utilitarianism is therefore an ethical system with many drawbacks. Applications of social welfare functions should always be treated with caution and inspected for flaws.

Chapter 3
Sustainability

Sustainability is a core concept in environmental policy. It is sometimes interpreted as a property of the social welfare function, but more commonly as a constraint we should impose on any decision we make.

3.1 Roots

John Stuart Mill (1848, Principles of Political Economy) wrote

> If the earth must lose that great portion of its pleasantness which it owes to things that the unlimited increases of wealth and population would extirpate from it, for the mere purpose of enabling it to support a larger, but not a happier or better population, I sincerely hope, for the sake of posterity, that they will be content to be stationary long before necessity compels them to it.

Like his fellow Classical economists, see Section 1.2.2, Mill believed that economic growth must come to a halt. In the above passage, he argues that economic expansion should stop before economic output reaches its maximum because there is "pleasantness" apart from material wealth. He further argues that we should do this not for our own sake but for those who come after. Mill thus captured the essence of sustainability.

Gro Harlem Brundtland and colleagues (1987, Our Common Future) give the following definition

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

This is intuitively appealing. We should develop but not hurt our children. The appeal of the Brundtland report led to a rapid and widespread support of sustainability. Every country and every organization wants to develop sustainably. Sustainability is the shared end goal, sustainabilizability the intermediate target.

The Brundtland definition is vague. What are needs? Food and water are beyond dispute, but I sometimes have a desperate urge to watch a silly show on TV. What

is the ability to meet needs? Are we content if our descendants could have met their needs but did not? And what does compromising that ability mean? If their ability is reduced by 10% is it compromised, or is the threshold at 90%?

Brundtland's vagueness is her strength. The direction of travel is clear, but there is no precise prescription, which allows people from different convictions to subscribe to sustainable development.

Academics do not like vagueness. There have therefore been many attempts to give a precise definition of sustainability. I review these below, in three major groups.

3.2 Weak sustainability

Jack Pezzey argued that sustainability means that utility should not fall. We want to sustain human happiness. Utility is an elusive concept, though. John Hartwick therefore argued that sustainability means that consumption should not fall. In 1977, he formulated the Hartwick Rule: A constant level of consumption can be maintained perpetually from an environmental endowment if all the scarcity rents (net price, profit) from resource extraction are invested in other capital. That is, we should keep the principal intact, live off the service flow alone. Robert Solow argued that, with finite resources, non-declining consumption is indeed constant.

The Hartwick Rule appears sensible—do not run down your capital stock—and precise. Nor does the Hartwick Rule specify whose consumption should be kept constant, however. Is it the median consumer's? Everyone's? Nor does it say at what time-scale should consumption be constant? Every year, every decade, every century? And it does not define the bundle of consumption, however. Is it the same bundle over time?

In order to overcome the last problem, Talbot Page and Robert Solow suggested that production possibilities should not fall. This avoids the problem of defining consumption for now and forever. As an analysis of sustainability is done by current scholars, assumptions about future consumption necessarily reflect current preferences. A focus on production is less paternalistic. Problems of time scale and representation remain, however.

A key aspect of all these definitions is that substitution is allowed. The Hartwick Rule explicitly says that it is fine to run down natural resources as long as the revenue is used to build up physical capital. According to these *weak* definitions of sustainability, what matters is that human welfare will not fall. A walk in the forest can be replaced with a walk in virtual reality.

3.3 Strong sustainability

The defining feature of weak sustainability is that human-made capital can substitute for natural capital. Advocates of strong sustainability disagree. Some go as far as arguing that sustainability means that natural capital stocks should be maintained.

This has far-reaching implications. Fossil fuels can no longer be used, or fossil water. Trees can only be cut for lumber if new trees are planted. Building materials would be scarce, a mining for sand and limestone comes to an end.

If all natural capital stocks are to stay at their current levels, human activity would be severely curtailed. A new road takes up space, necessarily taking away space from something else. Building a new house thus means taking down an old one. If strong sustainability is defined at the local level, the old house needs to be in the same county.

In practice, therefore, some substitution must be allowed. But at what spatial scale? If forest has to make way for a new road in England, should new trees be planted in England or is it fine to plant new trees in Hungary? To what extent do new trees substitute for old trees, which provide a much richer habitat for birds, plants and insects?

What natural capital stocks should be maintained? Ecosystems, species, or genes? The polar bear is a subspecies of the brown bear. Not much genetic diversity would be lost if the polar bear goes extinct. Or maybe we do want to preserve individual species from extinction, whether caused by humans or evolutionary dynamics. And what should we do with viruses and pests? Should we let malaria roam freely?

The desire to maintain natural capital stocks reflects a static view of the natural environment. Things should stay as they are or return to how they used to be. An alternative view on strong sustainability argues that, instead, services from natural capital stocks should not decline. What matters is that there are enough photosynthesizing plants to make sufficient oxygen; it does not really matter what species these plants are. What matters is that there are coastal forests to break storms and provide shelter and sustenance for fish larvae; it matters less whether there are more mangrove palms than buttonwoods.

A focus on nature's services begs the questions a service to whom or what? Plants can live without animals but animals cannot live without plants? And at what spatial or temporal scale should services be maintained?

A third group of definitions of strong sustainability centres on ecosystem stability and resilience. This does not solve the fundamental problem of lack of specificity, because stability has to be defined in terms of either stocks or services.

The key feature of strong sustainability is that it imposes stronger constraints on human behaviour than does weak sustainability. Weak sustainability argues that all is fine as long as humans are fine. This is a utilitarian perspective. Strong sustainability wants other species to be fine too, even if it comes at the expense of humans. This is a naturalist perspective.

3.4 A social construct

The academic quest for a more precise definition of sustainable development than Brundtland's has thus led to a variety of definitions that are not particularly precise either. There is a third group of definitions: Sustainability is what we decide it to be.

This is a truism. Sustainability is not some property of the real world that we try to uncover. Sustainability is an abstract human desire, a social construct. But the people who argue this have a deeper motive. Brundtland's recommendation that development should be sustainable was so popular that it crowded out other objectives of government. Advocates of other worthy goals can either resist the new kid on the block, or seek to co-opt the item newly at the top of the agenda. People who argue that sustainability is a social construct also argue that it matters how society construes sustainability, a libertarian focus on procedure over outcome, and typically advocate deliberative, participatory democracy.

Sustainable development was initially about environmental quality, but this was quickly replaced by the three pillars of sustainable development: Environmental quality, distributional justice, and economic efficiency. The United Nations now has no fewer than 17 *sustainable development goals*: a half one about economic growth, one about participatory democracy, three about the environment, and eleven and a half about development.[1] Sustainable development is now more development than sustainable.

Blurring concepts and re-purposing slogans is excellent politics but poor policy. Putting its three pillars under one heading masks the real trade-offs in sustainable development. Agriculture puts a lot of pressure on the environment. Cleaner forms of food production are more expensive. Greater environmental quality implies lower economic growth. Food is a necessary good. Poorer people spend a larger share of their income on food. Greater environmental quality implies a more unequal income distribution. Lumping everything under sustainable development hides these trade-offs. Vague words that appeal to every constituency is great politics. Ignoring the negative consequences of interventions is poor policy.

Jan Tinbergen showed that if you have N policy problems, you need N policy instruments. This is a corollary of Joseph-Louis LaGrange's work on constrained optimization. A simple example illustrate this. If you have two cars, you need two steering wheels. You can imagine a single car with two steering wheels, but negotiating a bend in the road requires a lot of coordination between the two drivers. Two cars that share a single steering wheel do fine as long as they go straight. Turning a corner is rather tricky. Killing two birds with one stone is so remarkable we made it a proverb.

Returning to example of food production, there are three objectives. A reduction in environmental pollution requires a change in farm practices. Economic efficiency demands that you do so for the lowest possible cost. As shown below, that is best done through a tax on emissions. Distributional justice dictates that part of the tax

[1] Sustainable development goal #12 says that production and consumption should be sustainable. This is a tautology.

revenue be used to raise the income of the poorest. Giving three problems the same name suggests there is only one problem, and that one intervention is enough to solve it.

Part II
Valuation

Chapter 4
History of value

4.1 Proto-economics

Adam Smith (Wealth of Nations I-IV, 1776) formulated the paradox of value thus:

> The word VALUE, it is to be observed, has two different meanings, and sometimes expresses the utility of some particular object, and sometimes the power of purchasing other goods which the possession of that object conveys. The one may be called 'value in use', the other 'value in exchange'. The things which have the greatest value in use have frequently little or no value in exchange; and on the contrary, those which have the greatest value in exchange have frequently little or no value in use. Nothing is more useful than water: but it will purchase scarce any thing; scarce any thing can be had in exchange for it. A diamond, on the contrary, has scarce any value in use; but a very great quantity of other goods may frequently be had in exchange for it.

Smith's words echoed earlier writers. The oldest surviving account is by Plato (Euthydemus, 304BC), who, remarking on Crito's easily copied oratory style, wrote

> for only what is rare is valuable; and "water" which [...] is the "best of all things" is also the cheapest.

The Ancient Greek philosophers, led by Aristotle, had little interest in price formation and why prices *are* as they are. They gave little consideration to value in exchange. Instead, they focused on value in use, using ethics to reason what values *should* be. They worried about the deviation of the actual price from the right price. The market was deemed *immoral*.

Some 750 years later, St Augustine replaced Aristotelian ethics by Christian theology. Like Aristotle, he was mainly interested in what values should be. Unlike Aristotle, he argued that the right price can only be found by examining the will of God. Working some 850 years after, Thomas Aquinas by and large adopted Augustine's position.

In 1662, William Petty wrote

> Labour is the Father and active principle of Wealth, as Lands are the Mother.

Petty maintained the notion that there is an absolute yardstick for value, but he replaced an intangible God with tangible assets.

The 18th century Physiocrats, led by François Quesney, followed Petty to a limited extent. They put God at one remove from value. Quesnay argued that society should be based on the *ordre naturel*, the laws of nature as dictated by God. Agriculture was society's interface with nature, and therefore only agriculture can yield a net surplus. Other economic activities do not add value, take as much in inputs as they make in outputs. Note that, according to the Physiocrats, it is nature that creates value. Farmers merely reap that value. The source of value is the land.

The land theory of value thus replaced one absolute yardstick—God—with another—land. It is easy to see how the Physiocratic theory of value served the landed elite of France. Quesney was a land-owner himself, and served at the court of Louis XV.

4.2 Classical economics

Adam Smith disagreed with the Physiocrats, arguing that labour rather than land is the true source of value.[1] David Ricardo and Karl Marx further elaborated Smith's labour theory of value.

Smith, Ricardo and Marx maintained the notion, going back to Aristotle, that value is absolute. Marxian economists held up another part of the Aristotelian tradition: If the market price deviates from the labour value, that is because the market is *immoral*.

Smith and Ricardo instead argued that the market is *moral*. The invisible hand guaranteed the greatest good for the greatest number.

4.3 Neo-classical economics

The neo-classical revolutionaries argued that value is relative. They abandoned the labour theory of value of Smith and Marx and the earlier absolute value theories, whether anchored on land or religion or morality.

[1] Ibn Khaldun had earlier developed a labour theory of value, but this was not known in Europe until much later.

Part III
Regulation

Part IV
Topics

Appendix A
Optimization in continuous time

A.1 Discrete time

You are familiar with constrained optimization. If we want to find the optimal consumption path in a production economy, you could

$$\max_{C_0, C_1, \ldots} \sum_t U(C_t)(1+\rho)^{-t} \text{ s.t. } \Delta K_t = -\delta K_t + (Q(K_t) - C_t) \tag{A.1}$$

where U denotes utility, C_t consumption in year t, ρ the utility discount rate, K_t the capital stock at time t, δ the depreciation rate, and Q the production function.

In order to solve this, form the Lagrangian:

$$\mathcal{L} = \sum_t U(C_t)(1+\rho)^{-t} - \lambda_t \left(-\delta K_t + Q(K_t) - C_t - \Delta K_t\right) \tag{A.2}$$

The Lagrangian is the objective function minus the Lagrange multiplier times the constraint-rearranged-to-equal-zero.

The first-order conditions are

$$\frac{\partial \mathcal{L}}{\partial C_t} = U_{C_t} + \lambda_t = 0 \forall t \tag{A.3}$$

and

$$\frac{\partial \mathcal{L}}{\partial \lambda_t} = 0 \Leftrightarrow \Delta K_t = I_t - \delta K_t \forall t \tag{A.4}$$

where I_t is investment in year t.

The problem with these first-order conditions is that they are not particularly informative. For instance, we find that the shadow price of capital, λ_t, should be equal to the marginal utility of consumption, U_{C_t}, at every point in time—this follows from Equation (A.3)—but we discern nothing about the evolution of the shadow price over time. Equation (A.4) reproduces the equation of motion of capital, rather than its price.

A.2 Continuous time

You could also write the maximisation problem in continuous time

$$\max_{C(t)} \int_t U(C(t))\mathrm{e}^{-\rho t}\mathrm{d}t \text{ s.t. } \dot{K}(t) = -\delta K(t) + (Q(K(t)) - C(t)) \tag{A.5}$$

There are a few differences between Equations (A.1) and (A.5). Instead of a summation over time, we have an integral. Recall that a Riemann integral is summation in infinitisimally small steps. Instead of subscripts to denote time, variables are now functions of time. This is just a convention. Instead of the discount factor $(1+\rho)^{-t}$ we have $\mathrm{e}^{-\rho t}$. In the former, ρ is the annual discount rate. Measuring time in annual time steps is arbitrary. Instead of solar years, you could measure time in lunar months, or in days, hours, minutes, or seconds. If the time step goes to zero, $(1+\rho)^{-t}$ approaches $\mathrm{e}^{-\rho t}$. Finally, $\dot{K}(t)$ replaces ΔK_t. The latter is the difference between two periods, $\Delta K_t = K_{t+1} - K_t$. The former is the change at time t, $\dot{K}(t) = \frac{\partial K(t)}{\partial t}$. Although the notation has changed to account for the fact that we are working in continuous rather than in discrete time, our representation of the system has not changed.

You cannot use the methods developed by Joseph-Louis Lagrange to find an optimum in continuous time. Instead, you have to use the methods of William Rowan Hamilton and Lev Pontryagin. So, in order to solve this, we form the Hamiltonian, or more specifically, the current-value Hamiltonian[1]:

$$\mathcal{H} = U(C(t)) + \eta(t)\dot{K}(t) \tag{A.6}$$

The Hamiltonian consists of three elements. The first element is the current value of the objective function. That is, get rid of the integral. Only take the bit that you integrate, in this case $U(C(t))$. The second bit is known as the co-state variable, $\eta(t)$, which is a shadow price just like the Lagrange multiplier. The third part is the left-hand-side of the constraint, $\dot{K}(t)$. Compared to the Lagrangian, the Hamiltonian is considerably simpler.

This simplicity helps greatly with the first-order conditions. There are two. The first is

$$\frac{\partial \mathcal{H}}{\partial C(t)} = U_{C(t)} - \eta(t) = 0 \tag{A.7}$$

The first first-order condition has that the first partial derivative of the Hamiltonian to the control variable be equal to zero, just like in Lagrange's constrained optimization. As with the Lagrangian, this says that the shadow price of capital should equal the marginal utility of consumption. This is because we sacrifice consumption to invest so as to accumulate capital used to produce consumption goods.

The second first-order condition has no analogue with Lagrange. It is

[1] Mathematicians and physicists are better used to the present-value Hamiltonian. The results are the same. The current-value Hamiltonian is more readily interpreted for economic problems.

$$\dot{\eta}(t) - \rho\eta(t) = \frac{\partial \mathcal{H}}{\partial K(t)} = \eta(t)\left(Q_{K(t)} - \delta\right) \tag{A.8}$$

That is, the first partial derivative of the Hamiltonian to the constrained stock variable equals the change in its co-state variable minus the discount rate times the co-state variable.

This can be rewritten as

$$\frac{\dot{\eta}(t)}{\eta(t)} = Q_{K(t)} - \delta + \rho \tag{A.9}$$

The left-hand side is the proportional rate of change of the shadow price of capital. This is a variable with an economic interpretation. It is the equation of motion of the *price* of capital.

The elements on the right-hand side are intuitive too: the marginal productivity of capital $Q_K(t)$, the depreciation rate δ, and the utility discount rate ρ. Equation (A.9) thus says that the value of capital should increase with its productivity, and fall with depreciation, and rise with discount rate. The last result may not be intuitive. If the discount rate is higher, you care less about the future, therefore invest less, and thus have less but more valuable capital as a result.

A.3 Conclusion

Optimization in continuous time is daunting at first sight. However, it is just a trick. Constrained optimization is a trick. Form the Lagrangian. Write down the first-order conditions. Continuous time optimization is a trick too, albeit a different one. Form the Hamiltonian. Write down the first-order conditions. The good thing about the Hamiltonian is that its first-order conditions immediately lead to economic insight.