It's the entropy, stupid!

Towards a thermodynamic and complexity-based framework for macro-economic policy

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Abstract

This paper provides a non-technical introduction to the semantic and fundamental issues around 'growing systems' from a thermodynamics and complexity perspective. Specifically, it addresses economic growth in the anthropocene and its challenges. Eventually it suggests a formal and general definition of 'growth'. Finally, it suggests how mainstream (macro)economics could mature towards a more scientific paradigm, based on this thermodynamics and complexity perspective, to address these challenges.

1 Introduction

In trying to address the current global challenges such as climate change, loss of biodiversity, an exponential increase in energy- and resource consumption, increasing inequality and much more, it becomes clear that our traditional macro-economic models and policy frameworks are not up to the job. Apart from the fact that 'a model' is always a reduction of reality and, as such, will always have its limitations for application, the last few decades we have witnessed a sudden and huge increase in complexity of our domains, which outpaces our models even more. Especially the IT-revolution and globalization have created many more inter-dependencies between human and natural domains, and much more dynamics (financial, economic, logistic, social, information, etc).
It now appears we still have limited understanding of how our 'systems' actually work, and in all the discussion about new paradigms (de-growth, circular, etc) we are still having mostly semantic discussions instead of fundamental ones. One could even state that the academic economic discipline is in fact not even empirically grounded, not really scientific, for that matter.

A century after the foundational crises in mathematics, physics, arts and politics, we are now witnessing a foundational crisis in (macro-)economics.//
So, we have a special multi-headed hydra: next to all our global challenges, we have the head of *inadequate models* and policies to address these challenges.

2 The big picture

The models currently used in macro-economics are, roughly speaking, flawed in two distinct ways:

1. our economy is part of a larger system, but the models ignore this
2. they are focused too much on so-called 'aggregate metrics', and don't look at trends in the underlying distributions

2.1 The larger system

The anthropocene can be described as the era in which the scope of the globalizing financial-economic system has reached the level of its hosting system: the earth. The levels of human resource-extraction, pollution and land/forest degradation are not local anymore, but have global impact.
This means that actual limits and thresholds within the hosting system (resource-levels, pollution-levels, ecosystemic balances, etc) must be taken into account in the macro-economic models. Currently they are not, and even worse, we still have little notion of these material boundaries, especially concerning all kinds of indirect effects.
Natural domains, such as the climate and ecosystems, show all kinds of intricate dynamics, lots of them in some cyclical way. Such dynamics remain stable only within a set of thresholds within the environment. Outside these thresholds, some of these can become unstable, or even collapse.
So it does not only concern hard absolute limits, but also thresholds within dynamics.

1. Pollination is a good example: currently several bee-species are being decimated, as a result of intensive agriculture, for example. Since bees are a major source of pollination, at some point this may result in severe changes within the vegetable ecosystem [EPI14].
2. Another example is of course the sensitivity of the climate system to sudden changes, such as an increase in CO_2-levels that we are witnessing. The relationships between the atmosphere and the hydrosphere/biosphere/lithosphere existed for billions of years, but these spheres are now also increasingly related to the human '*technosphere*'.

3. A current example is the outbreak of the zoonotic corona-virus SARS-CoV2. The risk of zoonotic disease outbreaks becomes larger when growing urban environments enter animal habitats, such as the Wuhan region. It is also strongly related to biodiversity [IPB20].

4. Yet another example is that of decades of soil degradation [MSB18]. Many old cultures came into trouble because of intensive soil-usage, which caused severe degradation: the implosion of microbial soil ecosystems with severe droughts as a consequence. The US Dust Bowl during the 1930s is the textbook example. Even today there is a world-wide, slowly progressing desertification. Desertification is hard to reverse. In most cases the intensification results in increasing yields, but only local in time and region. Every year it requires higher levels of pesticides, more monocultures, etc., and is eventually unsustainable.

All these examples have in common that they exist of slowly progressing trends, that suddenly result in severe responses. They compare very well to the intricate balances within the metabolic systems in living organisms, and our immune-systems, for example.
Macro-economic models currently do not provide for such systemic aspects, internally or externally (in relation to the hosting earth-system), but treat the economy as an isolated system. It is clear that in the current era these models do not meet their demands anymore.

2.2 Metrics

The best-known macro-economic metric is GDP (gross domestic product), which can be applied to small economic regions up to the whole world. The framework of capitalism, on which our current macro-economic policies are based, is based on the notion of economic growth as primary health-metric. After all, economic growth will create jobs and increase living standards, for example. The current critique of this metric is that it does not disclose any information on increasing wealth-gaps and other social inequalities, and that policies that target only economic growth are too limited in scope, ignoring social and environmental values. Many alternatives are in the making, of which the R3.0 initiative and their blueprint on Value Cycles [BT20] and the 'systemic risk' manifesto of the International Association of Actuaries [Chi+20] deserve special attention.
Other important examples of traditional macro-economic metrics are the inflation-rate (which has target-values in central-bank policies), the interest rate, and the unemployment rate. These metrics certainly signal some valuable information. In this era of low interest rates and unprecedented quantitative easing by central banks, we see no inflation in consumer-prices (CPI) (because they are not directed towards consumers). But there is no comparable metric for the inflation in other classes, such as asset-prices, for

example. This policy certainly creates all kinds of bubbles in some asset-classes, but they are not used as a 'signal-metric' like the CPI.
The unemployment rate is another example of a highly aggregate metric, that does not disclose any trend (good or bad) of its distribution over social classes, regions or sectors. Of course these distribution are available, but macro-economic policies generally assume linear dependencies between these aggregates. As much as that may or may not be the case, in our current globalized and hyper-connected world these dependencies have certainly become much more nonlinear and intricate.
The key takeaway is that any macro-economic policy based on traditional metrics in the current complex environment is too limited in scope, and its effects (if present) can hardly be distinguished within the environment of nonlinear noisy dynamics that have their own undercurrents.

3 A single undercurrent for all domains?

From the previous section we can conclude that any successful macro-economic policy should look at the whole earth system, not just the (macro-)economic subsystem. This suggests that we take a multidisciplinary approach: ecological, biological, climatic, social, financial, etc. and try to take all aspects into account this way. There are initiatives that take this route already, with evonomics/econophysics and multicapitalism approaches as great examples. However, a multidisciplinary approach may not be enough to provide us with a real understanding of what is actually going on at a deeper level.
After all, we humans have established the collection of many disciplines, that all have their own domain-specific reductionist approaches. But the dynamics on earth do not care about the way we humans divided it up in different domains: in reality it is just one big system. So, next to the integration of relevant disciplines, it makes sense to try to determine common denominators between these disciplines.
From a certain point of view, this common denominator is clearly visible in many domains. In both natural and human domains, we recognize the concept of 'growth'. Evolution is bringing ever more and increasingly complex species and beings. The information age has catapulted into a huge increase in data and storage-facilities, computing-devices, etc. The health-care domain produces more and more medicines, therapies and technologies. Bureaucracies produce more and more rules and compliance measures. The financial systems produces more and more derivatives, ETFs, trading platforms, technologies, etc. All traditional talk about the economy is about growth: more products, more jobs, more money, more everything.
It takes some distancing to recognize that within natural domains, these growth-patterns have often found some natural ceiling, and that this holds for any scale you look at. Ant-hills have a certain maximum size, all or-

ganisms within species have a certain maximum size, and on a larger scale, growing ecosystems have found some level in size, that is in balance with its environment. There is no rampant growth of a forest somewhere, or some barrier reef, or some bird population. Sure, locally (in region and in time) there can be short bursts of fast growth, but these dynamics mostly settle down relatively quick without disturbing the hosting system.
Only within human domains we see this increasing level of growth in so many areas. But logic dictates that even this kind of growth must reach some ceiling, some saturation level.
So, intuitively, one of the most basic of all common denominators looks like 'growth'.

3.1 Growth

'Growth' may seem like a trivial and exhaustively debated concept, but there are still some serious caveats concerned with it. The first caveat concerns **semantics**: although we are familiar with metrics like GDP-growth, economic growth, growing plants and trees, and growth from childhood to adult, these are all very superficial or merely intuitive notions. We still have no *formal definition* of growth which applies to the commonly denominated concept in all domains.
The second caveat concerns **fundamentals**: with the current economic degrowth/post-growth narratives gaining track, we still haven't answered the most fundamental questions:

1. why are things growing at all? What is the *physical logic* behind it?

2. and why do they suddenly stop growing?

If we are able to fix these semantic and fundamental issues, we will have a much better understanding of what we are really up against, which increases our odds of actually developing effective macro-economic policies against the current challenges of the anthropocene.
So in order to really advance, we first need to take some steps back. Again, as trivial as it may seem, these issues have not been addressed at a rigorous level yet at all, and failing to do so will keep us in mazes of Babylonian speech disorders, and at risk of fighting the wrong enemies (or the right enemies in the wrong way).

4 Let's dance

Imagine being at the reception of a wedding, in a large room, with closed doors and windows. The air is filled with several scents, varying from appetizers to expensive perfumes. Then suddenly you have the urge to fart. Discretely you move towards a corner of the room, and let go. You know

that by the time it will reach the other guests, the concentration will be so low that it won't be noticed anymore. In principle, some time after all the guests have gone home, all scents within the room will show a near-perfect distribution across the room (apart from some molecular weight-differences etc).
This process is called '*dissipation*'. It is a well-known concept in heat-energy transfer environments (thermodynamics), called ***entropy***, where hot air and cold air (or fluids) mix and ultimately reach some equilibrium. This holds for so-called 'closed systems', where no energy is removed or added, and where the population stays the same. Such an equilibrium is not static, though, it is specifically what is called a 'dynamic' balance: from a macro-perspective all changes cancel each other out. In relatively simple systems (such as the reception) this process will progress gradually, in a 'linear' fashion.
There is a key to the growth-questions here, by the way: the closer it reaches an equilibrium, the slower this process will progress. This is called '*logistic growth*'. Remember this aspect, we will encounter it later on.
But farting at the wedding-reception is boring because it is simple. We can upgrade this scenario in two ways, to allow for some dancing: we can 'open the system' to be able to add and release energy, and we can add all kinds of stuff (transactional dependencies, complex material infrastructure) to get some turbulent, dancing effects.

4.1 Non-equilibrium economics

The academic discipline of (macro-)economics uses models that are based on so-called 'equilibrium dynamics' [Wik21]. It regards the economic domain as a 'closed system', just like the room at the wedding reception. In such models, a sudden change in the system (changing interest-rates or money-supply, for example) will have a ripple effect that eventually fades out into a (new) equilibrium. In low-profile economies such models can be useful, to some degree. But in our current globalized, resource-hungry and environmentally crushing economy, such models are utterly useless. Although academic curricula in economics still hold on to these models, a growing group of 'heterodox' economists (and non-economists) are working on so-called 'non-equilibrium models' [Art10].

4.2 Non-closed economics

An economy is not a closed system at all, from many points of view. Not only from the obvious environmental and social points of view, but also from the point of view that the earth systems get their energy from the sun and some geothermal supplies. If we want to understand what is happening in an economy, as part of a single global earth system, we cannot ignore the huge inputs of energy from outside. After all, even all of earths biomes, from the microbial life in sea to all higher orders of life and ecosystems, cannot exist without these energy resources. Our atmosphere, from the scale of the daily weather to the seasons and to the long-term climate, is entirely driven by the sun. Therefore, a new macro-economic paradigm cannot keep ignoring this continuous throughput of energy through the economy.

4.3 Non-linear economics

Economic systems are not homogeneous systems. The more sophisticated technology is deployed in economic systems, the more this holds. They display all kinds of local differences. Some populations respond early to changes, others much later. Our (global) economy is a complex system, with lots of chaotic behaviors. Dependencies between actors can be very intricate, indirect, and multi-faceted. This means that there is not always an easily discernible 'cause and effect'. Lots of changes cause lots of other changes. The weather is an ultimate example of such a complex system. There are so many dependencies and actors that it is very hard to make prognoses. This is also the case with managing interest-rates and unemployment-rates: there is no single policy that directly influences unemployment rates, or inflation rates, in always the same way. There are many factors at play, and they cannot be ignored. The mathematical discipline that studies these systems is called 'non-linear dynamics'.
Traditional macroeconomics has always used models based on linear dependencies. This makes sense up to some point, but not when modeling modern, inherently nonlinear economic systems.

4.4 Fractal economics

The systems on earth (climate-, ecological-, social -, financial -, economic -, technical - and information-systems, etc) are all very large and complex. It is typical for these kinds of systems that they display all kinds of patterns at different levels of scale, sometimes even similar. In the weather-system you can see very small tornado's in the outside corner of a building, medium tornado's that destroy some houses, and at the largest scale we have hurricanes. These are all the same kind of dynamic, but at different scales. Typically, small-scale dynamics are shorter-lived than their large-scale dynamics. The same holds for ecosystems: a forest can live and grow for centuries, while trees and animals live much shorter, and at a micro-level most cells in your body will die every few weeks (apoptosis) to make place for new cells.
There is also significant interaction between small-scale and large-scale dynamics (and everything in between). Some large-scale patterns 'emerge' as a result of ensembles of smaller-scale dynamics: small-scale dynamics 'bubble-up', and encounter large-scale dynamics. It associates strongly with the mathematical 'fractal' images (figure 1).

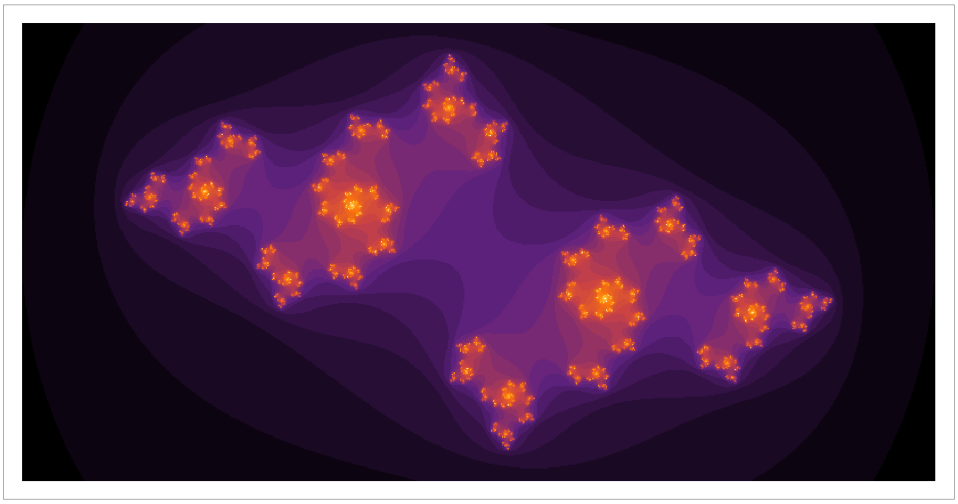

Figure 1: An example of a fractal with a 'continuous hierarchy'

What we call 'an economy' also has this scale-principle: the whole system can only exists by means of several levels of lower subsystems with all kinds of dynamics. The key takeaway is that we understand that the combination of all kinds of microdynamics enable the emergence of meso- and macro-dynamics, and that any new macro-economic model should reflect this principle.

4.5 Energy

If we return to the wedding-reception, with the comforting knowledge that the gradual dissipation of a fart will go unnoticed, and add these non-equilibrium, non-closed, and non-linear aspects, things can get wild again. The only thing we need to do is slowly 'turn up the energy-volume'. Where we first saw our fart evenly distribute across the room, from a certain volume-level things can get so wild that there is no such thing as 'gradual dissipation' anymore. When adding energy, the dissipative processes can get caught in all kinds of weird loops, pulsating dynamics, and boom-bust cycles: dancing turbulence.
That is *exactly* what life (the global ecosystem) is: dissipating solar energy that gets caught in some intricate fractal biochemical infrastructure, with all kinds of boom-bust cycles (birth, growth, death), at every scale.
And this is also *exactly* what our economic system does by means of its technological, social and financial infrastructure. At every fractal scale.

5 A generalization of the concept of 'Growth'

The saying goes that water will always find the easiest way to stream downwards. If you think about it, streaming water is also a kind of dissipation, just like with the scents in the room. If you throw a stone in a pond, the ripples will dissipate across the surface. The water falling down a waterfall will also dissipate when it falls into a pond below. If this pond has a small exit towards another waterfall (to keep from overflowing during heavy rainfall, for example), the depth of this pond determines the saturation point (when the water will flow to the next waterfall).
If we dig the pond deeper (the pond 'grows'), this saturation point will increase. If it starts raining, the water-level will rise: the pond 'ages'. We have now used 'growth' to describe the increase of some saturation level, and we have defined 'aging' as the actual saturation process.
One could imagine an intricate cascade of waterfalls and ponds, with ponds with many waterfalls, and cases where several waterfalls end up in the same pond. The natural process of erosion that digs out ponds deeper determines the growth of this cascade, and periods of rainfall show the fractal saturation processes from pond-level to cascade-level.
This cascade is a complex, fractal, nonlinear system, based on a single dissipative dynamic. And even in such crazy scenario's, the water will still find the easiest way, instantly.
Now we apply this principle to the dissipative process of solar energy in biochemical infrastructures (what we call 'life'). Growing organisms look like a waterfall-cascade with eroding ponds. Their cells are myriads of microscopic ponds with waterfalls, with relatively short saturation-cycles, new ones popping up, old ones being destroyed. And the hosting ecosystem is the image of the complete waterfall cascade, with a huge saturation cycle.
And we can also apply this principle to the dissipative process of solar energy in financial, economic, social and technological infrastructures (macroeconomy): a huge and very intricate ensemble of interdependently saturating dynamics. It is the ultimate complex, non-linear, logistic dissipation process on earth.

5.1 The semantic issue

We have now generalized the concept of 'growth' across all interesting domains:

> Growth is the increase of the saturation point of a local dynamic.

This is fundamentally different from the *actual* saturation process itself, which we call *aging*, but we are not really used to thinking about it this way. This formal definition allows for describing the following scenario: what if

the saturation point *temporarily increases faster* than the saturation process itself? Normally we only encounter processes in which there is a fixed saturation point, which is eventually (logistically) reached. But in this scenario saturation is impossible, until the saturation point increases slower than saturation itself. This may seem an absurd scenario, but our information systems currently display this scenario, and also our financial systems: the increasing amount of new computing devices (computers, smartphones, sensors, smart devices) and infrastructure does not allow any kind of saturation. Even the global economic system might currently display this scenario (no-one has ever quantified this).
When this type of behavior occurs in our bodily systems, medical doctors would qualify such excessive growth as malign tumors, and cut it away as soon as possible. An interesting analogy.
A saturation process normally follows the *logistic pattern*: it starts slow and accelerates (or starts fast), and then slows down when reaching the end (see Figure 2. It is always a temporary and local process.

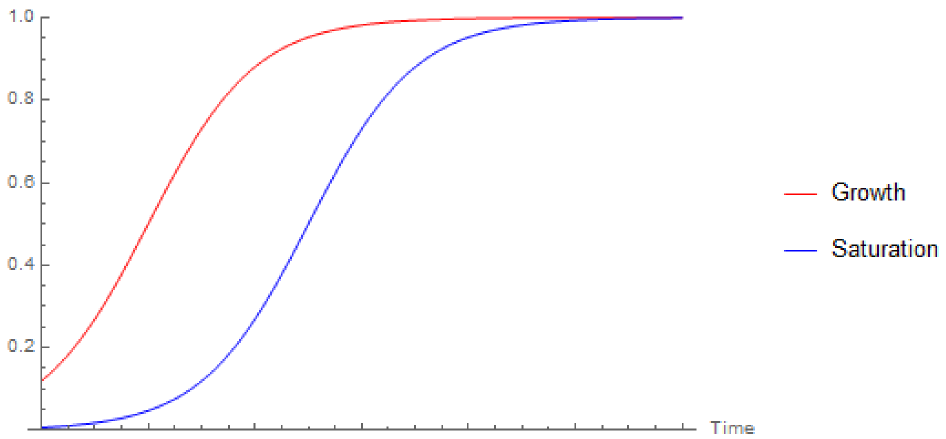

Figure 2: Growth and Saturation

An increase of the saturation ceiling (growth) is also a temporary process: it will saturate itself as well (aging will lead to death).
An simple illustration is the growth of a human being: it *grows* for only about 18 years. The saturation (aging) process itself continues afterwards, for some 70 years.
If you look at big complex systems (ecosystems, economies, climate, etc), they are often fractally renewing ensembles of such saturation processes, bubbling at every scale-level: the death of a tree will nourish other organisms in the forest, and every day many cells in your body die, to facilitate other processes (apoptosis).
In fact, in these systems all these processes are very much intertwined, so

much that (at some levels of scale) you cannot clearly distinguish between 'growing' and 'aging' processes anymore. With the cascading waterfalls this may still be possible, but in systems with much more diversity and dynamics it's not.
It is actually us humans that make some arbitrary choices in scale to look at something as a whole: an organism, 'life', a corporation, an ecosystem, etc. For us it only makes sense to talk about growth after we have chosen such a boundary. But reality does not mind about our choices of such boundaries. In reality it is just one system, everything else is just semantics: it depends on what you are looking at (the scale in time and space), whether or not you can make a qualitative distinction between process of saturation, and the process of a changing saturation ceiling.

5.2 The fundamental issue

Now that we have resolved the semantic issue, we can address the fundamental issue: why do things grow? What is causing this flow in the first place, before it hits some saturation point?
Well, just like the water finds the easiest way towards equilibrium, and the scents at the wedding reception, so does the energy of the sun that reaches earth. It if hits a rock, the rock will warm up, spreading the heat over its entire body. But in more complex systems, such as the weather, this dissipation can get turbulent. In even more complex systems, such as living systems, this dynamic gets temporarily trapped in the intricate, fractal bubbling of the mechanic and metabolic biochemical infrastructures. And in the same way, this dynamics is the undercurrent in our economic, financial and technological systems.
So, in essence, it is all the same generic class of dissipation dynamics: the difference sits in the specific material and transactional infrastructure, the medium of the system at hand. It is the same dynamic, on different carriers. When you add flexiblity to these material, transactional infrastructures (an organism, an economy, etc), they themselves interact with the dissipating dynamics, to eventually find some optimum. Often, this means an increase in the complexity of a structure (a growing organism, a growing economy), until it finds this optimum. Then, in some cases, after a while, the dynamic gets locally saturated (or exhausted). Then it fades, or the structure collapses.
When we say that something is growing, we look at a specific structural region that temporarily shows an increase in complexity, which enhances the dissipation-potential of energy within that region: a tree, your body, an economy, etc. From a macro-perspective, it is part of a continuum of turbulence in a superstructure of dissipation mechanics.

6 Complexity and growth

In the last few decades we have seen spectacular growth in several domains: smartphones, big data, artificial intelligence, financial products, etc. In fact, technological progress often results in some products suddenly showing huge growth. The advent of the T-Ford is still the hall-mark example of this.
Given the previous paragraphs, this makes total sense. New technologies are often enablers for more efficient energy dissipation. The whole earth-system can dissipate the sun's energy much easier. There are much more efficient options to choose from, when there are highly complex infrastructures available. In fact, *life itself* can be seen as a huge increase in '(bio-)technological' complexity on earth, from the perspective of the facilitation of energy dissipation.
If a dissipation-dynamic, in its turbulent chaotic movements, encounters a more efficient way, it will follow it. Exactly like water.
A better word for technology, to generalize in this context, is 'complexity'. Simply stated:

> The complexity of a system is the measure of the amount of, and diversity in participants and their interactions.

An increase of the level of complexity means an increase in the (types of) interactions, and/or the (types of) participants. When complexity is higher, the number of more efficient solutions is higher, and therefore dissipation dynamics are more likely to encounter these solutions.

6.1 Landscapes

There is an important caveat over here. Because such an efficient state may not be *the* absolute most efficient way possible. After all, if you think of the state of a system as a *path*, that travels through a so-called 'state-space', it cannot suddenly jump towards the most efficient state possible. Think of it as a marble within a landscape with mountains and valleys: the marble can't jump, but just moves towards the closest valley (a local maximum of efficient dissipation).
Such landscapes (where a marble depicts the state of a system) is often called 'a stability landscape' (see Figure 3).

6.2 Changing landscapes, and fractals

And in systems like ecosystems, organisms, and economies, this landscape continuously changes. New mountain-tops appear or disappear, and valleys as well. Even events comparable to earth-quakes can occur in these kinds of landscapes: for the state of the system to cross it, it may require a large detour. So if the marble sits in some valley, it does not mean that that is

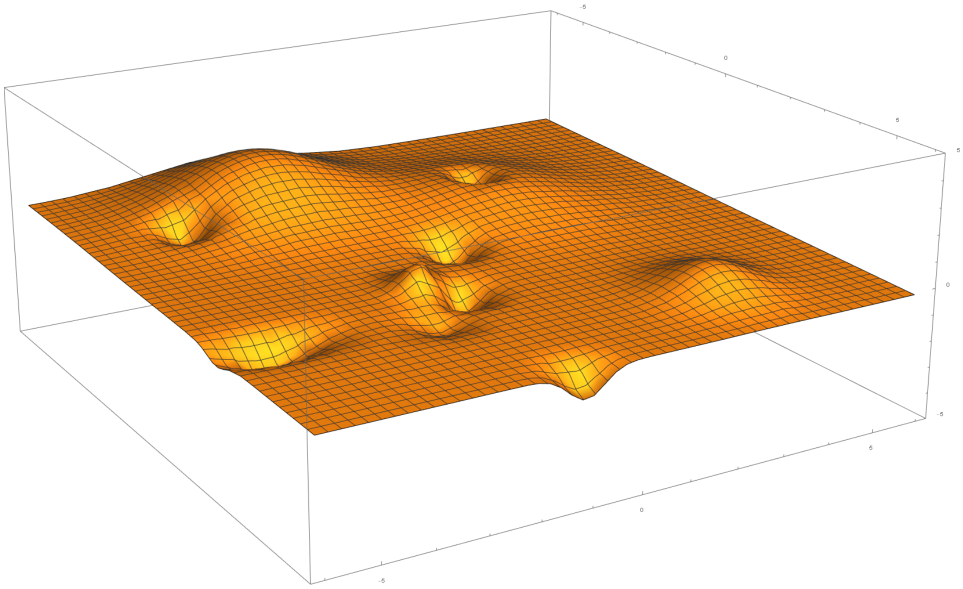

Figure 3: An example of a 'stability landscape'

the end of the story: the valley can become a mountain, etc.
These changes in the landscape can be caused by the interaction between the dynamics and its infrastructure (just like the erosion of a river, and from wind).
Obviously such a landscape is a simplified depiction of a small subsection of the actual system. If we elaborate this model, then given the fractal nature of these dynamic structures, most changes are caused by the saturation/exhaustion dynamics of the surrounding undercurrents. Like with the Russian puppets, a marble represents the landscape of fractally lower dynamics, which hosts some marbles, which in turn represent landscapes of even lower dynamics, etc.
(Actually, this is a discrete model for illustration purposes. It is key to understand that it is actually a continuum, where we humans just choose some scale, and slice a sub-region to look at that makes sense to us.)

7 Complexity as a key proxy for energy dissipation

We have now seen that a complex system that gets energy from 'outside' will try to dissipate it as efficient as possible. We have also seen that structural complexity can increase this dissipation efficiency. In our economy, 'dissipation' is what we know as the burning of fossil and renewable energy. So, if an economy sees some technological progress, it will burn up energy and resources more and faster, for as long as it is possible.
So next to the fact that 'consumers want the newest smartphone', this prin-

ciple explains why it is much harder to *undo* the adoption of smartphones, than to accelerate it.
Another aspect of increasing complexity is that, given the infrastructural flexibility, you get these clustering effects. Simple examples are big banks and big tech. There appears to be some power-law: there are few big, really complex participants, and many small, simpler participants, in some dynamic. One single super-entity is less efficient, apparently, and so are a big number of small ones. There is always some optimal distribution in complexity, and again: given enough flexibility, a system is able to move towards the most optimal distribution.
Again: a complex system optimizes towards the state with the highest level of energy dissipation. But not only that, it will always do this *as fast as possible* [Vee21]. This means that **any proliferation of technological or economic complexity will be used by the system to increase its energy dissipation potential** (i.e. its energy consumption efficiency).

7.1 Alignment of incentives

Over time, a complex system will stumble towards ever higher levels of dissipation, as much as its infrastructure allows for. We could look at this like an 'incentive': the system has an incentive to dissipate as efficiently as possible: the *'dissipation incentive'*.
We are all familiar with the *financial incentives* in our capitalist economy. If we ignore any normative distinctions between kinds of incentives, and just look at the direction of it, we can now state that in some cases *the systemic dissipation incentives are perfectly aligned with financial incentives.* Such an alignment obviously has an amplification effect.
There are many more 'incentives' that play a role in our socio-economic domains, but, given the challenges of our era, this is probably the most interesting combination. We will come back to this interesting alignment later.

8 Policy instruments

What does this all mean for macro economic policy instrumentation?
We now understand that growth is actually local energy dissipation, facilitated by increasing complexity within the domain. In an economy, that is mostly technological complexity, and financial, logistic and data-complexity as corollaries.
If we look at the current big challenges for mankind, they are mostly caused by runaway economic growth dynamics. So if we want to 'curb' this economic growth to prevent societal and environmental damage, we have to address the infrastructural complexity that enables it.
In the same way that it is pointless to tell the water to flow differently on

its infrastructure, it is also pointless to make rules for economic actors to act differently on its infrastructure. Instead we should address the infrastructure, and specifically, its complexity.

9 Complexity profiles

As previously described, a complex system does not have a homogeneous distribution of complexity across the whole domain. It will have all kinds of local differences. And some regions of clustered complexity will have numerous relations across the domain, others may be mostly isolated.

1. For example, the technology of smartphones has been deployed on a massive scale, with all kinds of new ecosystem of business cases in data profiling, marketing, gaming, software development, sensors, health-tracking, etc. So the deployment does not only require resources and energy to build and use the devices, but it also requires new resources and energy for all these new business-cases.

2. Nuclear energy has another profile: it is densely concentrated (technological) complexity, in time and space: it is built in a few years, and then just runs. The added logistic complexity sits mainly in the building process, and is very limited during its lifetime.

3. Another example is Bitcoin. Most mining is done in China because of low electricity prices. The total amount of energy consumed is estimated around the amount that Belgium uses [Vri20].

These examples suggest the concept of a 'complexity profile' of a certain technology.
Let's apply this to blockchain-technology: blockchain technology has resulted in a huge ecosystem of IT-applications, huge financial and intellectual investments, trading-platforms, application ecosystems, and even compliance measures. The complexity-profile is very deep (very high levels of complexity and dissipation of the computational mining/transaction-infrastructure) and also broad (large ecosystem with many dependencies). This profile is even increasing in depth and width over time (unlike the nuclear energy complexity profile for example). But does it result in a decrease of energy dissipation somewhere else, or later on? Does it have any benign, long-term orthogonal effects? So far it does not. So, it's net impact is a huge increase of structural dissipation potential, both in depth and in width, for its own sake: that is problematic.

So in order to curb the runaway dissipation processes, we have to identify these complexity profiles. Such a profile can then be qualified as 'malign' or 'benign', according to some normative and quantitative framework (which we have to develop as well): does it facilitate systemic and long term runaway dissipation? And how does it align with other incentives?

9.1 Managing complexity with policy interventions

After identifying suspect aspects (or regions) with possible malign runaway dissipation profiles, one could develop a policy intervention to address this aspect. And the success of a policy intervention can then be assessed on whether it curbs this complexity profile or not.

The key takeaway is that infrastructural complexity is a *proxy* for energy dissipation. It will often concern a new technology or its deployment. So 'managing complexity' can reduce any unwanted increase in energy consumption (and the complementary pollution). Such management requires mapping the alignment of existing incentives, against the dissipation incentive. If this mapping shows that the added complexity results in a long-term reduction of orthogonal complexities elsewhere, it can be supported by funding etc. Governments can then allocate financial and intellectual resources towards 'smart reduction of complexity'-programs, as a policy-instrument. Conversely, emerging technologies that show amplifying incentives can be progressively taxed.

Obviously, any macro-economic policy that addresses only symptoms is doomed to fail (which we are currently witnessing everywhere). But this complexity-framework allows macro-policies to address the actual causes, which increases the rate of success significantly.

9.2 Caveats and remarks

Ultimately, aspects like 'systemic resilience' and 'thresholds' are still anthropocentric, contextual and intuitive notions, and they must be formalized into a dynamic landscape of bifurcating *chaotic attractors of entropy production.* This allows systemic diagnostics to be formalized to something like: 'the sudden occurrence of many new chaotic attractors', or 'the narrowing of a basin of attraction', of some aspect. The life and death of a 'living system' can be described by the bifurcation of a limit cycle, for example (which, incidentally, translates easily to the doughnut of Kate Raworth [Ent20]).

In order to really develop such a complexity-based macro-economic policy framework, a lot of work needs to be done, of which most is non-trivial and highly technical, based on 'nonlinear dynamics' and chaos-theory. It requires a multidisciplinary approach, and it requires a foundation of a highly technical level that includes exotic aspects such as the maximization of entropy production, limit cycles and Lyapunov-exponents. Also, it requires a matured quantitative, Bayesian and empirical framework.

Lost of tools are already available from the complexity sciences, nonlinear dynamics, chaos-theory and statistical mechanics.

Given the inherently high levels of uncertainty that are associated in such a framework, and the notorious difficulty in communicating about this (internally and to the public), guidelines such as the Lorentz Principles [SPT19] should be adhered to.
For clarity's sake: not *everything* can be modeled in such a framework, of course. Not everything can be explained only by a dissipative undercurrent. It specifically serves the macroeconomic-perspective, and the material constraints of dynamic systems.

10 Conclusion

As we have generalized macro-economics to a complexity-science (because our economy is part of a single super-complex system that, given its increasing technological complexity, does not show any tendency towards any kind of 'equilibrium'), and given that complexity is a key proxy to energy dissipation (entropy), we can map the associated complexity profiles to a normative valuation framework. This allows for a scientific macroeconomic policy framework that can yield effective policies, which can be evaluated empirically.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

"It's the entropy, stupid!"

The title of this paper is an adaptation of the famous quote

> *"It's the economy, stupid!"*

coined in 1992 by James Carville, a strategist for the US presidential campaign of Bill Clinton. (https://en.wikipedia.org/wiki/It%27s_the_economy,_stupid).

Image credits

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