NOTE TO FILE
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A Critique of my Restatement of Odum's MPP

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1 References

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2 Purpose

The purpose of this note is to attempt a critique of my draft Ref A paper, and to provide an apologia for it, if appropriate.

3 Background

The bulk of the text of this NTF originally formed the MPP section of my Economic SOAK (at Ref C), but it was clearly dominated by my self-questioning of the Ref A paper, so I thought it was better as an NTF in its own right.

Since about March of 2015 I had been looking for a clear statement of the MPP in Odum's own words, or those of someone near to him, but it always seemed to me that there were two different ideas, both partial, and both competing, presented as the MPP. Like the old story of the seven blind men with their different opinions about elephants, it seemed both views were right. One of these views involved the nature of the power-efficiency curve associated with energy conversions. The other involved the nature of the evolution of systems towards some elemental ideal operations at maximum destructive power. My attempt to fuse these two views resulted in the Ref A paper, which I had the privilege to present at the CANUSSEE conference in Vancouver. I confess that I worried that I would be seen as arrogant, having the nerve to edit the description of the concept that was so key to much of Odum's insight. It was a little, I suppose, like one of the audience in Galilee deciding to edit Jesus' sermon on the mount.

After the conference I went back to re-read the paper by Cai, Olsen and Campbell (See Ref D), only to discover that they had expressed a similar opinion about the MPP (or M(Em)PP) as follows:

> *"An integrated formulation of the principle applicable to its operation within particular selective environments has not yet been achieved. Such a formulation, however, together with its accompanying symbolic expression through mathematical*

> *equations and the energy circuit language developed by Odum (1975, 1994), could provide a basis for both theoretical understanding and empirical investigation of more specific principles or processes of selection and self-organization (Odum, 1983, 1994).”*

Dr Campbell is in some sense my mentor, having steered me towards the role of natural selection in the MPP back in January of 2015. That “integrated formulation of the principle” is, I suppose, what I was seeking, not realizing that Dr Campbell, himself, had noted that such an formulation was missing.

At the end of the Ref D paper, the authors go on to say:

> *“A large-scale, collaborative effort based on a consistent, rigorous, and empirically informed application of systems diagrams and accompanying mathematical models might be useful in establishing whether the maximum empower principle is indeed, as Odum suggested, a universal principle and 4th law of thermodynamics.”*

Amen, to that!

So, here is my critique of the restatement of the MPP, as presented in my Ref A document.

4 The Maximum Power Principle – A 4th Law?

4.1 Concept

This MPP phenomenon was first given a name by Lotka in a paper in 1922. It was given more detailed study by Odum and Pinkerton in a paper in 1955, in which Odum proposed it be considered as the 4th law of thermodynamics. Since then, many of Odum’s students and admirers have argued that it is of great importance. But, I have been unable to find, in writing, a clear statement of exactly what the phenomenon is. After spending about 8 months in search of such a clear statement, to no avail, I decided to write my own. (See Ref A). I am uncertain that my version of it captures it well-enough, but here is the summary, below.

A great example of the anecdotal evidence in support of one aspect of this phenomenon is a chainsaw. When you are running the saw, if you push down too softly, you don’t cut much wood and the saw runs fast. If you push down too hard the saw runs very slowly, and you don’t cut much wood. But, if you push down with just the right pressure you get the maximum amount of useful work out of the saw as it burns its gas. (See Ref E.) I have begun calling this the Goldilocks effect. It happens in many instances, and is closely associated, I think, with the “diminishing marginal returns” effect in economics. (See Refs F-H, especially H.)

Lotka and Odum argued that systems evolved over time to function at maximum power, but at some intermediate efficiency, just like the chainsaw.

4.2 Proposed hypotheses

At Ref A I have proposed that the Boltzmann/Lotka/Odum MPP can be captured by these three falsifiable hypotheses:

- **MPP I –** All persistent adaptive autocatalytic physical systems are characterized by energy fluxes through persistent types of energy stores, and persistent energy pathways through which energy flows from storage type to storage type.
- **MPP II –** Within all persistent adaptive autocatalytic physical systems, all classes of persistent linkage events within persistent energy pathways are characterized by power-efficiency relationships for which power is maximized at some intermediate efficiency.
- **MPP III –** All persistent adaptive autocatalytic physical systems evolve to capture and degrade energy at a maximal possible rate consistent with available inputs. In contrast, the efficiency of the linkage events will not be maximized but will tend towards some intermediate value.

I am not 100% happy with this, but it works for me for now. Here are some thoughts on it:

4.3 Strength – Falsifiable

- **Falsifiable** – These hypotheses are designed to be falsifiable, and they give me direction on finding ways to prove or disprove the existence of the phenomenon, and its importance. In fact, I suspect that the first two hypotheses are tautologically true, by reason of their definition, and so can in fact be verified as true, in that sense. IF THAT IS THE CASE, then they are not falsifiable, but remain as interesting observations.

4.4 Weaknesses

- **Special Terminology** – These hypotheses use terminology that is developed and explained in the draft paper in which I proposed them. (At Ref A.) It is a bit arcane, but I wanted to make it specific so as to be falsifiable.
- **Independence** – The three hypotheses do not appear to be independent of each other.
- **Evolution** – The key notion from Lotka, that processes compete for control of energy flows, in a Darwinian-style competition, is not immediately apparent.
- **Logical/Capital Concepts** – The focus on energy, rather than, say capital, makes it unclear that I strongly believe that it applies to logical systems, such as ABMs and financial economies, as much as it does to energized systems.
- **Dominant Role** – The idea that I believe this is THE means of feedback that causes auto-catalytic development, including the reduction of entropy internal to the system, is not apparent in these hypotheses.

I need to think carefully about each of these strengths and weaknesses, so I discuss each of them in some detail below, starting with the weaknesses.

4.4.1 Special Terminology

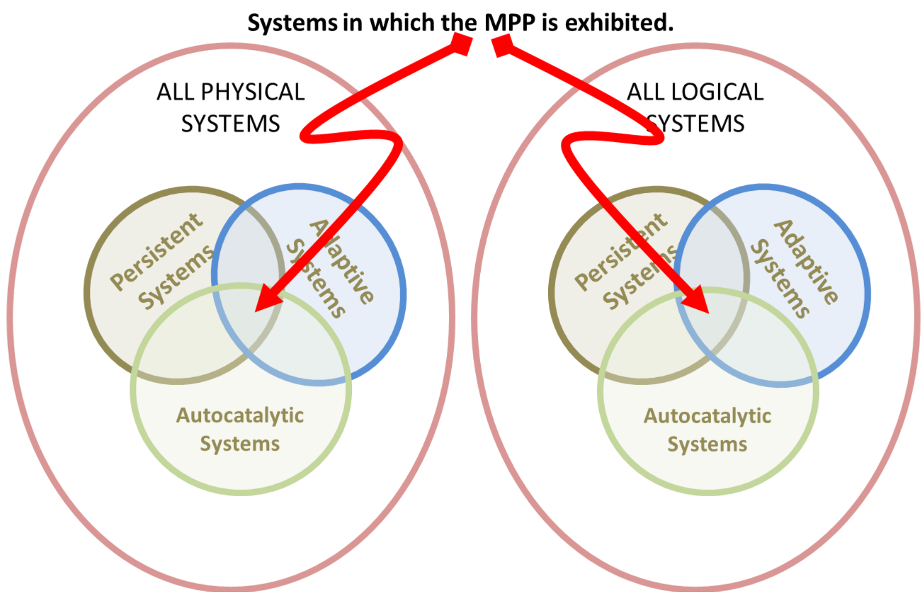
For example, in hypothesis MPP I, I need to qualify the circumstances of application with the six words: “All persistent adaptive autocatalytic physical systems”. Even with those six words, in their everyday meaning, I am not certain I have qualified it sufficiently or correctly. For example:

- I do not say “open” systems. I thought it would be redundant to restrict the principle to open systems, as the other qualifying adjectives would seem to imply the system must be open. Can a closed system be adaptive and auto-catalytic. I would say it can “relax to equilibrium state", but that is not the same as adaptive. Such relaxation is with respect to its own internal drivers and constraints, so it might be called auto-relaxation, but I would not call that auto-catalyzation. So, I think the addition of the adjective "open" would be logically redundant.

- Is such an open system a complete system, or should I be saying "sub-system" there? If I think too hard about what "system" means, the problem of the fuzzy boundary arises, and the distinctions between the universe and its systems, sub-systems, sub-sub-systems, etc. tend to fade. All open systems are necessarily, by reason of the 1st law of thermodynamics, sub-systems of the universe.
- I say "physical" to exclude purely logical systems, but only because Odum did not seem to explicitly include logical systems (largely, I guess, because there were few or none in his day). However, I strongly believe that the MPP is equally applicable to logical systems in which some other quantity, other than energy, is conserved. By logical system, I mean for example Agent-Based Models (ABMs), or the upper level of the modern global financial system in which money incarnated as bits located in a network of banking computers can blink at rates approaching 4 GHz.
- I say both adaptive and autocatalytic because I am pretty sure that they are not the same in meaning, and both characteristics need to be there. By auto-catalytic I mean to say they consume and replace their own components with others having the same function. By adaptive I mean to say they alter the nature of their components according to some process that allows for variation of function and selection.
- The same goes for persistence. Can a system be autocatalytic and adaptive, and yet not be persistent? I think so. Therefore, I need this word to be included.
- Finally I say "all", but then qualify that very general word with the other five qualifiers.

What I am implying is that the overlap of meaning of these words looks like a Venn diagram like this.

Figure 01 – Venn diagrams illustrating the set of systems in which I believe the MPP is active.



In the Ref A paper I am leaving out the purely logical systems, with the goal of restricting the topic of the paper to those systems that I imagine were in Odum's mind, though I would like to be a little more expansive. The word physical here includes economic systems.

Ultimately, I need a lot of words to capture the concept, and each word narrows the field of applicability. And/or I need precise technical definitions of some of these words. On the other hand, the biophysical, sociological, economic and logical systems of interest to me would all seem to fall in the target area, so these qualifying adjectives appear to be both necessary and sufficient for my purposes.

My three hypotheses (i.e. MPP I, MPP II and MPP III) are all qualified by these words, and are intended to make statements about the small area of overlap within the left-hand (physical) universe in the above diagram. I could define this type of system and give it its own word that encompasses all of those qualities, and use that new word as a jargon short form. Does that go too far?

Similarly, I found it necessary to define other jargon-like words and phrases to give them some precision of meaning, such as the following:

- all persistent adaptive autocatalytic physical systems (highly qualified subset of systems, discussed above)
- energy fluxes (an abstract aggregate concept)
- persistent types of energy stores (an abstract aggregate concept)
- persistent energy pathways (an abstract aggregate concept)
- storage type (an abstract aggregate concept)
- classes of persistent linkage events (an abstract aggregate concept)
- power (Odum's concept of useful power)
- efficiency (Odum's concept of efficiency)
- power-efficiency relationships (a type of mathematical relation)
- capture and degrade energy (degrade instead of consume; related to the emergy concept)
- available inputs (Lotka's concept)

I hate jargon because it comes across as so pedantic, and it requires careful (meticulous) reading and translation. I like Lotka's writing because it is so brief and sparse, and yet so pungent with implications. I think it was Einstein who said that if you cannot use common words to explain a concept briefly, then you don't really understand it. I like that idea. I am clearly not there yet, because I feel I need the precision of this invented jargon. I suppose that the classic or modern literature on the topic has stock jargon for such concepts, but I do not recall coming across it, and do not have the time to look for it, and suspect it would constrain my thoughts.

4.4.2 Independence Of Hypotheses

Although I have attempted to come up with three independent hypotheses, they may not be independent. By independent, I guess I mean that each could be true or not true independently of the other two, and it is only when all three are true that the MPP is operational. Then each would identify a necessary but insufficient condition for the emergence or exhibition of the MPP as a phenomenon. If I could achieve that, then I would consider that I have a good understanding of the MPP. However, that does not seem to be the case here.

Hypothesis MPP I may be tautological. I.e. once I have layered on the five qualifying words, it may be logically obvious that this subset of systems conform to MPP I. In that case it may be merely restating a semantic truth having little insight into how the real world functions. On the other hand, how many people think about this particular subset of systems that cut across so many disciplines of study? So the wide applicability is a valid point to make, whether it is a semantic tautology or not.

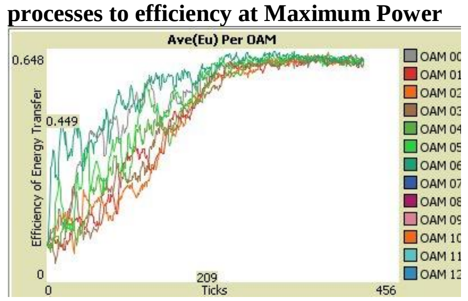
MPP II hypothesizes the existence of power-efficiency relationships that have a maximum at places other than at efficiencies of zero or one, i.e. at an intermediate efficiency. This is associated with Odum's particular definition of power ("useful energy" over elapsed time) as exemplified in his study of the Atwood's Machine, and his particular definition of efficiency ("useful energy" over total energy). Again, once we accept those definitions of power and efficiency, this hypothesis may be merely a semantic truth, one that is by definition right. So, while it is dependent on different definitions (i.e. the definition of target systems, vs the definitions of power and efficiency) MPP II is similar in effect to MPP I, in that it may be semantically necessarily true, though not obvious.

So, I am personally convinced that hypotheses MPP I and MPP II are independent. I am not convinced that they contain any deep comment on the nature of reality, except for this: the "Goldilocks" type of phenomenon in the real world (not too hot, not too cold, but just right) would seem to be anecdotal evidence that this kind of power-efficiency relationship is present and active. If hypothesis MPP II is true, then I might go so far as to say: If there is no real-world Goldilocks relationship associated with a type of energy transfers, then the real-world system that exhibits energy transfers of that type is not, and could never be, a persistent adaptive autocatalytic system.

That leaves me with hypothesis MPP III, which is where the concept of Darwinian-style evolution of SYSTEMS AND PROCESSES, not organisms, is brought in. This idea was hinted at in the last few pages of Darwin's book "On the Origin of Species", and was pre-positioned by Boltzmann's views on the role of energy in natural selection, as identified by Lotka. But, ultimately, this idea was Lotka's contribution, it seems, and is the insight that Dr Dan Campbell brought to my attention. And this is the idea that Dr Charles Hall returns to each time he is pressed for an explanation of self-organization. This is the idea that I explored in a couple of ABMs:

- In OamLab, I demonstrated the evolution of a system of processes explicitly, leveraging hypothesis MPP I (see Figure 02).
- In MppLab I, I demonstrated the evolution of a system of such processes implicitly, leveraging hypothesis MPP II, as organisms evolved.
- In both cases, they were in apparent agreement with MPP III.

Figure 02 – OamLab – Convergence of processes to efficiency at Maximum Power



I copy hypothesis MPP III here, from the Ref A paper, for easy reference:

- **MPP III –** All persistent adaptive autocatalytic physical systems evolve to capture and degrade energy at a maximal possible rate consistent with available inputs. In contrast, the efficiency of the linkage events will not be maximized but will tend towards some intermediate value.

On thinking about the implications of this, I have come to realize that the phrase “maximum power” has two different meanings within this one principle, and that has been a source of confusion to me (and to others, I think) in the past.

- **First meaning** – In the terminology of the Ref A paper, every type of linkage event in an MPP-exhibiting system (i.e. persistent, adaptive and auto-catalytic) has a power-vs-efficiency curve that shows maximum “useful” power at an intermediate efficiency. Here we are talking about the energy which is “still useful” after the linkage event is completed. This is a flux of still useful energy which remains non-degraded through the event. It is, perhaps, more concentrated, if I understand Odum’s concepts around emergy. It is available for later use. The maximized flow of this energy is selected for, at the level of linkage events between stores. I would say the evidence in support of this contention is that organisms, in general, are extremely efficient in respect of their internal metabolic processes, but are extremely profligate in their diversion of still useful energy to the businesses of growth and reproduction. The trophic web benefits from this profligacy as the amount of still useful energy made available as potential food is maximized. This first meaning is somehow closely associated with the view “inside the fridge”, where Shannon entropy is driven down and order and complexification increase.
- **Second meaning** – In the terminology of heat engine analysis, the degradation of the overall flow of energy through the system is maximized. This means that (a) the amount of available energy flows captured by the system is maximized, increasing the scope of effect; and (b) of the captured energy, the fraction of energy degraded is maximized. I use the word “degradation”. Some authors (e.g. Prigogine) like to say dissipation. Others would say “consumption”. This is how most people would see the MPP, and wonder why systems don’t then just burn up and disappear. They would argue that this clear lack of immediate one-step consumption of energy proves that the MPP is not valid. But, I say that this second meaning is the view “outside of the fridge”, and can be expressed as a Maximum Entropy Production Principle (or MEPP), being the obverse side of the coin. The MPP (second meaning) and the MEPP (my meaning) then are the same phenomenon. When energy is degraded at this maximum rate, universal entropy is also produced at a maximum rate.

Somehow, Odum’s idea about the MPP being “nature’s time regulator” plays a role here. The real dynamic core of the MPP is to be found in the interaction of these two apparently contrary meanings. How can the MPP maximize the flow and non-degradation of energy at the level of linkage events, and yet maximize the capture and degradation of energy at the system level? This conundrum, this contradiction, is at the very heart of the MPP, but what I have discovered via my ABMs is that both meanings would seem to be correct. At one level the system is driven to conserve the grade of energy, and at a higher level it is driven to destroy it (i.e. degrade it). The battle between these two drivers results in persistence and complexification.

I would think that it means the internal processes of the system are lengthened (in number of steps, and in drop time) by reason of the first driver, and yet made more fine-grained and complete by the second driver. The dynamic between these two kinds of maximization explains both the persistence of the system (in time) and the completeness of the degradation. Natural selection would seem to act on both individual types of linkage events and entire processes in an arena of co-evolution of both.

Getting back to the draft paper (see Ref A) in which I proposed the restatement of the MPP, I found it necessary to add two derived and subsidiary hypotheses to this one:

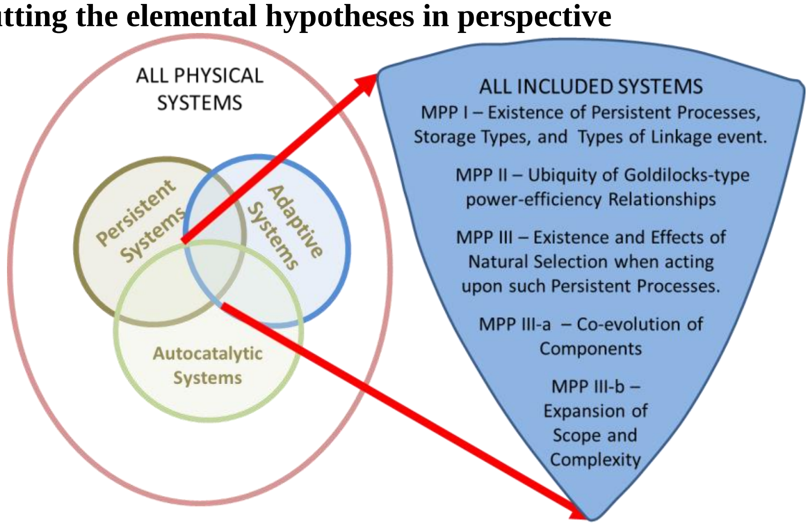
- **MPP III-a – Co-evolution of components** – Persistent energy pathways, together with the types of energy stores and of linkage events that they comprise, must all co-evolve to achieve overall maximum power at the level of the entire system.
- **MPP III-b – Expansion of Scope and Complexity** – Any such system for which its operation is constrained by a shortage of suitable inputs, but for which alternative inputs are accessible, will tend to adapt its pathways so as to access those inputs, with the effect that energy throughput will increase.

I believe that, because of the definitions given for the jargon used in hypotheses MPP I-III, these two hypotheses are logical outcomes of the truth of hypothesis MPP III, and so are not independent of hypothesis MPP III, but merely semantic expressions of the implications of hypothesis MPP III.

When I re-read the Ref D paper, I realized that hypothesis MPP-IIIa is in fact proposed in that paper. Evidently, when I read that paper in early 2015 I did not really understand it. Now I see why "co-evolution" of both species and processes is a necessary outcome of the MPP.

These all come together like this:

Figure 03 – Putting the elemental hypotheses in perspective



As I see it,

- Hypotheses MPP I and MPP II are semantic tautologies (in the same sense, say, that a trigonometric identity is a semantic tautology) that serve, as all tautologies do, to say in brief what was said elsewhere in many words.
- Hypothesis MPP III actually forms the content of the MPP.
- Hypotheses MPP III-a and III-b are logical consequences, or direct implications, of MPP III.

Perhaps I need to reword my hypotheses to more clearly reflect this perspective.

4.4.3 Evolution

The nature of a Darwinian-like form of natural selection, and its mode of operation, is not entirely clear, but strongly implied by these statements. I say "Darwinian-like" because natural selection as described by Darwin is about the origin of news species, and not about the origins of new energy-degrading processes. But, the type of evolution that is being referred in my Ref A paper, and in the Ref D paper, is happening at the level of the system – a system composed of energy-degrading processes – and the evolution of organisms and species is a sub-plot in the story. MPP III-a is the recognition of this.

I would see some differences. For reasons that I do not understand, evolution of species seems to require, or, at least, encourage:

- that species be very distinct and discrete, unable to breed with one another in most cases.
- that species reproduce sexually;
- that species within a trophic web range in size from excruciatingly small to incredibly massive;
- that restrictions develop with respect to who can catch and eat who;
- that cells experience apoptosis, or programmed death, within an organism;
- that organisms experience programmed death, within a species; and
- other such constraints on how organisms live, reproduce and die.

Two thoughts come out of this line of consideration:

- First – Why do these implicit rules and regulations govern and restrict the flow of energy? Why does this "red tape" arise in the bureaucracy of nature, preventing profligate acquisition and expenditure of energy? Who or what imposes these checks and balances on the rapid degradation of energy? The answer to these questions must be found in another constraint in which the innate and relentless tendency of energy to degrade itself as quickly as possible finds more effective and persistent expression. But the currently accepted "laws of thermodynamics" do not provide that answer. That answer is a 4^{th} law of thermodynamics, and the MPP is Odum's attempt to understand and express it.
- Second – I am not aware of any similar discussion about constraints on the evolution of processes and linkage events. Is there "red tape" that constrains the evolution of processes, other than the 1^{st} and 2^{nd} laws? (I don't see the so-called 0^{th} and 3^{rd} laws to be in the same category). I have not seen discussion of constraints on evolution of processes in the same way as I have for constraints on the evolution of species. Progress in this area might be a break-through in economic theory. Would this explain the dominance of capitalism over socialism?

4.4.4 Logical/Capital Concepts

I am convinced that whatever happens at the level of energetics and thermodynamics can also happen in partially logical systems, such as financial systems, as well as in totally logical systems, such as agent-based models (ABMs).

I have this hunch that within human societies we develop morals, laws, rules, regulations and other constraints on unfettered consumption, not just because it makes life more pleasant for all, but because it enables our societies to better capture and consume available energy. For example, property laws (prohibition on theft and fraud) allow people to capture energy stores outside of themselves for later consumption, while other species must either eat or hide their stores (like dogs burying carcasses, or squirrels burying acorns). Then the invention of money is a means by which that "still useful" property can be traded. Such social contracts (property laws and currency) create a regulatory environment in which the complexity of society can increase more readily, with the side effect that life tends to be more pleasant for those with sufficient property and currency.

This is all anecdotal evidence that a dynamic phenomenon such as the MPP is active in steering the course of development of societies in general. When such dynamics are harnessed by financial regulations, then the business of buying and selling currency and other derivative assets comes under the influence of the MPP. The development of new derivative financial assets is like the evolution of new detritivores, whose role is to degrade that last iota of still useful energy in the refuse of the biosphere.

As is true for all abstracted diagrams, Figure 01 is useful to make a point, but it has limitations. For one, it hides the fact that there is a continuum from purely physical systems (such as hurricanes) through simple metabolic systems (workings of bacterial metabolism) all of the way up to abstruse global financial systems. The division between physical and logical systems is a fuzzy line arbitrarily drawn in a place I choose. Figure 01 implies a distinct duality of existence that does not reflect reality. Nevertheless, it is a line that is, I think, significant, and so, for the purposes of this deliberation, I draw it that way.

There is a sense in which computer-based ABMs are purely logical systems. Sure, they run on computers that degrade the energy supplied via electricity, but that energy is supplied on an on/off basis and so enables persistence when ON, but it does not otherwise affect their logical evolution or their logical persistence. The question of persistence of computer operations is often referred to as the "halting problem". (See Ref J.) That logical persistence is a matter of how the code is written, and whether it enables dynamic feedback with variation and selection among alternates. An agent-based model (ABM) that has appropriate design characteristics can demonstrate the MPP and other powerful evolutionary phenomena – systems for which the flow of energy through the computer is physically necessary, but not logically relevant.

ABMs that are persistent, adaptive, and auto-catalytic, do seem to demonstrate the MPP and other fundamental behaviours. The "red tape" around conserved logical quantities (such as wealth) invoke the MPP. I consider such an ABM to be a purely logical demonstration of the MPP in action. This is an important point, because I would argue that the MPP does not arise from physical thermodynamic constraints. I would argue that the MPP is a logical effect that imposes itself on dynamic systems of all kinds, whether they be entirely logical or embodied in thermodynamic systems. It was simply first observed and studied in the realm of thermodynamics and ecology.

In summary of the above arguments, Odum believed that, since economies are thermodynamic heat engines, economies must exhibit the MPP in the same way, and for the same reasons, that ecosystems do. I, personally, would go a step further, based on my work with ABMs. There is a part of the effect of the operation of the MPP in economies that does not derive from concerns of energetics and thermodynamic arguments, but has a purely mathematical – a purely logical – origin.

IF this is correct, then it means that the MPP is PRIMARILY A MATHEMATICAL PHENOMENON, that happens to exhibit itself in thermodynamic systems, and may well exhibit itself in other analogous systems.

The paper by Jeremy England (at Ref B), perhaps, provides some window into the mathematics of this. It is fundamentally an argument from thermodynamics, but it doesn't need to be. It is mostly an argument using entropy and statistics. Boltzmann's constant "k" appears in some of his examples, his applications, but there is nothing in the development, as I see it, that requires physical constants be identified prior to interpretation. I wonder if his paper can be re-worked to apply to ABMs and financial systems, i.e. logical systems. (I must try that.)

In any case, my restatement of the MPP at Ref A does not address my personal beliefs here. I stayed within what I believe to have been Odum's vision, which was still pretty broad.

4.4.5 Dominant Role

I suppose it is not obvious that I mean that, within metabolic, biophysical, social and economic systems, EVERY transaction that degrades energy in a persistent process is selected to function at maximum (useful) power possible, as discussed below.

That extremely dominant role makes the observation either trivial, or incredibly important. When I presented these ideas at the CANUSSEE 2016 conference (in the BPE track) I had one rather dismissive comment to the effect that "So, are you just saying that trade-offs are common." Of course the comment is correct, so I did not have a ready response. But, on thinking about it afterwards, I had these opinions:

- "Things fall when dropped" is also a common, even trivial, observation. However understanding that concept led to Newton's universal law of gravitation which was useful in landing people on the Moon;
- I am NOT "just" saying trade-offs are common. I am saying that ABSOLUTELY EVERY persistent type of energy transfer involves a trade-off of efficiency for power. Also, by implication, EVERY persistent type of capital exchange also involves a trade-off of efficiency for power (profits/time). And, I suspect that this means that EVERY persistent type of matter transfer in persistent metabolic systems, in persistent ecological systems, and in persistent economic systems follows this pattern. This would tend to put it on a par with Newton's "universal" law.

This argument is intentionally implied by my repeated use of the word "All".

4.5 How Can You Verify or Falsify These Hypotheses?

I have been able to demonstrate hypothesis MPP III in the context of a system that is consistent with hypothesis MPP I (OamLab), and in the context of a system that is consistent with both hypotheses MPP I and MPP II (MppLab I). That was using agent-based models (ABMs). That effectively verifies that the MPP as specified in my hypotheses can work as expected, but does not show, and cannot show, that it will work in every such instance.

Those are special cases, in ABMs, in which I can precisely define "types of energy transfers", regulate their operational characteristics, and measure them accurately, on a per-predation-event basis. I could not do that for an ecosystem, or metabolic system, or even a financial system. The financial system might be the one in which such precision of definition and availability of data may be the easiest.

For example, in the arguments made in Ref A, the interpretation depends a lot on what I mean by "**type** of energy transfer" and "persistent". Such words imply clear static meanings, when the concepts described are abstract non-physical, morphing, ever-changing targets. An organism, such as a frog, may exist temporarily and be considered a discrete object. It is persistent for a while, for the maximal life time of a frog if it is lucky, and then vanishes. A species does not exist anywhere except in the imaginations of biologists. It is a sub-classification of the set of currently existing frogs, and has defining characteristics that are meaningful at the time the description is written. But, frogs evolve, so a species of frog that existed 100 years ago may not look or behave quite the same now. Has the species persisted, or is this a new species? That would be a matter of choice – a matter of judgement. But suppose we decide that the precise genome of the frog is not what defines a species, but its role in the trophic web. Well, its role is also changing, either quickly or slowly, as time passes, depending on how quickly changing are the roles and behaviours of other species in the contemporary cohort, and in the contemporary ecological systems in which it has a role. So, while it is relatively clear that species exist as discrete classes or types of organism, that discreteness is not static, and not 100% clear.

On the other hand, a type of molecule such an ATP molecule is clearly defined and has had a very important and distinct role in the persistence of energetic pathways in organisms for many millions of years.

4.5.1 Karl Popper

Karl Popper's argument was that science cannot move forward by verification of general claims, but only by falsification of very specific claims. (See Ref K.) When a hypothesis is so falsified using empirical data, then scientists must propose a modification of the hypothesis that now conforms to the new empirical data. Another way to say it is like this. If our hypotheses are always verified, we learn nothing, though our confidence in their veracity is improved. But, if our hypotheses are shown to be wrong, it gives us the opportunity to learn how they are wrong, correct them, and have more accurate hypotheses. So, a hypothesis that can be falsified is a good hypothesis. A hypothesis that cannot be falsified does not leave room for an opportunity to learn, and, in fact, may not be true.

But, we often think that a hypothesis that cannot be falsified must be a very good hypothesis. I suspect, and many argue the same, that all models are mere approximations of reality, and therefore, if we try hard enough, we should be able to find some empirical data that varies from the model and shows its area of weakness. Such efforts may fail for two reasons:

- Such data is technically very hard to collect, and possibly beyond our abilities to do so; or
- The hypothesis is so disconnected from reality that no data can be collected that would disprove it.

For example, to illustrate the second point, consider this. The hypothesis "All pink elephants can fly" requires only that we find one pink elephant that cannot fly to falsify it. On the other hand, the hypothesis "No pink elephants can fly" requires that we find all pink elephants and test their aerodynamics. You may never know that you have found and checked them all. If pink elephants exist, the first is falsifiable, the second is not. But, if you never find a pink elephant of any kind, both hypotheses are non-falsifiable. Many para-normal and meta-physical claims are like these "pink elephant" hypotheses.

These three hypotheses about the MPP are written to be falsifiable, in the tradition of Karl Popper. In fact, the three main hypotheses are framed to apply to "all" processes or events mentioned. To disprove any one of these would merely require the identification of a single instance in which the hypothesis is false. That sounds like it would be easy. However, it will not be. I am treading along the edge of the jungle where pink elephants are rumored to be found, and I am not 100% certain that these are not "pink elephant" hypotheses. The reason is complicated, and it is best explained in terms of what I learned in my second model, MppLab I, and what I think might be done for ecosystems.

For reference, here is the complete set of hypotheses again:

- ***MPP I*** *– All persistent adaptive autocatalytic physical systems are characterized by energy fluxes through persistent types of energy stores, and persistent energy pathways through which energy flows from storage type to storage type.*
- ***MPP II*** *– Within all persistent adaptive autocatalytic physical systems, all classes of persistent linkage events within persistent energy pathways are characterized by power-efficiency relationships for which power is maximized at some intermediate efficiency.*
- ***MPP III*** *– All persistent adaptive autocatalytic physical systems evolve to capture and degrade energy at a maximal possible rate consistent with available inputs. In contrast, the efficiency of the linkage events will not be maximized but will tend towards some intermediate value.*
- ***MPP III-a – Co-evolution of components*** *– Persistent energy pathways, together with the types of energy stores and of linkage events that they comprise, must all co-evolve to achieve overall maximum power at the level of the entire system.*
- ***MPP III-b – Expansion of Scope and Complexity*** *– Any such system for which its operation is constrained by a shortage of suitable inputs, but for which alternative inputs are accessible, will tend to adapt its pathways so as to access those inputs, with the effect that energy throughput will increase.*

4.5.2 Hypothesis MPP I Revisited

As I said before, hypothesis MPP I is somewhat tautological, and is true by definition of all of the words. The concept, however, is not simple. A "persistent type of energy store" might be a type of molecule in a metabolic pathway, a species in a food chain, or a type of business in a supply chain, or a type of tool in a manufacturing process. If I focus on the concept of species, just as an example, it is an abstract concept that includes many averaged characteristics of a group of organisms, and it is often fuzzy at the edges. When a species ranges over a wide geographic area, the extreme limits of the range (e.g. north to south, or mountain-top to valley, or desert to rain-forest) often present sub-species and variants that stretch its definition. A species is not really a discrete concept, but a fuzzy aggregate idea. We tend to see the word "species" as describing a discrete group of organisms, when the reality is that there are many dimensions of that space of characteristics of the population that are continuous, and few that are discrete. My point, I suppose, is that one must pay careful attention to the definitions associated with any particular system (metabolic, ecological, social or economic). So, even though I think a statement like hypothesis MPP I is self-evident, much care is required to make it so. That is a little paradoxical, and maybe problematic.

4.5.3 Hypothesis MPP II Revisited

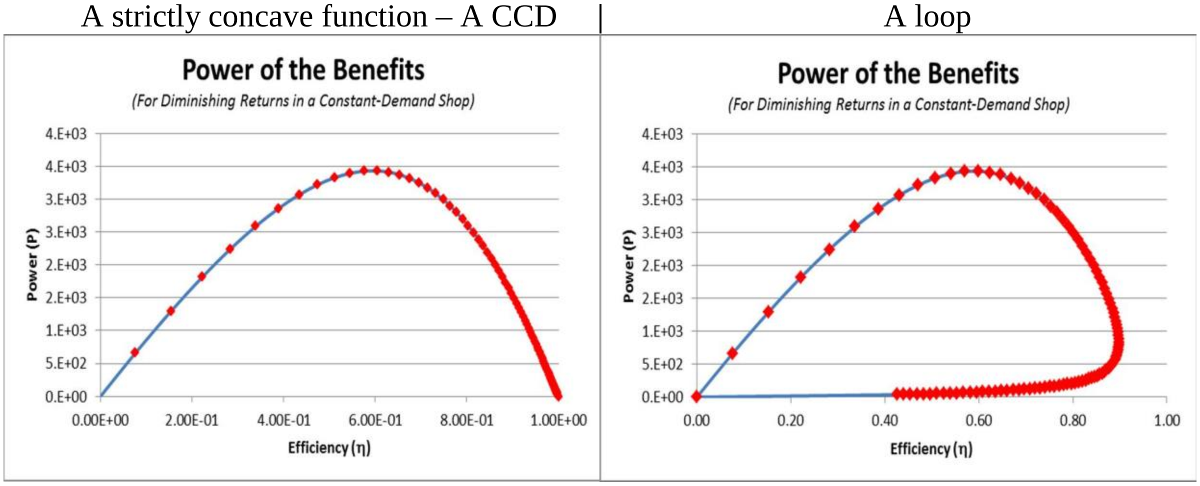
Similarly, hypothesis MPP II is somewhat tautological, depending on careful definition. In particular, with a focus on "useful energy" when defining power and efficiency, you get a peculiar type of power-efficiency graph that I have come to call, in my various diary notes, one of:

- A hump-backed curve (I avoid this now);
- A concave-downwards (CCD) function (still applies to some);
- A strictly concave unit map (a more formal normalized version of a CCD function); or
- A Goldilocks relationship (a more general description covering two archetypes: the hump and the loop.

Here are two examples, one of each archetype, drawn from Ref H:

Figure 04 – The two archetypes of Goldilocks relationships

A strictly concave function – A CCD | A loop



In both archetypes, the power is maximized when efficiency is at some intermediate value between zero and one. There are other sorts of power-efficiency curves that are maximal at efficiencies of zero or one, but in my experiments with agent-based models, systems that exhibit or depend on those types of power-efficiency relationships are not persistent, and quickly evolve to an untenable state near the point of maximum power and collapse. So, these Goldilocks sorts of curves (not too hot; not too cold; but just right) lead to persistent systems.

Again, it is Odum's particular focus on "useful" energy, as opposed, I suppose, with "used" energy, that leads to these Goldilocks curves. When energy is passed from one store to another, there are three streams of energy, and three ways to define power, and two ways to define efficiency. There is the total energy released by the upstream store (E_T), the energy that is reversibly stored in the downstream store (E_U), and the energy that is irreversibly degraded in the process of transfer (E_W). The transfer of energy requires the passage of time (T). Useful power is defined by Odum as $P_U=E_U/T$. Efficiency is defined by Odum as E_U/E_T.

But, here is the problem. How would you prove that a particular "type of energy transfer" (say a species of frog eating a species of fly) can be represented by a Goldilocks type of curve? You would need many frogs of that species, and many flies of that species, and you would need to make many careful measurements, and you would get one averaged number for power, and one averaged number for efficiency. This becomes an empirical ordered pair (power, efficiency) – a data point. If the efficiency is either zero or one, then you would have disproved hypothesis MPP II. And, if hypothesis MPP III is valid, then you might assume this data point represents the point of maximum power and intermediate efficiency. But, if you don't want to make that assumption, all you have is one point on a hypothesized curve. For reasons explained below, I think this is all you would have.

To actually show the evolution of such a type of energy transfer, you would need to produce such an average data point for each generation of frogs and flies of those species for many generations, and show that the general trend is either towards more useful power, or is at a stable number. But that is getting into the real issues in MPP III. In this hypothesis I merely assume the existence of such a curve.

So the proof of the existence of these curves in all energy transfer events becomes not one of empirical data collection, but of mathematical proof that no other possibility exists. That is what I am trying to do in Ref H. It admittedly needs work, but it is getting there.

4.5.4 Hypothesis MPP III Revisited

Hypothesis MPP III (together with its two lesser component hypotheses) is not tautological, but it implicitly identifies a complex of behaviours that amount to a significant extension of the laws of thermodynamics, and the laws of economic systems. It incorporates an extension of Darwin's law of natural selection to describe how systems evolve, as organisms evolve. It presents a partial explanation of Adam Smith's "invisible hand". (I believe an extension of the second law of thermodynamics to logical systems provides the other part.)

But, how would you verify by demonstration or example, or falsify by experimentation? If you assume that hypotheses MPP I and MPP II are true (and we can make them true by careful definition of words and phrases), then, surely we can just calculate the power and efficiency of the system and see if hypothesis MPP III is verified or falsified by the empirical data. OK. But, what do we measure? How many times must we measure it? What calculations do we apply to the empirical data so collected? To what expected numbers do we compare the numbers coming out of those calculations?

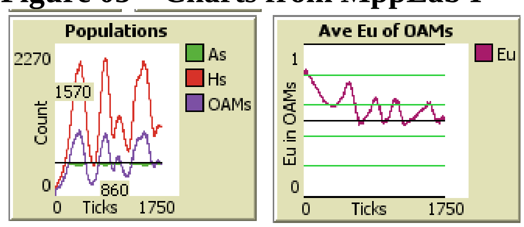
Here's the nub of the dilemma as I see it. A species of frog will, in the course of its life, eat many species of flies, having different (power, efficiency) operational characteristics for each type of predation event. No one energy transfer event will be optimized, but, rather, some averaged (power, efficiency) characteristic for the species of frog might be obtainable. My experience with MppLab II ABM is that the ENTIRE SYSTEM becomes optimized. Optimization is NOT at the level of species-to-species (prey-to-predator), nor at the level of many prey to one predator (though I cannot check that with the current ABM), but at the level of all prey to all predators. Verification of that would be very difficult.

4.5.5 MppLab I As An Example

This is what I did with my "MppLab I" NetLogo application, as a test of hypothesis MPP III:

- I built a model ecosystem populated by logical animals (heterotrophs):
  - which fed on plants (autotrophs) and/or each other (see Figure 05, left chart),
  - which could not reproduce until old enough and energetic enough,
  - which reproduced by simple fission with some small stochastic mutation of genes, and
  - which died of old age if they had not been eaten, or were unable to reproduce.
- Initially, this model ecosystem was not sustainable (persistent) in the long term, and so did not meet the description of an included system as per hypothesis MPP I. I added design features until the system became persistent. A key feature so added was a restriction to energy transfers with an efficiency above 0.25.
- The feeding behaviour of the animals was controlled by one gene subject to mutation. When an animal met another edible organism (either plant or animal) the values of the control genes would be compared (all plants had a standard unchanging value) to determine whether feeding would occur, to assign roles of predator and prey, to set the parameters for energy transfer, and to set up the calculation of power and efficiency of that feeding event. I chose a common power-efficiency curve that was used in all such linkage events (also called feeding events, predation events, or energy transfer events) and the values of the genes of the two participating organisms were the parameters that determined the power and efficiency. By this means I ensured that hypothesis MPP II was satisfied, and all energy transfers within this persistent system were represented by a single known Goldilocks curve with a known maximum power when efficiency equals 0.5.

Figure 05 – Charts from MppLab I

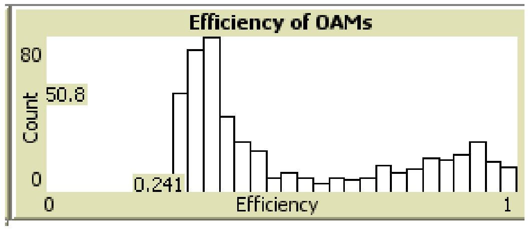


First 1500 ticks – number of autotrophs, heterotrophs, and predation events (OAMs) – average efficiency of all current predation events converges on 0.5.

- I reasoned that the changes in values of the mutating genes:
  - Happened only at the moment of reproduction (by fission);
  - Was stochastically unbiased, by design;
  - Happened only to animals that had avoided predation to survive to reproductive age;
  - Happened only to animals that were successful in foraging on other plants and animals; and

  - Was equally likely to confer either evolutionary disadvantage or advantage.
- I also reasoned that, since it was possible for a wide range of feeding behaviours, all feeding events would have very varied power ratings and efficiency ratings. This expectation was born out when the model was run, showing efficiencies from close to 0.25 (the lowest allowed value) up to close to 1.00 (the highest value allowed). (See Figure 06.) Many hundreds of animals were birthing, living, feeding on one another, reproducing and dying within this model ecosystem at any moment in time, with power levels and efficiency measures of the predation events widely varied.

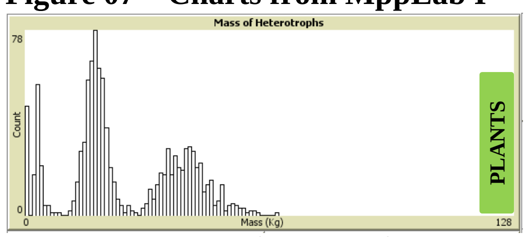
Figure 06 – Charts from MppLab I



At 1500 ticks – distribution of efficiencies of all 488 currently active predation events – varies from 0.25 to 1.00.

- However, I was able to calculate the average efficiency for all simultaneous feeding events across the system. This average efficiency started at a value determined by my model construction routines, but very quickly changed as the system evolved. There were two distinct trends as this persistent system evolved to a stationary state:
  - The average efficiency of the system, as a whole, changed, approaching the expected value of 0.5, fluctuating about that value as the trophic structure developed, and ultimately remaining close to that value. (See Figure 05, right chart.)
  - The population of animals developed a trophic structure including plants and herbivores (there by design), carnivores, up to apex carnivores, having from four to nine clear trophic levels, the first three or four of which were relatively stable. (See Figure 07.) When I watch it, it reminds me of a long pennant flapping in the wind, for which the part close to the flag pole undulates slightly and regularly, but the end far from the pole flaps with wild turbulence.

Figure 07 – Charts from MppLab I



At 1500 ticks – distribution of gene values of all 1,035 currently living heterotrophs – shows trophic structure.

- I consider this a verification of Lotka's/Odum's claim that systems will evolve to function at maximum power, and support for my version of that claim as expressed in hypothesis MPP III.
- However, it also provides some insight as to how best to interpret that claim, and how to study that claim in a natural ecosystem. Many, or most, linkage events, in fact, were at less than maximum power. (See Figure 06 – i.e. at less than efficiency 0.5.) This would tell me that a slightly more nuanced version of hypothesis MPP III is needed.

4.5.6 Implications

So, how would the MPP be studied in a real-world system:
- Careful attention to the definition of terms;
- Careful attention to the identification and measurement of linkage events throughout the system as it functions.

And here it gets sticky. In my case I was working with a single known power-efficiency relationship. In the case of the real world, I don't know how many different kinds of power-efficiency curves there might be, or at what efficiency the power might peak, in each of these unknown relationships. Every (predator, prey) pairing of species might have its own power-efficiency relationship. Each pairing would have a contemporary (power, efficiency) data point that lies somewhere on that relationship graph, but that would not tell you the shape of that graph, or where the point of maximum power should be. A single data point tells you little.

I suppose one could put a variety of species into a large terrarium, let it evolve for many generations, and estimate the power and efficiency of each feeding event. That would be difficult. The only real way, that I can imagine at the moment, to explore and test these hypotheses and this MPP phenomenon, is via agent-based models, in which the identification of events and the capture of relevant data is cheap, easy, and scalable in volume.

As an addendum to the above thought, I have re-read the paper by Cai (et al.) at Ref I, and that, essentially, is what they did. They put an ecosystem of algae in a tank, used a computer to monitor the acidity of the tank, and created a feedback such that the changes in acidity altered the length of time the lights were on providing energy to the ecosystem. The question then is, did the ecosystems evolve to turn the lights on full-time? There were some problems with the interpretation, so the answer was yes, with some big "but"s attached. The experiment was statistically significant enough to warrant a re-design and a re-test of the results.

4.6 Why Continue?

If it is so difficult to come up with a falsifiable statement of the MPP, and, having a version of that, if it is so difficult to imagine an experimental technique that could be used to falsify it, why continue? Why am I so convinced that it is worth sorting this out?

It is clear to me, and to most people who think about it, that something causes complex systems to self-organize. Even as the second law (of thermodynamics) drives systems to exhaust the abilities of available energy to "do work" while driving up universal entropy, open systems, nevertheless, store up energy and become more complex as they reduce their internal entropy. There is a backwards driving force that causes turbulence and eddies, that causes the temporary appearance of structures which, though temporary, persist in specific case and in general kind, for extended periods, being ever destroyed and replaced by more complex structures. This backwards force is not captured in any extension of the first and second law that I am aware of. The Ref B paper by Dr England seems to open the door for such a thing, but does not go far enough.

More to the point, this phenomenon is largely responsible, I believe, for the dramatic rise in power and scope of the modern global capitalist economy. If we cannot find a way to understand it, we will remain tied to the obsolete grow-forever equilibrium-enraptured economic theories conceived a century ago. Those theories have led the world to the brink of destruction, and must be replaced, if humankind is to survive.