HIGH-LEVEL DESIGN
And
USER DOCUMENTATION
For OamLab V1.10
(OPEN ATWOOD MACHINE LABORATORY)

Mj - Mt * Eu

Mt = Tb / Td

Eu = Ml / Mh

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2   Background

2.1   About the References

This document is the design and user documentation for the Ref A agent based model called **OamLab**. The diary entries at Refs B through E are highly recommended read-in material for this model. They can be downloaded from the Ref F site. Refs G through R develop and present the current concept of the Maximum Power Principle (MPP). My own understanding of the MPP varies somewhat from those views, but is not wholly inconsistent with them either. This, and the other related models, were developed in a personal study seeking a deeper understanding of the implications of the MPP.

An Atwood's Machine (AM) is a closed mechanical system. At Ref D, in a "thought experiment", I posited the existence of a linkable array or chain of Halves of Open Atwood Machines (OAMs), and **OamLab** is a continuation of that thought experiment. An OAM is a totally imaginary concept which is not practical to build, but which captures the essence of an AM that can function as a component of open (i.e. non-isolated) energy system. A half OAM (or HOAM) contains a hold/release mechanism, a pulley, and a mass (M). Each such half-a-machine has the ability to link on the left, or on the right, to another such machine. Together they make a complete Open Atwood's Machine (OAM).

The theory in the Maximum Power Principle (MPP) is that a system will configure itself such that the OAMs will function at maximum power, but at an efficiency $\eta <= 0.5$.

2.2   Overview

This overview is pulled from the 'Info' tab of the Ref A model:

> **OamLab** - *This is the first of a series of three planned models in a study of the maximum power principle (MPP) - the other two models being* **MppLab** *and* **TpLab**. *In* **OamLab** *energy arrives in a steady stream from the Sun and is captured by plants that form the heads of trophic chains. These trophic chains do not form a trophic web, but remain as distinct and competing entities. The energy passes from organism to organism down each trophic chain until the final organism (the apex predator) consumes the penultimate holder of the energy, and the last of the original endowment of energy is degraded to waste heat and released. By this means we have direct insight into the basic implications of Lotka's argument (Lotka, 1922a) about the evolution of system-wide processes that compete for energy and evolve to function with maximized energy flux. That argument by Lotka is now a fundamental piece of the concept called the MPP. But, how do you measure the fitness of processes that compete for access to energy? How do you compare the respective efficiencies of many competing system-wide processes that are, themselves, composed of many linked energy transformation processes? What are the effects on the individual transformations? With* **OamLab** *I begin to address some of these questions.*
>
> **MAXIMUM POWER PRINCIPLE (MPP)** - *It is clear that, when isolated and left alone, all systems die, run down, erode, decay and/or dissipate their matter and energy. This process is closely associated with the phenomenon of entropy production, and the 2nd law of*

thermodynamics (sometimes referred to as the maximum entropy principle, or MEP) easily describes how this happens. Any such energetically isolated system automatically alters and reconfigures itself, moving through a series of ever more probable states along a trajectory of ever increasing entropy, until a most probable configuration or state of maximal entropy is achieved. This state of maximal entropy is usually characterized by an excess of sameness, a lack of structures, shapes or spatial variations, and by characteristic distributions of energies among the parts. Once having achieved such a configuration, the isolated system then remains in a state of maximal entropy (a most probable state) forever after. However, when we look around ourselves, virtually everything we see is characterized by remarkable improbable variety, a plethora of structures and shapes, and turbulent distributions of energy. Clearly, when a system is not isolated and left alone, there is another dynamic able to overpower the 2nd law and undo its nasty work. Such is the nature of the proposed 4th law of thermodynamics. A.J. Lotka, H.T. Odum and R.C. Pinkerton called this the Maximum Power Principle (MPP). H.T. Odum (1924-2002) went on, over four decades, to argue that the MPP is the best candidate for the fourth law of thermodynamics, having explanatory value for such things as ecosystems, economies, and other self-organizing systems. However, in spite of the fact that there is plenty of anecdotal evidence in support of the concept, it remains little understood, and little studied it seems. The MPP says (my words) that any self-organizing system that is open with respect to a flow of energy will configure itself to store/consume/use energy at the maximum rate possible. This model is a "laboratory" in which I can study the nature of the MPP.

*Atwood's Machine - The approach in **OamLab** is to study the Lotka/Odum MPP using a marvelous gizmo called Atwood's Machine (AM). This machine was invented in 1784 by the English mathematician George Atwood for the study of Newton's laws of motion. It has since become a common device in the design of a variety of lifts which use counterweights. Odum and Pinkerton used the AM as an example in their 1955 study of the MPP. In a variety of diary entries that I have written in an attempt to understand the MPP, I have developed a rather arcane notation of OAMs, HOAMs and OAM chains. It is highly recommended that interested people read those notes prior to studying this model. They are summarized below.*

*SUSTAINABLE ECONOMICS - **OamLab** is being written as part of a personal study of the dynamics of a sustainable economy. It has become clear to me that a modern economy is a sterling example of a system that has evolved to extract matter and energy from its environment, and to degrade and disperse those resources at a maximal rate. That observation has led to the study of the MPP. During the course of that study I have become aware that there are two principles that have been consistently proposed by scientists as candidates for the fourth law of thermodynamics. One is the MPP, as described above. The other is often referred to as the Maximum Entropy Production Principle (or MEPP). Note that this goes beyond the 2nd law - the MEP. The MEPP says (my words) that any self-organizing system that is open with respect to a flow of energy will configure itself to continuously **produce** entropy at the maximum rate possible. Now, I have intentionally reworded the two principles to draw attention to the similarity. I believe I have not mangled either idea too badly. I am personally convinced of two things:*

- The MPP and the MEPP are two sides of a single little-understood phenomenon, and in both cases the proponents argue that these laws play a significant role in the organization of both ecosystems and economic systems. In these days of daily news of ecological and
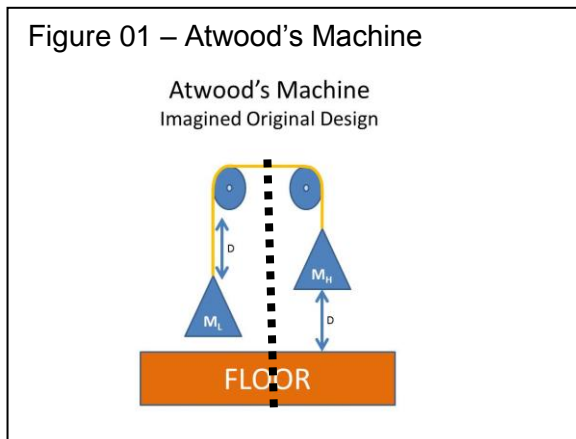
economic perils, it seems we might want to put some effort into understanding such a phenomenon. And so, my study of economics has taken an unexpected turn towards the MPP and the MEPP for a while.
- The very same phenomenon that is actively shaping our ecological and economic destinies is also active in many agent-based models (ABMs). I am NOT saying that I believe they are simulated in ABMs. I believe they are the organizing phenomena that cause unexpected emergent behaviour in ABMs. These principles are exhibited, or can be exhibited, in ABMs. What better place to study them, then, than in ABMs?

Atwood's Machine Understood *- I will here provide a description of an AM that will help*

you understand the **OamLab** *and* **MppLab** *applications. This differs only in mechanical design from other descriptions you will find, but not in function. An AM consists of two masses, one heavy and one light, coupled by a rope that is hung over a pair of non-leveraging simple pulleys. Most descriptions show a single pulley. I prefer to view it as a pair of pulleys, because I am going to split the AM into two halves, and each half has a pulley, a mass, an energy sink, a rope to couple*

Figure 01 – Atwood's Machine

Atwood's Machine
Imagined Original Design

masses together when needed, and a hold/release latch that can be used to pin the mass in place after it has been raised. In the AM, the heavy mass is primed with gravitational potential energy as it is raised a distance D off of the floor and latched in place. It is then coupled, using the ropes, to the lighter mass that rests on the floor, as a counterweight. When the heavy mass is released, it glides slowly to the floor as the lighter counterweight mass slowly rises. When the lighter mass has risen a distance of D, it is latched in place. At that point, the two masses may again be uncoupled.

I apologize for the use of a variety of acronyms in the following explanation, and in the interface of the model, and in the code, but without them I find I get really tangled up in my words. So, here is a list of the acronyms that are important. For more detail, read the notes mentioned below in the reference section:

- ***AM - Atwood's Machine in its original design*** *- a mechanical system that is closed with respect to energy, in the sense that most analyses of the original system start with the heavy mass already raised, and do not consider how the energy is first put into it. I use the AM as a metaphor for time-regulated transformation of energy. According to Odum, all energy-driven changes require time to complete, and I am using the mechanics of a mechanical system to stand in as a time-based speed regulator for the biomechanical and biochemical changes that might happen as energy is passed from predator to prey in an ecosystem. I am using the well-understood mechanics of the AM to model the biochemistry of digestion.*
- ***OAM - Open Atwood's Machine*** *- an imaginary version of the AM that is open with respect to energy, allowing a flow of energy into the system on the right, and out again on the left, as it runs its course.*
- ***HOAM - Half of an OAM*** *- two of which remain when an OAM has its masses uncoupled and it is split in half. Each half consists of, as stated above, a pulley, a rope, a mass, an*

energy sink (the floor), and a hold-release latch that can be used to pin the mass up off of the floor.
*- **RH-HOAM** - An HOAM that has been linked to the right side of another HOAM to form an OAM. The RH-HOAM must have a mass larger than the mass in its counterpart.*
*- **LH-HOAM** - An HOAM that has been linked to the left side of another HOAM to form an OAM. The LH-HOAM must have a mass lighter than the mass in its counterpart.*
*- **Chain of HOAMs** - a series of HOAMs formed into a distinct chain. They are linkable in pairs to form OAMs such that each side-by-side pair of HOAMS can form a well-formed OAM. Energy can flow into the head of the chain, and, as OAMs are formed, and as the masses are coupled and uncoupled, the energy flows through the chain to the tail. Each HOAM may be uncoupled, coupled as an RH-HOAM, or coupled as an LH-HOAM. You can think of such a chain as a simulation of energy flow through a trophic chain (along one chain in a web), of energy flow through the organic molecules that make up the cytoplasm in a cell, or, possibly, of capital flows through a supply chain of economic agents in an economy. [This is the crazy concept I am chasing in my study of sustainable economics.]*
*- **Web of HOAMs** - a collection of free-moving HOAMs that are freely linkable to other HOAMs with which they come in contact. They link in pairs to form OAMs such that each side-by-side pair of HOAMS forms a well-formed OAM. Energy flows from HOAM to HOAM as the masses are coupled, forming OAMs, and uncoupled again. Ultimately, the energy flows through the web. Each HOAM may exist in uncoupled form, coupled as an RH-HOAM, or coupled as an LH-HOAM. You can think of such a web as an analogy of energy flowing through an ecosystem, of energy flowing through the organic molecules that make up the cytoplasm in a cell, or, possibly, of capital flowing through independent economic agents in an economy. [Again, this is the crazy concept I am chasing in my study of sustainable economics.]*

*In **OamLab** I present preformed and persistent chains of OAMs competing for survival. In **MppLab** there are free-swimming HOAMs that form OAMs at will and so make virtual chains of OAMs of fleeting existence as the HOAMs compete for survival and devour one another in that competition.*

3   Purposes

Construction of this model is part of a larger project to understand sustainable economics. Models built during the course of this study are **PSoup**, **ModEco** (C++ platform), **ModEco and the PMM** (NetLogo platform), **EiLab** (C++ platform), **CmLab**, **OamLab**, **TpLab** and this model - **OamLab**. A brief description of each of these models can be found at Annex C.

As stated in the overview, I have become convinced that the very same phenomena that are actively shaping our ecological and economic destinies is also active in many agent-based models (ABMs). I am NOT saying that I believe these phenomena are simulated in ABMs. I believe they are the organizing phenomena that cause unexpected emergent behaviour in ABMs. That is, the MEPP and the MPP are exhibited, or can be exhibited, in ABMs. What better place to study them, then, than in ABMs? This is why I wrote the **ModEco** and **EiLab** applications, and why I continue to develop more related models.

Of the two concepts, it seems that the MPP may be the most complex, but also the most accessible to direct exploration via ABMs, at the moment. I am working on the MEPP via

studies with **EiLab**, but I think I have a better chance of solving the riddle of the MPP first - at least, to my satisfaction.

Therefore, the purposes for building this **OamLab** model are:
- To demonstrate the MPP in an agent-based model.
- To lay the ground work for connecting the MPP to the MEPP.

I usually do only high-level designs before I dive into coding, and then make notes as needed to cover difficult technical details. This document is a summary of those notes, but is, in no way, meant to be a complete design document. The best such documentation is in the "info" tab and "code" tab of the Ref A NetLogo file.

Therefore, the purposes of this document are:
- To summarize some of the more technical decisions make while constructing the model, and record them after the fact, and
- To provide some technical documentation and user documentation that supplements the contents of the Ref A model.

4   Discussion

The discussion proceeds in two parts. In the first part I address the concepts that inspired and shaped the development of the model. In the second part I address some technical aspects of the implementation. Then, there are three annexes. In Annex A I describe the user interface in some detail. In Annex B I present some of the "debug" data stream that the model is able to produce. In Annex C I briefly describe the related models developed in my study of the dynamics of sustainable economic systems.

4.1   Conceptual Development

4.1.1   Legend of Acronyms and Variable Names:

When describing this model which is the result of a highly imaginary "thought experiment" one has each foot, metaphorically speaking, planted firmly each in three different paradigms. On one side, we have the paradigm of Newtonian mechanics with its masses, ropes and pulleys and its precise analytical equations and mathematical symbols. On the other side, we have the paradigm of ecosystems with predators and prey participating in trophic chains as they capture and consume energy, and as they capture and consume one another in the process. Relatively speaking, ecosystems are trackless jungles, when compared to mechanical systems. There are conceptual bridges across the gap between these two paradigms, and those bridges get a lot of traffic. In short, it gets very wordy describing those bridges each time I wish to cross one, so I use acronyms to reduce the wordiness. Then, a third paradigm had to be introduced – the paradigm of computer models with its own subroutines, variables, and arrays. The following definitions were developed within the referenced diary notes and within the **OamLab** application, and are a merger of the three different paradigms from which they spring: some are computer code variables, with long names; some are mathematical symbols, with short names; some are acronyms replacing long descriptive names, and all are doing double duty as bridges

between the mechanical systems of Newton and the ecological systems of Odum. Throughout this document, those variables that are instances of computer code variables or model parameters are put into bold print, as they can be found somewhere in the Ref A model.

- **tick** – a discrete time step in the model, or the current time step measured from tick 0
- AM, or the AM – Atwood's Machine
- M_L – the lighter of the two masses in an AM or OAM
- M_H – the heavier of the two masses in an AM or OAM
- M_t – total of two masses within an AM or OAM; $M_t = M_H + M_L$ (Note, this symbol does double duty as total mass and as time-related fitness measure. The context tells the meaning.)
- M_d – difference of two masses within an AM or OAM; $M_d = M_H - M_L$
- D – Drop distance; = **g-drop-distance**; a parameter of the model
- g – acceleration due to gravity; = **g-acceleration**; a parameter of the model
- OAM – Open Atwood's Machine, of which energy flows into it, through it, and out again
- HOAM – Half OAM, which, when joined to another HOAM, makes an OAM
- RH-OAM – Right Hand HOAM, having the heavier mass of the two (M_H)
- LH-OAM – Left Handed HOAM, having the lighter mass of the two (M_L)
- W_t – Total energy in the AM at start, all stored in M_H; $W_t = g{\times}D{\times}M_H$
- W_u – Still usable energy transferred from M_H to M_L; $W_u = g{\times}D{\times}M_L$; = **energy-to-transfer**; an attribute of an OAM
- W_e – Energy converted to kinetic energy then exhausted as waste heat; $W_e = W_t - W_u$; = **energy-to-discharge**; an attribute of an OAM
- T_b – Base time to drop for an uncoupled mass
- T_d – Time to drop for an AM or OAM; $T_d > T_b$; = **oam-time-to-drop**
- η or E_u – H. T. Odum's measure of efficiency; $\eta = (W_u / W_t) = (M_L / M_H)$; = **Eu-in-oam**; an attribute of an OAM, and also a fitness criterion
- M_t – A time-related fitness criterion; $M_t = (T_b / T_d) = $ **Mt-in-oam**; an attribute of an OAM (Note, this symbol does double duty as total mass and as time-related fitness measure. The context tells the meaning.)
- M_j – A joint time/efficiency fitness criterion; $M_j = (E_u \times M_t) = $ **Mj-in-oam**; an attribute of an OAM
- MEP – Maximum Entropy Principle (2nd law of thermodynamics)
- MPP – A. J. Lotka's and H. T. Odum's Maximum Power Principle (proposed 4th law)
- MEPP – Maximum Entropy Production Principle (proposed 4th law)

An AM starts with stored total gravitational potential energy (W_t) equal to [the acceleration due to gravity (g)] times [the heavier mass (M_H)] times [the distance from the mass to the floor (D)]. We write that as $W_t = g{\times}D{\times}M_H$. After M_H is released, and as the AM runs to completion, this energy is transformed in two ways. The coupled mass assembly (M_t) accelerates, and picks up kinetic energy. At the same time, the lighter mass (M_L) is raised off the floor by a distance D, gaining gravitational potential energy (W_u) according to the equation $W_u = g{\times}D{\times}M_L$. When M_H strikes the floor, the kinetic energy of both masses is dissipated into a heat sink. The energy is either transferred from the RH-HOAM to the LH-HOAM as stored high-grade gravitational

potential energy (W_u), or exhausted as low-grade waste heat (W_e). No entropy is produced as W_u is transferred and stored (due to the frictionless nature of the pulleys and ropes). Entropy is produced as the waste energy (W_e) is exhausted. Odum defines the efficiency (η or E_U) of the AM in transferring and storing high-grade energy as $\eta = W_u / W_t$, which simplifies to $\eta = M_L / M_H$. The behaviour of the AM varies across the spectrum of settings of M_H and M_L:

- When $M_H \gg M_L$ then η is close to zero, M_H falls quickly, and the time-to-drop is short, close to T_b. This baseline value of time-to-drop (T_b) is given by the formula $T_b = \sqrt[2]{2D/g}$. Most of the initial endowment of gravitational potential energy is transformed to waste heat, and very little useful energy is stored in the LH-HOAM.
- When M_H is just slightly larger than M_L, then M_H descends very slowly, the time-to-drop is very long, η is very close to 1, and most of the endowment of energy is transformed into useful energy stored in the LH-HOAM.
- Curiously, Odum found that the fastest transfer of the endowment of energy to still useful energy in the LH-HOAM (i.e. the maximum power) occurs when $M_H = 2 \times M_L$. That is, maximum useful power happens when and $\eta = M_L / M_H = 0.500$.

The MPP says (my words again trying to summarize Odum's vision) that any evolving self-organizing system based on such HOAMs will configure itself in such a way that the temporary OAMs, as they form, tend to operate at maximum power and at efficiency less than or equal to 0.500.

Another vision of the MPP (Lotka's) puts it this way. In every self-organizing system there are processes that gather and process energy. Through a kind of Darwinian process of natural selection, those processes that transfer useful energy (W_U) down the chain at the fastest rates will persist, and prevent the less effective processes from surviving, and so the system evolves (reconfigures itself) such that it is capturing and processing energy at maximum rates consistent with available resources.

Here are my research questions for OamLab:

- Under what conditions does such a self-organizing system of competing chains of HOAMs converge to a system that has a common or average efficiency per OAM of $\eta <= \frac{1}{2}$, as predicted by Odum (1955) in consideration of the operation of the AM?
- What system dynamics can be understood from the study of such evolving self-organizing systems?

I think that, if the MPP/MEPP concepts contain any real useful insight, then HOAMs exist as molecules, organisms, or economic agents that interact temporarily and transfer energy or capital. As the energy (or capital) flows through such systems from component to component (from HOAM to HOAM), some is degraded and exhausted, while the rest is passed on down the trophic web/supply chain.

4.1.2   The Role of Atwood's Machine

Please note that there was one aspect of this model that some people have questioned, quite

reasonably. I use the "**mass**" from Atwood's Machine as a primary phenotypic attribute (gene) of my biological agents, but I do not in any way intend it to represent the real mass of the agents. It represents the genetic ability of organisms to consume and digest one another. In the follow-on model I take extra care to highlight that change in role by re-labeling the gene called "**mass**" in **OamLab** as **getf** (genetic energy transfer factor) in **MppLab**. The confusion arises from my "borrowing" of the mechanics of Atwood's Machine (the AM) to model the chemistry of digestion. The logic for doing so is as follows:

- Odum showed that in the dynamics of the AM we find a great example of the trade-off between power and efficiency that is ubiquitous and a fundamental characteristic of all energy transfers. He also argued that all energy transfers take time, and that the MPP is the common time regulator (see Odum and Pinkerton, 1955).
- I do not have empirical data describing chemical digestion of one species by another. In fact, to simulate a real-world trophic chain, I would need such data for all relevant species trying to digest all other relevant species. And, for each such potential transfer of energy, I would need both efficiency and speed of all such energy transfers. However, since I am not attempting a simulation, I can dodge that problem by using a proxy.
- On the other hand, we have an exquisitely precise analytic description of the energy transfer that happens in the AM, providing both efficiency and power (rate of energy transfer), and implicit therein is the time required to complete the transfer (coded in the **oam-time-to-drop** attribute of OAMs).
- So, I reasoned, I could emulate the efficiency and rate of energy transfer of digestion using the precise analytic description of the AM. Since the **mass** of the two components of the AM are the critical factors, I have inserted a proxy for **mass** into all organisms. Whenever two organisms meet, I use their respective **mass** values to determine:
  - (a) who is predator and who is prey;
  - (b) how long it takes for predator to digest prey; and
  - (c) how much of the consumed energy of the prey is turned to "waste heat", and how much is retained as "still-useful-energy" incorporated into the predator.
- This does not give me a simulation of any particular act of digestion, but it does give me a template for emulation of all possible acts of digestion (all possible efficiencies and powers and time durations) and thus allows me to investigate the nature of real-world trophic webs without actually simulating one.

So, to be clear, the concept of biophysical **mass** that we all know and understand as playing a significant role in biology is not explicitly used anywhere in this model. But, the ability of one organism to digest another organism is determined by the interaction of the relative values of the **mass** genetic factors, and I use the mathematics of energy transfers that derives from the AM and the masses therein to compute the dynamics of digestion when they interact.

How does the **mass** work?
- **Newtonian:** Well, when two HOAMs form an OAM, the side with the smaller **mass** receives energy in any energy transfer.
- **OamLab:** Similarly, when two HOAMs meet and form an OAM in **OamLab**, then the HOAM (the organism) with the lesser **mass** genetic value receives energy (eats) and the HOAM

with the greater **mass** delivers energy (gets eaten).

You can think of **mass** as an indicator of the "quality of the energy carried".   Energy transfers would then always go from higher quality to lower quality. That idea sort of works here!

4.1.3   Operational Concept of the Model

See Panel 01 in Annex A for a screen grab of the main panel. The basic entity under study in **OamLab** is a trophic chain – a series of organisms ordered from primary producer to apex predator. Each chain consists of a string of HOAMs. A small population of chains of HOAMs is initially created, and they evolve in competition with one another. Each chain has a HOAM that acts as a head (primary producer), several HOAMs that act as body links, and a HOAM for a tail (apex predator, decomposer, or detrivore). The head has a smiley face. All but the tail can be RH-HOAMs, and all but the head can be LH-HOAMS. An index number can be used to access any HOAM within a chain. A chain with five HOAMs has them numbered from 0 to 4. Any two HOAMs that are side-by-side can link and temporarily form an OAM. The formation of an OAM represents a feeding event in which the LH-HOAM is devouring the RH-HOAM. A chain with 5 HOAMs can form 4 OAMs numbered 0 to 3.

There is some ability to select how the chains are created, having high E_u at start, low E_u, or mixed E_u. A chain is initialized by assigning the **mass** of the tail, then generating E_u values for each OAM and calculating the appropriate **mass** value. When each chain is so initialized each potential OAM has a characteristic drop time, and the entire chain has a drop time equal to the sum of the drop times of the OAMs that comprise it.

For example, the first OAM (formed by linking the head with the next HOAM) might require 6.4 seconds for M_H to fall and hit the floor. As it is running, the head HOAM and the next HOAM turn yellow. Then, on the seventh tick, the first OAM will exhaust its waste heat, delink, and then the next OAM will link up and begin operation. The mass that played the role of M_L in the first OAM has now become the M_H of the second OAM. The little yellow indicators of the active OAM will move to the left.

Technically, the chains exist in a library with a limited number of slots. There is an upper limit on the number of chains that the model allows. When the last OAM in the chain discharges, the chain is done. It then replicates itself via fission, one successful chain producing two daughter chains. During fission each daughter chain mutates slightly. Within each of the two daughter chains one random HOAM is selected, and the size of the **mass** is adjusted randomly upwards or downwards by a random distance. Once they are mutated, one daughter inherits the library slot occupied by its parent, but a place must be found to put the other daughter. If the library is full, all other chains are scanned, and the chain that is least fit is removed and replaced by the daughter of the successful chain. It's survival of the fittest!

You can choose not to allow head HOAMs to mutate. You can choose not to allow tail HOAMs to mutate. This causes some insightful and perhaps counterintuitive and unpredicted results.

There are three fitness measures that may be used to decide which chains are removed and replaced:

- M_j – JOINT - a chain manages a trade-off between fast replication (short time to drop) and maximal transfer of high-grade energy towards the tail of the chain (efficiency).
- M_t – TIME - a chain replicates as quickly as possible, without regard for efficiency.
- E_u – EFFICIENCY - a chain transfers as much useful energy as possible towards the OAMs in the tail of the chain, without regard for time to drop.

Fitness of the chain is calculated as the geometric average of the associated fitness measures of each OAM within it.

There is some logic behind these choices of fitness measure. HOAMs (organisms) suffer the good and bad effects of random mutations. However, the characteristics of energy transfer processes within OAMs (chemistry of feeding events) are also thereby affected. And the ability of the chain to deliver energy to the tail HOAM (apex predators, decomposers, and detrivores) is also affected. Evolution is happening at three hierarchic levels: HOAM, OAM and chain. Rapid reproduction has an evolutionary advantage over slow reproduction when competing for the same resources. On the other hand, an organism that can endow its offspring with the maximal amount of energy at birth has an evolutionary advantage. Nature must find ways to trade off these two opposing demands at all hierarchic levels. These fitness measures are calculated for every OAM (for every feeding event) and aggregated to chain-level fitness measures as geometric averages of the OAM-level measures.

4.1.4   User Experience

You have heard, I suppose, of one-player games. One of my tutored students calls programs like this a zero-player game. You set the parameters, you start it, and you watch it.

There are a total of $3{\times}3{\times}4$ = 36 different scenarios, and each of those 36 scenarios can be run with different random number seeds.

To perform a run of the model:
- Select two scenario options:
  - Choose one of the Darwinian fitness measures (M_j, M_t or E_u);
  - Choose one of the configuration options (high E_U, low E_U, or mixed E_U);
- Select a random seed;
- Click on the "Setup" button to configure the system according to the options chosen;
- Set the switches that control mutation (heads on/off; tails on/off) or horse-race mode;
- Click on the "Go" button.

There are other advanced optional sliders in Panel 02 by which you can change the length of the chains, or change the number of chains on start, or the operational characteristics of the OAMs.

If you turn on the debug feature and click the switch to send debug data to the command centre,

you can watch a stream of information about the changes as they happen. (See Annex C for an example of debug output.)

As a run proceeds, within each chain, OAMs are formed from right to left. It takes each a while to "drop", so you may see no movement for the first few clicks. The active OAMs are yellow. Graphs display current values for M_j, M_t and E_u for each class of OAM, so you can see a cross-section of the chains as they evolve.

4.1.5   What Is Demonstrated?

To my knowledge, Odum did not talk about chains of OAMs, or anything of the sort. Nevertheless, I think I have translated his ideas into a demonstration of the MPP. All energy captured by the head of a chain is degraded to waste heat by the time it reaches the tail of the chain. We can surmise that entropy is produced as the energy is degraded, though the production of entropy is NOT explicitly modeled in **OamLab**. So, to see evidence of entropy production, one needs to watch the production of "waste heat" by the system. I admit that interpretation of some scenarios is difficult due to the fact that the carrying capacity is artificially placed at 30 chains, and the population of chains never falls below that value. This is not an unconstrained population of chains free to find their own population equilibrium. However, some scenarios are easy to interpret

- **TAIL AS THE LOAD – THE MPP/MEPP** – When the tail is not allowed to mutate, the mass in the tail remains at its initial value (e.g. 16 kg). You can consider this as the load on the chain. The chain must transmit enough 'useful' energy to the end of the chain to lift that load as quickly (time fitness measure) or as efficiently (energy fitness measure) as possible. Then, as the system evolves to a stationary state, the average size of all heads evolves to take in sufficient energy to handle that load. Those that are poor at lifting the load in the

Figure 02 – Maximum Power

prescribed manner are selected out of the population. In any scenario in which (a) the tail cannot mutate and (b) all chains start with high efficiency (low rate of degradation of energy), the heads evolve to increased size until the maximal amount of energy possible (for this system design) is being captured and degraded. This demonstrates my interpretation of the MPP and the MEPP. It also raises the difficult question "What does 'maximum' mean in this circumstance?" Clearly it could go higher, but it approaches an equilibrium of sorts and is leveling out. It is constrained by available resources (30 chains), and system design (17 HOAMs per chain, AM mechanics, and other things??). Perhaps instead the principle should be called the "Power Maximizing Principle". ☺
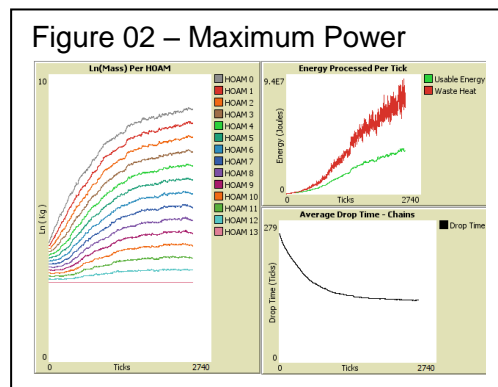
- **GENETIC DRIFT** – There is a list called the "chains library" which will hold up to 30 chains. As long as there is space for new chains in the library (and on the playing field) there is no selection going on, whether natural or otherwise. There is room for all daughters. But, once the library is full, the chains are competing for a scarce resource - the spaces in the chains library. Fit chains can find room to place a daughter on the list by removing the unfit

offspring of a less fit chain. Look for a period of genetic drift before selection kicks in. This is, perhaps, difficult to see in this implementation since the library is full after only five generations of chains experience fission.

- **COMPETITION FOR POWER** – I am uncertain that I have given the MPP a thorough work-out in the model as it currently stands. There is room for improvement. In the literature (See the Refs) it is implied that competition is for power sources. Energy absorbed per tick is power. As described in the paragraph immediately above, the chains compete for a slot in the library. I wonder if results would be different if the carrying capacity was determined by the size of the flow of energy into the heads, rather than the number of slots in the library. Suppose each time an OAM in class OAM01 discharged, the head immediately sought to recharge from a flow of energy and form an OAM00. Suppose the energy source had a steady flow of K Joules of energy into an endowment fund of energy, and suppose the number of slots in the library was really large, say 1,000,000 slots. Suppose the fitness test was environmentally based, such that those chains that failed to gather sufficient energy to lift the tail-load in the tick in which they captured energy would perish. Then too large of a requirement for priming energy would eliminate the 'whales' among the herd. Those that could take in the most energy and reproduce the fastest would survive, without the somewhat contrived business of computing fitness measures and selecting discards. In other words, it would be less of a breeding program, and more of a natural selection program. That needs some thought.

4.1.6   Things For Users to Try

- **SEEDS** - Note the behaviour of the system for the same scenario that differ only by different random seeds.
- **EXPERIMENTATION** - Explore some of the 36 possible scenarios. Alter the scenarios and some setup parameters, and note how the different averages and quantities react. E.g. keep your eye on drop time and fitness measures.
- **A VIEW INSIDE** - [NOTE: Do not let this run for a long time. It generates very large debug log files in a short time.] This is a four step process: (Step 1) Open the command centre by clicking on the teeny tiny upwards-pointing arrow at the bottom left of the screen. (Step 2) Then when the command centre appears at the bottom of the screen, click on the 'upsize' and 'clear' buttons at the top right of the command centre. (Step 3) Then use the debug button and the associated 'chooser' (scroll the view screen to the right to find these in panel 3) to turn on debug reporting for one or all of the steps. (Step 4) Click on 'one tick'. Then scroll through the debug info that has been written into the command centre log.
- **DATA EXPORT** - Right click on any of the graphs, and choose export. Or, open the command centre as described above, and in the observer command line input box at the very bottom of the screen, enter the command EXPORT-WORLD "filename.CSV", where filename is a name of your choosing. I suggest, that e.g. if the model is at tick 35, the filename might be "world35.CSV". The quotes are needed. Then, use MS Excel, or a similar spreadsheet to load that file. Every piece of data in the model will be found there somewhere in the output. Or, toggle on CSV data export for DPX (data per mutation event) or DPT (data per tick) output. These files can be loaded with MS Excel.
- **ALL OF THE WAY INSIDE** - There are key routines in the code that provide insight into how

the model operates. Go to the code tab and search for each of these routines: **f-assign-high-e-to-new-chain**, **fr-compute-energetics-of-oam**, **f-replicate-this-chain**, or **f-mutate-this-chain**.

4.2   Technical Perspective

4.2.1   Agent Based Models

OamLab is an agent-based model (ABM). There are three breeds of NetLogo agents that interact with each other – heads, bodies and tails – forming trophic chains. Each agent has attributes such as stored energy and genome that control its behaviour. Agents interact by rules governed by their genes and other attributes.

Attributes of Heads: The heads have three roles. As organisms (as HOAMs) they act as primary producers, receiving an initial endowment of energy from the Sun. The size of the endowment is determined by the **mass**. In energy transformations, they play a role as food (RH-HOAM) and are able to form an OAM only in that role. Information about OAMs is only maintained in the RH-HOAM. And, of course, they are the head of the chain. The key attributes of the heads are:

- `;; `**`Associated with chain.`**
- **`mas-sn`**`                  ;; serial number of parent chain.`
- **`chain-sn`**`                ;; serial number of this chain.`
- **`index-into-chains-lib`**`   ;; the index of this chain in `**`gl-chains-lib`**
- **`primed-rh-hoam-index`**`    ;; index of active RH-HOAM`
- **`primed-lh-hoam-index`**`    ;; index of active LH-HOAM`
- **`chain-time-to-drop`**`      ;; total time required to discharge all OAMs`
- `;; For these measures, the least fit has the lowest measure.`
- **`Mj-geo-this-chain`**`       ;; Geometric Ave of Mj of chain`
- **`Mt-geo-this-chain`**`       ;; Geometric Ave of Mt of chain`
- **`Eu-geo-this-chain`**`       ;; Geometric Ave of Eu of chain`
- **`fitness-measure`**`         ;; currently active fitness measure selected by chooser`
- `;; `**`Associated with HOAM.`**
- **`index-into-chain`**`     ;; the serial index (position) of this HOAM in the chain`
- **`mass`**`                ;; the mass in this HOAM`
- `;; `**`Associated with rh-hoam.`**
- **`oam-time-to-drop`**`     ;; time required for heavy mass to fall`
- **`age-to-discharge`**`     ;; age at which discharge is possible`
- **`energy-to-transfer`**`   ;; amount of high-grade energy to be transferred`
- **`energy-to-discharge`**`  ;; amount of low-grade energy to be exhausted`
- **`Mj-in-oam`**`            ;; Mj is joint fitness measure`
- **`Mt-in-oam`**`            ;; Mt is time fitness measure`
- **`Eu-in-oam`**`            ;; Eu is Odum's efficiency measure`

Attributes of Bodies: The bodies occupy all positons between the head and the tail. They feed on the HOAM to the right, and are food for the HOAM to the left. So, they are able to participate in an OAM in both RH- and LH- roles. All information about OAMs are maintained in the RH-HOAM. The key attributes of the bodies are:

- `;; `**`Associated with chain.`**
- `;; Nil.`
- `;; `**`Associated with this HOAM.`**
- **`index-into-chain`**`     ;; the serial index (position) of this HOAM in the chain`

- **mass**   ;; the mass in this HOAM
- ;; **Associated with rh-hoam.**
- **oam-time-to-drop**   ;; time required for heavy mass to fall
- **age-to-discharge**   ;; age at which discharge is possible
- **energy-to-transfer**   ;; amount of high-grade energy to be transferred
- **energy-to-discharge**   ;; amount of low-grade energy to be exhausted
- **Mj-in-oam**   ;; Mj is joint fitness measure
- **Mt-in-oam**   ;; Mt is time fitness measure
- **Eu-in-oam**   ;; Eu is Odum's efficiency measure

Attributes of Tails: The tails represent the final consumer in a trophic chain: apex predator, or decomposer, or detrivore. They are able to participate in an OAM only in the LH-HOAM role. All information about OAMs are maintained in the RH-HOAM, so none is stored here. The key attributes of the tails are:

- ;; **Associated with chain.**
- ;; Nil.
- ;; **Associated with this HOAM.**
- **index-into-chain**   ;; the serial index (position) of this HOAM
- **mass**   ;; the mass in this HOAM
- ;; **Associated with rh-hoam.**
- ;; Nil.

4.2.2   Verification, Validation, Simulation and Demonstration;

When a new computer model is constructed there are two ways to test it:

- **Verification** – Is the code free of error – does the software process data as intended?
- **Validation** – Is the model a valid simulation of reality?

A computer model can represent reality in two distinctly different ways:

- **Simulation** – The model is attempting to reproduce, with as much accuracy as possible, a data stream that can be obtained empirically from measurements in the real world. When simulation is sufficiently accurate, then the model may be used to predict future events from past events. Weather models, for example, are of this type. Usually they are built on macro-level mathematical models involving otherwise intractable differential equations.
- **Demonstration** – The model is demonstrating dynamic behaviour that is implicit in its design, and can be studied as a dynamic system in its own right. While the understandings gained from such studies may be applicable to real-world systems, there is no intent to use the model to duplicate empirical data streams obtained from real-world systems. The "Game of Life", or the study of "Finite State Machines" would fall into this category. Whereas few would argue that such models simulate, or even emulate, reality, they are clearly applicable, and the things learned in their study has been hugely informative. ABMs excel at this sort of modelling.

OamLab is NOT a simulation of anything. It is a demonstration of the dynamics that emerge out of the rules of random predation with digestion modeled using the mathematics of Atwood's Machine. That is all that it is. The process of "validation" of a model involves comparison of model output with real-world data. **OamLab** is not meant to be validated by comparing numeric output from this model to real-world data. The goal is NOT to replicate some stream of real-world data accurately. The goal is to generate data that exemplifies the interactions of such rule-based systems, so that the dynamic relationships between variables can be better

understood.

On the other hand, the process of "verification" of computer code is the process of finding and eliminating all of the bugs and programming errors. A computer program is considered verified if it has no logical bugs, and runs as intended. This application contains many hundreds of debug calls that are designed to find and eliminate all such bugs. As far as I know, the ecological engine of this application is 100% verified to be running as I intended. All design decisions are documented in detail in this document, and in the code itself, and all evidence of bugs of all sorts in the engine has been addressed.

So, I prefer to say that **OamLab** is not a simulation of any ecosystem that needs to be verified. Rather, it is a demonstration of the dynamics of a highly abstracted ecosystem, or economy.

4.2.3   Development Platform

I used NetLogo 5.0.5 for fast development. I got a working model up and running in seven days in early 2015. I have then returned to it many times to improve it as I learned how it worked.

4.2.4   Maximum Power Emergence

The goal was to study the evolution of trophic chains in a simple ecosystem (or supply chains in a simple economy). As discussed above, I have used Atwood's Machine as a source of information about a typical energy transformation. But, when working with the AM as a model there are at least three different "power vs efficiency" curves that can emerge. Two of these curves peak at intermediate levels of efficiency, as described by Odum (1955), but the third one

(the red one) peaks at efficiency of $\eta = 0$. (See Figure 03, which is explained in detail in Ref E. Each small red point in this fingerprint graph represents a combination of power and efficiency for a different set of weights.) Each of the three highlighted sets of points depends on the lab procedure used to vary the weights in the AM when building the curve:

Figure 03 – Fingerprint Graph – The AM

- If the sum of the masses M_t is held constant and M_H and M_L are varied in conformance with that constraint, we get the blue curve for which power peaks at $\eta = 0.5$ as described by Odum and Pinkerton (1955).
- If we hold M_H constant, and vary M_L from 0 to M_H, then we get the green curve for which power peaks at $\eta = 0.618$. Curiously, this is $\eta = (1 - \tau)$ where $\tau = 1.618$ is the golden mean. This is the result as described by Silvert (1982).
- But, if we hold M_L constant, and vary M_H from M_L to ∞, then we get the red curve, for which
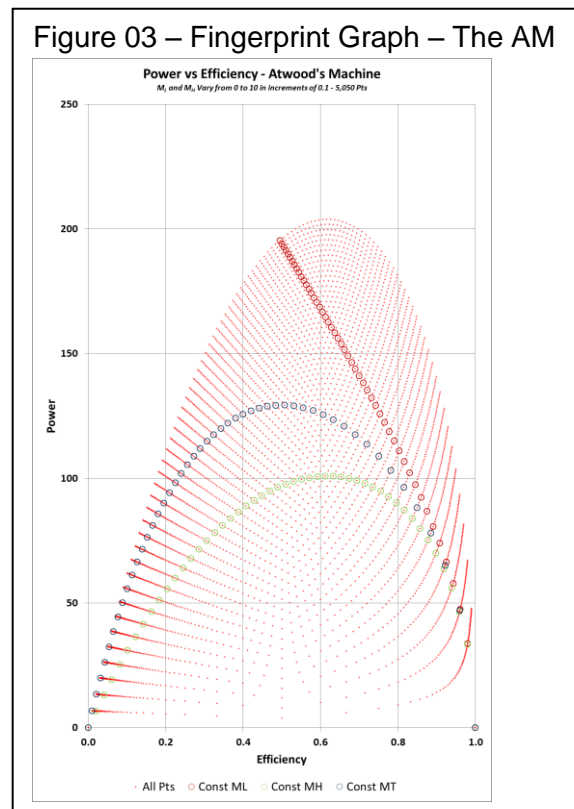
power peaks at $\eta = 0$.

Clearly other constraints on the way the weights are varied in the laboratory can produce other more exotic curves through the points in the two-dimensional fingerprint graph. My intuition after researching these curves was that those for which power peaks at some intermediate efficiency are characteristic of persistent phenomena, and those for which power peaks at either $\eta = 0$ or $\eta = 1$ would not result in persistent systems.

In **OamLab** the efficiency of a mature stationary state system is $\eta = 0.618$. But in **MppLab**, the efficiency of a mature stationary state system is $\eta = 0.5$. But, it was not always thus for all scenarios. In my first implementations for both models, the systems quickly evolved to a condition of $\eta = 0$ and the ecosystems collapsed. I argue that they evolved along the red curve towards a condition of maximum power and zero efficiency, at which point they become unsustainable. My intuition is consistent with the results of these two models. There appears to be a variation of the anthropic principle at work here. We know that all persistent systems that we see in the world must operate at some intermediate efficiency because, if they had extreme efficiency of either kind, they would not be persistent. The mere fact of their existence and persistence argues that they must function at intermediate efficiency. This has major implications for economic theory, I would think. These models probe the way in which such power vs efficiency curves shape the nature of the ecological and economic systems in which we live, move, and find our own means of persistence.

4.2.5   Structural Design concept

- A set of up to 30 linkable chains of HOAMs is placed in 30 slots in a library (enumerated list) for chains. Each chain contains from 3-14 HOAMs, for a total of no more than 420 HOAMs, and 390 potential OAMs.
- Suppose there are N HOAMs per chain. Name the masses in each linked set M_0 through M_{N-1}.
- Call the HOAM with mass M_0 the head of the linked chain.
- Call the HOAM with mass M_{N-1} the tail of the linked chain. All tails have a mass of $M_{N-1} = M_{min}$ (default is 16).
- The drop within each OAM is D = 100 metres.   This is the default value of the parameter **g-drop-distance**.
- Use a value for g of 10.0 m/s^2. This is the default value of the parameter **g-acceleration**.

The size of the **mass** placed in the tail, and how it is managed, is a design issue that has some theoretical implications. I would predict the following:
- If M_{tail} is allowed to float freely during a run, it will evolve in a direction that maximizes fitness.
- If M_{tail} is fixed for all chains at some value other than 0.00 that would determine a kind of target load that the chain must support. This makes sense to me. E.g. if photosynthesis must support root development, and root development requires a certain amount of power (energy per second), then the energy storage and transport mechanisms must be able to

support that power of delivery.
- If M_{tail} is fixed at zero, then the goal is zero 'useful' power, and all OAMs can function at almost zero efficiency.
- If M_{tail} is fixed at close to M_{max}, then the goal is almost perfect transfer of all energy, but it will happen very slowly.

There is a trade-off between speed of completion, and load delivered. The faster the delivery, the less energy can be delivered. But, the higher the requirement for energy, the slower is the delivery. So, the design issue is, how do I set the fitness measure for which chain lives, and which dies, without biasing the answer towards the MPP-predicted answer? I am, of course, not at all certain that I have resolved that issue in this model. I have left active a number of tools that I used to explore that issue, in the form of switches and things that can create special scenarios.

4.2.6 Initialization concept
Sliders allow the user to set the initial number of chains in the library, up to 30 chains, and the length of each chain, up to 14 HOAMs. Also, the user can select a different value for D and g. Switches allow the user to enable or disable mutation of each of heads and tails. The "Setup" button then populates the field with the chains of the right sort as per the above choices. When the "Setup" button is pressed, the model will be initialized, masses assigned to each HOAM, and the dynamic attributes of each potential OAM and each chain calculated. Depending on the scenario chosen, it can happen three ways:
- **High efficiency scenario**: Start at the tail. M_{N-1}=16, For all others, E_U=0.90 and $M_n=M_{n+1}/E_U$.
- **Low efficiency scenario**: Start at the tail. M_{N-1}=16, For all others, E_U=0.10 and $M_n=M_{n+1}/E_U$.
- **Randomly mixed scenario**: Start at the tail. M_{N-1}=16, For all others, E_U = a random number between 0.10 and 0.90 and $M_n=M_{n+1}/E_U$.

An initial endowment (a charge) of energy is then given to the head of each of the chains of HOAMs. This is implicit, and is equal to $M_0{\times}g{\times}D$.

To Setup: Initialization of the chains library is effected by running the "to setup" routine which does the following"
- Clears away all vestiges of the previous run in the form of agents, global variables and data stored in plots.
- Re-establishes:
  - Version number
  - Reseeds the PRNG
  - Status of the debug and CSV export files
  - All of the administrative structures and variables needed to support a run
- Builds the new library of chains according to the settings in the current controls
- Resets the model's tick manager to the beginning (tick = 0)
- Updates all of the aggregates used to populate the monitors and graphs

4.2.7   Operational Design concept

There are two modes of operation for a run: Horse race on, or horse race off.

Horse Race On: When a run starts, all chains will begin processing their energy at the same time and will process energy in parallel with all other chains, but progressing at a speed consistent with the time-to-drop characteristics of the active OAMs. Active OAMs are coloured yellow to make them visible. As the energy moves down each chain, the moving yellow markers look vaguely like horses in a race, ergo the name of the mode of operation.

From the perspective of a chain, processing within one chain will proceed as follows:
- Starting at the head with n=0, $HOAM_n$ and $HOAM_{n+1}$ will be linked to form an OAM_n in which $M_n > M_{n+1}$ and $E_U = M_{n+1}/M_n$
- Using the formula for time to drop (T_d) in Ref B, compute the time, in seconds, for this OAM to discharge, record the high-grade energy transferred from $HOAM_n$ to $HOAM_{n+1}$, and record the low-grade energy exhausted to sink. These calculations need to be done only once per OAM constituted, but the data can be stored in the OAM agent for use when needed on each tick. It will be needed when the time T_d is up, and this OAM is taken apart and the next OAM in the chain is constituted. I will implement this by aggregating the time to drop across all previous OAMs, and storing that as a **time-of-discharge** variable. When the variable ticks of the ABM clock passes this time, the OAM discharges and the next OAM is constituted (the yellow markers move).
- In other words, when time T_d is completed, discharge the waste heat from this OAM, disassemble this OAM, increment n, and use the LH-HOAM, to link with the next HOAM in the chain.
- Loop until the last HOAM in the chain is charged.
- All energy in the last HOAM is treated as waste heat and discharged.

However, the model steps forwards in discrete ticks, so from the perspective of a programmer, it happens like this. There is a sub-routine called "**To Go**" which is executed once per tick. It calls three sub-routines once each, per tick, in order, as follows: **to do-pre-tick**, **to do-check-chains**, and **to do-post-tick**.

4.2.7.1   To do-pre-tick

This is a purely administrative sub-routine that performs a few necessary house-keeping activities that are necessary at the beginning of each tick:
- The tick counter is advanced by one
- The status of CSV output files is checked and managed
- The chains are aged by one
- The "per tick" data collection variables are zeroed and readied for new data

4.2.7.2   To do-check-chains

This calls one of two main sub-routines:
- f-check-one-chain-hrmode-on
- f-check-one-chain-hrmode-off

Hr Mode On: Chains are checked in random order:

- Each chain has an active OAM consisting of two HOAMs, on in the RH-HOAM (prey) role, and the other in the LH-HOAM (predator) role. These two HOAMs are coloured yellow in the arena in Panel 01. The information about the OAM is stored in the RH-HOAM. The active OAM in the chain will be checked, and:
  - If '**ticks**' is less than the OAM's **time-of-discharge** variable, nothing happens.
  - But if '**ticks**' is greater than the **time-of-discharge** variable, then waste heat is discharged, useful heat is transferred to the LH-HOAM priming it for a new role, the OAM is disassembled, and the next OAM is assembled, and the heavy recently primed **mass** starts to move.
- If there are no more OAMs to be assembled, i.e. if at the end of the chain, then this chain can reproduce itself:
  - The mother chain is discarded.
  - Two offspring chains are created as copies of the mother, one to replace the mother, occupying the same slot in the library, and one to place in a new slot in the library. If there is no empty slot on the library, the least fit chain is removed, and the second daughter is placed in the empty slot.
  - Each daughter chain has one randomly selected mass mutated.

Hr Mode Off: In this mode, I abandon the horse race visual effect for two reasons. First, it is very slow.   Second, and more importantly, it may introduce some bias or noise such that the evolution is affected.

When the horse race mode is turned off, I simply calculate the fitness of all chains, select half of them for discard, and cause the other half to reproduce by fission and fill the slots removed. All energy consumed used to update the "per tick" statistics. This is clearly a "breeding program" for chains, and uses very un-natural selection, but it does cause the system to evolve in some fashion.

Either Mode: Chains will compete for survival by processing energy. The MPP predicts that the chain most fit for survival will have masses where $M_{n+1}=M_n/2$. I.e. if M_{tail} is fixed at 16, then the ideal chain, the most fit chain, will have $M_{head} = 512$, $M_1 = 256$, $M_2 = 128$, $M_3 = 64$, $M_4 = 32$ and $M_{tail} = 16$. This is the 6-HOAM chain that can deliver the required load most quickly at maximum power.

4.2.7.3   To do-post-tick
This is another administrative subroutine.   DPT (data per tick) data is sent to file, if enabled, and all aggregates are updated and made ready for display.

4.2.8 Equations for OAM operation
The fundamental equations of interest, taken from Refs B through E, are:

The base time to drop (T_b) for an HOAM that is uncoupled is:

$$T_b = \left(\frac{2D}{g}\right)^{1/2}$$

| | Equ 01 |

Note that, as discovered by Galileo, this is independent of the masses.

The time to drop (T_d) for an OAM:

$$T_d = \left(\frac{2D}{A}\right)^{1/2} = \left(\frac{2DM_t}{gM_d}\right)^{1/2} = T_b\left[\frac{1+\eta}{1-\eta}\right]$$

| | Equ 02 |

The total energy in the RH-HOAM (W_t) prior to release of M_H is:

$$W_t = DgM_H$$

| | Equ 03 |

Kinetic energy which becomes waste heat (W_e), is:

$$W_e = \left(\frac{M_t}{2}\right)\left(V_f{}^2\right) = \frac{M_t}{2} \times \frac{2DgM_d}{M_t} = DgM_d$$

| | Equ 04 |

The gravitational potential energy transferred to the LH-HOAM (W_u) is:

$$W_u = DgM_H - E_K = DgM_L$$

| | Equ 05 |

Note that $W_t = W_u + W_e$. That is to say, the total energy endowment before a 'run' of the AM is equal to the 'useful' energy saved for later plus the energy expended when the heavy mass smacks down on the floor.

4.2.9 Equations for Fitness Testing of OAMs

In the version 1.03 prototype I only tested fitness based on the total time for a chain of HOAMs to discharge. The efficiency always fell to zero in a long run, and the system became dysfunctional, or non-persistent. In retrospect, this made sense. So, I needed to devise a fitness test that both minimized time to discharge and maximizes useful energy. These two goals are in opposition, since as time to drop (T_d) approaches a baseline shortest time (T_b), the usable energy (W_u) drops towards zero, and as the usable energy climbs towards higher numbers, the time to drop grows very large.

In the back of my mind I have this idea that life has two distinctly different modes of operation when it comes to the use of 'useful' energy.
- When going through the daily functions of life such as growing, eating or just moving around, evolution has made most organisms extremely parsimonious with energy. Little or nothing is wasted, if it can be helped.
- But when it comes to reproduction, most organisms are profligate spenders. They spend

energy on dimorphic display tools, nest building, long stints of time without food, etc. and then they produce far more offspring than have any reasonable expectation of survival. The consumption of the immature offspring of such organisms is a major source of energy for most predators, and a major means of passing still useful energy on through the trophic web. The 'useful' energy of the organisms is stored and spent on the offspring, and they become the primers for the HOAMs of the predators, and of the HOAMs which are the next generation of their own species.

So, what are the criteria on which evolution is working? The faster one gets to reproductive age, the better the opportunity to push other organisms out of their occupied ecological niches. So, short time to drop is a good fitness test. But, speed to reproduce is only half the tale. Maximization of energy passed on to offspring is the other half of the tale. If an organism spends all of its gathered energy eating and walking around, there is nothing to put into offspring.

At Ref I Odum defined efficiency in terms of 'useful energy' storage, and in this model, and this document, E_u is one of two symbols I use for efficiency:

$$E_u = \eta = \frac{W_u}{W_t} = \frac{M_L}{M_H}$$	Equ 06

If the only fitness test is for minimum time to drop, the efficiency always ends up at zero. But, if the only fitness test is maximized efficiency of use of energy, the time to drop grows exponentially. I needed a fitness test that both shortened time to drop and maximized energy retained for later use. I came up with three alternate fitness measures that are implemented in the model:

- **M_t – Measured on time to drop** – Form a ratio of T_d / T_b. This ratio will always be greater than one, and will rise as an OAM is less fit. But, the reciprocal of this ratio will always be in the interval [0, 1], and will rise as the OAM is more fit, from the perspective of time to drop. Define M_t as $M_t \equiv T_b / T_d$.
- **E_u – Measured on energy efficiency** – E_u, as defined by Odum and Pinkerton (1955), will always be on the interval [0, 1], and will rise as the OAM is more fit, from the perspective of energy efficiency. Define E_u as per Equation 06.
- **Mj – Measured on both energy efficiency and time to drop** – The product of M_t and E_u will always be on the interval [0, 1] and will rise as the OAM is more fit, from the perspectives of both time and energy. Define M_j as $M_j \equiv E_u * M_t$.

An alternate definition of M_j was trialed but discarded. Let α be a number from the interval [0, 1], then define M_t as $M_t \equiv \alpha M_u + (1-\alpha)M_t$. I discarded this because I was uncertain whether finding the 'right' α was too much like fixing the experiment. Is there one α for which the MPP is supported, and others for which it is not? It was too arbitrary. But, on the other hand, so is a simple product of the other two fitness measures. Is there some empirically deducible formula for M_j?

The detailed equations for these fitness measures are as follows:

M_{time}:

| $$M_{time} = \frac{T_b}{T_d} = \left(\frac{M_d}{M_{total}}\right)^{1/2}$$ | Equ 07 |

Note that, in these equations, the two different meanings of my symbol M_t appear, so I indicate which is which.

E_u: Given in Equation 06.

M_j:

| $$M_{joint} = E_u \times M_{time} = \frac{M_L}{M_H}\left(\frac{M_d}{M_{total}}\right)^{1/2}$$ | Equ 08 |

The alternate possibility for M_j was:

| $$M_j = \alpha E_u + (1 - \alpha)M_{time} = \alpha\frac{M_L}{M_H} + (1 - \alpha)\left(\frac{M_d}{M_{total}}\right)^{1/2}$$ | Equ 09 |

All of these seem like rather contrived measures, but they are contrived on the basis that the 'most fit' model of an organism is one which (a) reproduces quickly and (b) passes on as much useful energy as it can (to offspring, and to predators), and there is a trade-off between these two opposing demands.

4.2.10 Equations for Fitness Testing of Chains

However, those measures operate at the level of OAMs, and OAMs are formed temporarily within chains of HOAMs. So, to be applicable in the context of systems of competing system-wide processes, I need to form stable chains of HOAMs, and then compute these fitness measures at the level of the chain. I need chain-level fitness indices. Again, I want these fitness measures to be defined on the interval [0, 1] so I can daisy-chain them by calculating means, and they remain within the same interval. Then measures of fitness are comparable regardless of the length of the chain or the method of calculation. For example, I can achieve this by taking the geometric mean of the fitness measures of the n OAMs in a chain. [Again, I tried two options (arithmetic mean and geometric mean) and the geometric mean showed the most promise.]

Let x represent one of the types of fitness measure j, t or u. Let M_x^n denote the fitness measure

for the nth OAM in a chain of N+1 HOAMs that can form N OAMs; where 0 <= n <= (N-1).

Then define the fitness measure for a chain as:

$$M_x^{chain} = \left[\prod_{n=0}^{N-1} M_x^n \right]^{1/N}$$	Equ 11

This simplifies for some, and not for others. For example, the chain-level version of E_u is:

$$E_u^{chain} = \left[\prod_{i=0}^{N-1} \frac{M_L}{M_H} \right]^{1/2} = \left[\frac{M_u^0}{M_u^{N-1}} \right]^{1/N}$$	Equ 12

In other words, if we use Odum's definition of efficiency for an OAM and extend that to a chain, we get the interesting fact that the fitness of the chain is independent of all of the in-between HOAMs and only dependant on the mass in the head and the mass in the tail. What happens inside the chain is not relevant. This leaves a lot of freedom for variation with the chains while maintaining a focus on the overall efficiency. How can we interpret this in practical terms? For a trophic chain in an ecosystem, or a supply chain in an economy, if all of the links in the chain are highly efficient (causing a little degradation of energy or capital as possible) then the chains can be very long and still deliver a significant payoff (in still useful energy, or still useful capital benefits) to the end of the chain, and it does not matter how long it takes to deliver the payoff. This might describe the supply chain for coal, oil and gas. Clearly efficiency has a role, both in ecology and in business, but it has a problem of timing. I am reminded of the old saying "The wheels of government grind slowly, but exceedingly fine!". Quality of process has a cost in time.

The geometric mean does not simplify, as far as I can tell, for the other two measures, and must be computed from the values in the OAMs.

This approach seems to work quite well, but does not give exactly the answer expected. The efficiency of an unconstrained system of chains does converge, when using the M_j fitness measure, but to the value of ~0.618 instead of 0.500. This discovery led to the exercise that brought to light the arguments of Silvert (1982), and, ultimately, my fingerprint graph shown in Figure 03.

4.2.11   The Issue of Mutation

Mutation happens during reproduction. When mutating a chain, I alter one and only one of the HOAMs within the chain. I select a random HOAM in the chain and alter its **mass** by a small but appropriate amount. The difficult question is "How much do I change the **mass**, and in what direction?" There were two aspects to this question that needed attention:

- The result has to be bracketed by the masses on the left and right. That is, I do not want to create a totally dysfunctional chain by breaking the pattern of declining masses along the chain. When a **mass** changes it will be stepping towards those two bracketing masses, but it must not overstep them.

- I must not get into an infinite loop of cyclic changes which would result if the probability of a reduced fitness as a result of a mutation is far greater than the probability of increased fitness. This is a matter of granularity – a matter of sensitivity to a sweet spot – a matter of approaching a stationary state with enough care that good mutations are not lost in the noise of random mutations. In other words, it's a matter of scaling the changes.
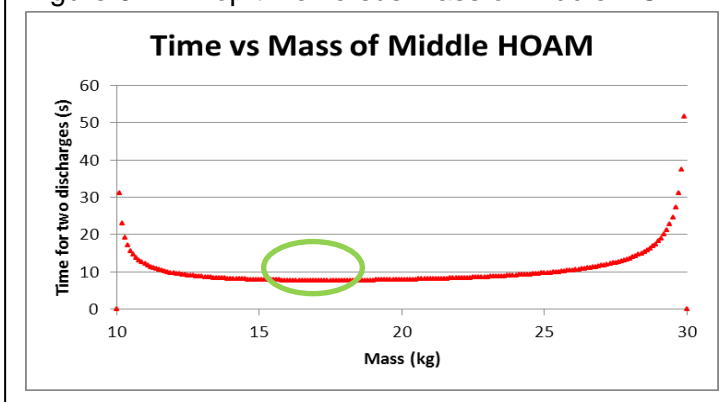
So the question is, by how much should the **mass** change? If I go too far in one step, I may overstep the brackets, or overstep the sweet spot by a noisy amount.

I put together a spreadsheet to examine the issue. When a single HOAM suffers a mutation only the two OAMs in which it can participate are affected, and all others remain the same, with the same drop time, efficiency, power, and other dynamic characteristics. So, I can focus on the effects on the two affected OAMs, and the three HOAMs that participate in those two OAMs. Consider 3 HOAMs in a row, the previous HOAM, this mutated HOAM in the middle, and the next HOAM. I will be modifying the mass in the middle one. If this one is a head or tail, then there is no previous HOAM or next HOAM respectively, but I still want to be able to adjust the mass up or down. Those are special cases (see the code tab in the Ref A file for details) but not described here. So, for this general example, the centre HOAM is neither the head nor the tail. To make the formulae understandable, however, I need to be able to distinguish between OAM-related characteristics across two OAMs, and HOAM characteristics across three HOAMs. Without loss of generality (WLOG), let the HOAMs be numbered 2, 3 and 4, with decreasing mass as the number climbs.

For this exercise, I must change my notation slightly. Then:

Figure 04 – Drop time versus Mass of Middle HOAM

- Let M_2 be the **mass** of the previous HOAM. Let M_3 be the **mass** of the middle HOAM in which the **mass** will be changed. Let M_4 be the **mass** of the next HOAM.
- We know that $M_2 > M_3 > M_4$.
- Denote the OAM formed by the previous and middle HOAMs as $OAM_{2\leftrightarrow3}$, and denote the OAM formed by the middle HOAM and the next as $OAM_{3\leftrightarrow4}$.
- Denote the efficiency of $OAM_{2\leftrightarrow3}$ as $E_{2\leftrightarrow3}$, and the efficiency of $OAM_{3\leftrightarrow4}$ as $E_{3\leftrightarrow4}$.
- Denote the time required for discharge of $OAM_{2\leftrightarrow3}$ as $T_{2\leftrightarrow3}$, and the time for discharge of $OAM_{3\leftrightarrow4}$ as $T_{3\leftrightarrow4}$.
- Then the total time required for discharge of both $OAM_{2\leftrightarrow3}$ and $OAM_{3\leftrightarrow4}$ in that order is $T_{2\leftrightarrow4}$ = $T_{2\leftrightarrow3}$ + $T_{3\leftrightarrow4}$.

Substituting from Equation 02 above, I get this equation for the drop time $T_{2\leftrightarrow4}$:

$$T_{2\leftrightarrow4} = \left(\frac{2D}{g}\right)^{1/2} \left[\left(\frac{M_2 + M_3}{M_2 - M_3}\right)^{1/2} + \left(\frac{M_3 + M_4}{M_3 - M_4}\right)^{1/2}\right]$$

Equ 13

I put this into a spreadsheet and got the graph shown in Figure 04. Here, WLOG, M_2 = 10, and M_4 = 30, and M_3 is allowed to vary from M_2 to M_4, and $T_{2\leftrightarrow4}$ calculated for each M_3.

If M_3 is close to either of the masses that bracket it, the combined time to drop of the two OAMs in which it participates rises dramatically. There is a sweet spot at about M_3 = 17.4 where the combined time to drop is minimized. Suppose M_3 has some random value in the allowed range, and suppose it was altered upwards or downwards by ¼ of the distance to the bracketing mass in that direction. Then the total time to drop will be altered. If short time to drop plays any role in a fitness measure, then masses closer to the sweet spot will contribute to a higher fitness measure for the chain as a whole. Based on this, for most values of M_3, if it changes by a random amount less than a quarter of the distance to the next mass, up or down, any step in the wrong direction would immediately reduce fitness measure, and the chain would be at risk of elimination. Over time, a reasonable percentage of mutations would be good. Since reproduction is by fission, there are two daughters per reproductive event, and, on average, one of the two would be more fit than the parent. The less fit daughters of the less fit parents would be quickly eliminated from the library of chains, and the system would converge to the most fit at a reasonably fast pace. I think this approach gives reasonable control over the noise of random mutations.

Figure 05 – M_t for two OAMs vs Mass of middle HOAM
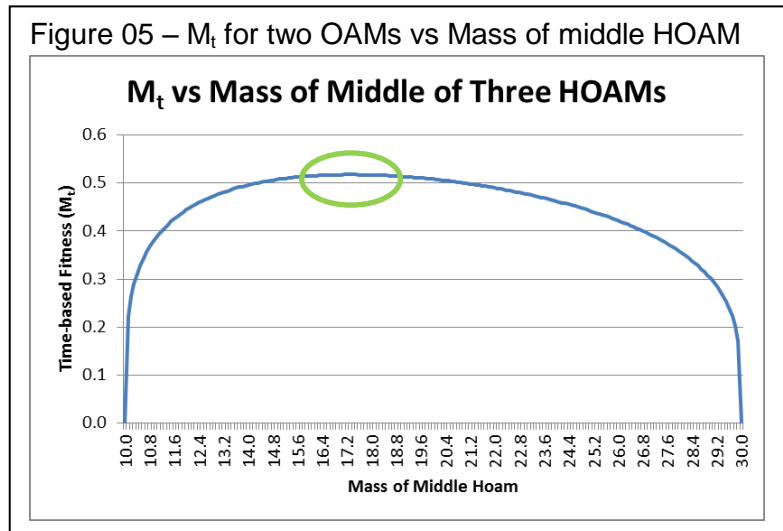
Another way to look at it is to analyse the effect of such a mutation on the fitness measure M_t itself. If the time fitness measure of one OAM is M_t^{OAM} then the fitness measure of two side-by-side OAMs taken together is:

$$M_t^{2\leftrightarrow4} = \sqrt[2]{M_t^{2\leftrightarrow3} \times M_t^{3\leftrightarrow4}}$$

Equ 14

Substituting from equation 7 into 14, with a suitable change of notation, I get:

Equ 15

$$M_t^{2\leftrightarrow4} = \sqrt[2]{\left(\frac{M_2 - M_3}{M_2 + M_3}\right)^{1/2} \times \left(\frac{M_3 - M_4}{M_3 + M_4}\right)^{1/2}}$$

While the variable $T_{2\leftrightarrow4}$ directly contributes to the drop time of the chain as a whole, this fitness measure fragment directly contributes to the fitness measure M_t^{chain}. If you find the derivative of equation 15 and set it equal to zero, then solve for M_3, you get $M_3 = \sqrt[2]{M_2 \times M_4} = \sqrt[2]{300} = 17.3205$. So, it would appear that changes in the time fitness measure target the same sweet spot as the total drop time. I.e. the extremums of both functions appear to be in the same place.

When I consider Odum's efficiency as a fitness measure, however, the situation is different.

$$E_u^{2\leftrightarrow4} = \sqrt[2]{\frac{M_3}{M_2} \times \frac{M_4}{M_3}} = \sqrt[2]{\frac{M_4}{M_2}}$$	Equ 16

The energy fitness measure taken over the two affected OAMs is a constant, independent of M_3, the mass of this HOAM. So, any mutation to the mass in the in-between HOAM has no effect on the combined energy fitness of the pair of OAMs in which it can take part, and can have no effect on the overall fitness of the chain as a whole. This is consistent with equation 12, of course, and is merely the same effect on a smaller scale. But, this means that only the mutations of heads and tails is of consequence when the efficiency measure is used alone. [I think this has some serious implications for economic supply chains that focus on low cost, such as the Walmart approach to business.]

Based on this, I would speculate that, if the heads and tails were all at common standard values at start, and if the energy efficiency fitness measure were used, and if heads and tails cannot mutate, then the masses of the body HOAMs would perform some kind of random walk with a wide spectrum of variations. But, in THAT case, my 'horse-race' technique for deciding who reproduces when, would apply a secondary time-to-drop fitness measure implicitly, and those chains with the shortest time to drop would dominate the field, all having, nevertheless, the same energy 'fitness'. Does this imply a hidden bias towards the survival of some chains, when their 'phenotype' interacts with the 'environment' in an unexpected way altering their probability of survival? Indeed, it does! And, in what direction is the bias? It will drift in a direction towards shorter overall time to drop for the chain, towards a larger ratio of 'mass of head' over 'mass of tail', and towards a smaller overall efficiency. This is why I abandoned the horse race, as cute as it is.

4.2.12 Sources of bias
Experiments with the model have shown that there are potentially three visible effects of hidden bias in the system as described so far:
- 1st – when (a) both heads and tails are allowed to mutate, and (b) the joint fitness measure is used, and (c) the system has reached a steady state, then there is a very slow and long-term drift towards smaller masses. This implies that the above-described joint fitness

measure has a very small bias towards smaller masses.

- 2nd – when (a) at most, one of heads or tails is allowed to mutate, and (b) the joint fitness measure is used, and (c) the system has reached a steady state, then the OAM-level and the chain-level efficiencies of the system all converge to a value of ~0.618 as discussed by Silvert (1982) rather than ~0.5, as predicted by Odum and Pinkerton (1955). This implies that the above-described fitness measure has a strong bias towards a 'sweet spot' of 0.618, or, that Odum did not have it quite right in 1955.

- 3rd – as described in the paragraphs immediately above, I speculate that when (a) neither heads nor tails can mutate and all are of the same value, and (b) the energy efficiency fitness measure is applied, then a hidden small bias towards chain-level shorter time to drop will select for those chains having the minimum time to drop, while respecting the enforced efficiency.

4.2.13   Aggregates

It is always difficult to decide how to get visibility into what is happening when there is, in fact, nothing visible happening.   The best way is in real-time graphs, and NetLogo is pretty good for that. In the background I have placed a number of aggregators. Some are embedded in the head HOAMs and are used to store chain-level aggregates per chain. Most exist in parallel to the library of chains, and exist as lists of characteristics of HOAMS in the library. Here's a list of all lists used in the code, with description of their uses. Some are display aggregates, others are not:

Global lists with 30 entries:
- `gl-chains-lib`   ;; the library of all chains, with slots for 30 chains
- `gl-chains-indices`   ;; a list if indices into gl-chains, used for ref and access

Global lists with one entry per HOAM, aggregated across HOAMs (organisms).
- `gl-new-chain`   ;; a list in which a new chain is constructed during reproduction
- `gl-ttl-lg-nrg-per-hoam`   ;; list; total of unusable energy
- `gl-ttl-mass-per-hoam`   ;; list; total mass per class of HOAM
- `gl-ttl-hg-nrg-per-tick`   ;; list; total usable energy throughput
- `gl-ttl-lg-nrg-per-tick`   ;; list; total of unusable energy throughput

Global lists with one entry per OAM, aggregated across OAMs (feeding events).
- `gl-ttl-hg-nrg-per-oam`   ;; list; total of high grade still usable energy
- `gl-pi-Mj-per-oam`   ;; list; product of joint fitness measures
- `gl-pi-Mt-per-oam`   ;; list; product of time fitness measures
- `gl-pi-Eu-per-oam`   ;; list; product of Odum Efficiency measures
- `gl-geo-Mj-per-oam`   ;; list; Geometric Ave of joint fitness measures
- `gl-geo-Mt-per-oam`   ;; list; Geometric Ave of time fitness measures
- `gl-geo-Eu-per-oam`   ;; list; Geometric Ave of Odum Efficiency measures

These two kinds of aggregators (per chain aggregates in heads, and per class aggregates in aggregators) are the source of data in most of the graphs and monitors in the application.

4.3   A Next Model?

What would a next model look like?

4.3.1   Free-Floating HOAMs

Chains of OAMs are not natural. Metabolic pathways in cells form webs, in which a particular type of molecule may take part in several pathways, forming part of many possible chains.

Trophic webs include species such as mice or foxes that can be eaten by, and do eat, many species, forming part of many possible chains. Economic agents deal with many other economic agents, existing in webs, and forming part of many possible supply networks. So, a more realistic, more natural, model might have freely associating HOAMs in place of these that are tied to the chain in which they are born.

Such freely associating HOAMs must interact and transfer energy in appropriate ways. If I use an ecosystem as the primary template, then an HOAM represents an organism. To be 'charged' or 'primed' the HOAM must link as an LH-HOAM to an already primed RH-HOAM. I.e., it must eat another already-energized HOAM. Some HOAMs must get their energy directly from sun-light. So, the 'heads' in the current model represent autotrophs. The 'body' and 'tail' HOAMs in the current model represent heterotrophs. The tails are at the top of the food chain. So, a model with freely associating HOAMs might have three species, or 'breeds' in NetLogo language: plants, herbivores and carnivores (perhaps).

There are a number of tricky design issues that would have to be resolved with careful attention to unintentional bias:
- How does an autotroph feed?
- How does a heterotroph decide which HOAM to consume? Clearly two criteria are (a) bigger mass; and (b) already primed with energy. Does it also look for an energy-efficient connection? Does it look for fast digestion (short time to drop)? Does it look for a trade-off? Is there some way to genetically code such search characteristics such that evolution makes the decision implicitly, and we can avoid a 'breeding program' and see actual evolution under natural selection? That would be best, as it would not bias the outcome towards the expected outcome. But it raises other issues.
- If the selection for survival is not based on calculations of time to drop or efficiency, then what is it based on? Old age? Starvation? Age of reproductive maturity? Health? All of these? We are starting to talk about a model very similar to **PSoup** and **ModEco** style eco-models.
- Only the 'usable' energy in the eaten HOAM is transferrable to the 'eater', and the HOAMs remain linked while digestion transpires – that is throughout the many ticks of the drop time.
- There is a curious non-intuitive topsy-turvy aspect to this concept, since there must be a multitude of large mass high-energy HOAMS that eventually feed a small number of small-mass tail HOAMS. The problem comes from the nature of Atwood's Machine, in which high-energy means large mass. In nature, high-energy means sugar, fat, starch or protein. Size is not the issue – more so its energy density. I suppose an amoeba could eat a sugar molecule as easily as it can eat the metabolites of such, from the perspective of physical size. So, in this model, mass would not be intended to be analogous to large size, but rather, analogous to large energy density.

4.3.2   Natural Carrying Capacity
In this model the carrying capacity of the system is determined explicitly by fiat at 30 slots.

I would prefer a model in which the carrying capacity is determined implicitly by rate of energy

input and rate of energy consumption. At steady state, the energy input and energy output per tick should be equal. Then the energy consumed per HOAM per tick, when summed across all HOAMs, would equal the overall throughput. If I show the average by angle brackets <> then the conservation of energy equation would look like this:

$$E_{Input} = E_{Output} = \sum_{OAMs} \langle \frac{E_{Expended}}{DropTime} \rangle = \sum_{OAMs} \langle \frac{M_d g D}{\left(\frac{2DM_t}{gM_d}\right)^{1/2}} \rangle = \sum_{OAMs} \langle \sqrt[2]{\frac{(M_d g)^3 D}{2M_t}} \rangle \qquad \text{Equ 17}$$

Equation 17 assumes that all HOAMs are in OAMs at the time of census, i.e. at the time the average is taken. Okay. That's an acceptable assumption, I guess. This boils down to E_{Input} = N_{OAMs} * C, where C is the average shown. Supposing that I could calculate that average, without reference to a specific case (a big supposition) then the number of OAMs supportable at carrying capacity is N_{OAMs} = E_{Input} / C. Then an additional number of HOAMs would be unlinked – say K HOAMs. Then the total number of HOAMs at carrying capacity would be $N_{HOAMs} \cong$ (2 * E_{Input} / C) + K. C may not be constant, but even if it drifts, there will be a practical value that can be determined empirically at any tick, and that might be interesting to know.

4.3.3 Operation

So, during each tick E_{Input} Joules of energy arrive and as many autotrophs as are hungry and not linked absorb energy and are primed, re-primed, or partially primed. When sunlight is insufficient to feed all, some go unprimed. Those that have exhausted their energy and have not yet reproduced die of starvation. If they are older than the age of maturity, they reproduce via fission. If they are older than the age limit, they die of old age and the energy is exhausted

Also, during each tick, the heterotrophs that are linked into OAMs continue to be linked. Those OAMs that complete a discharge separate, the LH-HOAM continuing to live, the RH-HOAM dies, having been eaten. Any HOAM that lives to reproductive maturity goes through fission, giving half its energy to each daughter, and then dies.

HOAMs that are unlinked, or LH-HOAMS, have a small metabolic cost of EPA Joules per tick, MAYBE. Maybe this is not needed. It would prevent latent HOAMs from sitting and living forever.

So, to propagate its genes, an HOAM would need to live to maturity, and pass on energy to its offspring, while eating other HOAMs.

4.3.4 Why?

Would the system self-organize into a web of species (HOAMs of different sizes) with average efficiency of η <= 0.5, as predicted by Odum and Pinkerton (1955)?

5 Summary

The application was ready for more serious research into its behaviour as of 150128, and revised substantially as of 170401. The more advanced version of the model, discussed above, was implemented and is called **MppLab**.

6   ANNEX A – User Interface Panels

6.1   Panel 01 – The Main Panel
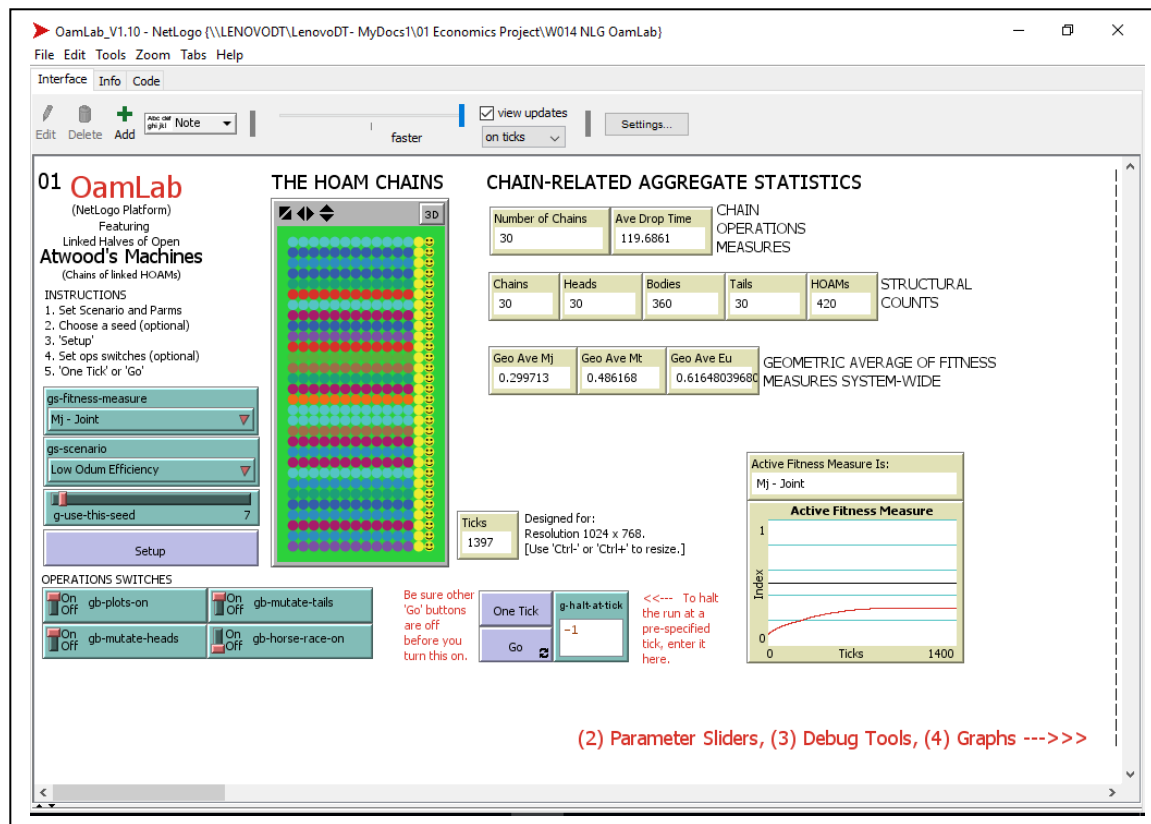
The main panel has the following controls and features:

- Note the two small carets at the bottom left corner. They are used to open the "command center" where debug output can be seen.
- Also note the two NetLogo standard speed controls at the top – a "faster" slider and a "view updates" tick box.
- **Gs-fitness-measure** – a chooser – this chooser is used to select one of three built-in fitness measures to be used when the chains are checked for fitness.
- **Gs-scenario** – a chooser – this chooser is used to select one of three built-in scenarios for initialization: low Eu, high Eu and mixed Eu.
- **G-use-this-seed** – a slider – select a seed for the Pseudo-Random Number Generator (PRNG).
- **"Setup"** – a button – Press this button to cause the model to clear the library of all chains, and build and initialize a new set of chains before starting a fresh run.
- **Gb-plots-on** – a toggle – this switch tells the NetLogo interpreter to collect data, display it in the various line graphs, and retain it for later dump to CSV files if wanted.
- **Gb-mutate-heads** – a toggle – this switch enables the mutation of heads during reproduction.

- **Gb-mutate-tails** – a toggle – this switch enables the mutation of tails during reproduction.
- **Gb-horse-race-on** – a toggle – this switch causes the NetLogo interpreter to operate in horse-race mode when on. Horse is cute but difficult to interpret. It is the mode of operation first implemented, and retained because it is cute, but it is recommended that it be turned off for serious data collection activities.
- **The HOAM Chains** – the arena – this is where the agents are presented in chains of HOAMs, with heads to the right and tails to the left. When in "horse race mode" you can watch as bolts of energy travel from right to left. As each OAM is formed it turns yellow, energy is transferred over several ticks, and then the OAM is dissolved. When "horse race mode" is turned off, you merely see all of the chains disappear each tick, to be replaced by the new mutated daughters, as half of them are discarded.
- **Number of Chains** – a ,monitor – starts a small number, rises to 30, then remains at 30.
- **Ave Drop Time** – a monitor – the sum of the drop time of all chains, divided by the number of chains.
- **Heads** – a monitor – – the number of heads, one per chain.
- **Bodies** – a monitor – – the number of bodies.
- **Tails** – a monitor – – the number of tails, one per chain.
- HOAMs – a monitor – – the total number of HOAMS, equal to the sum of Heads, bodies and tails.
- **Geo Ave Mj** – a monitor – the geometric average of the fitness measure Mj across all heads.
- **Geo Ave Mt** – a monitor – the geometric average of the fitness measure Mt across all heads.
- **Geo Ave Eu** – a monitor – the geometric average of the fitness measure Eu across all heads.
- **Ticks** – a monitor – the number of discrete advances in time since the beginning of this run of the model.
- **"One Tick"** – a button – advances the model by one discrete unit of time.
- **"Go"** – a button – advances the model by a continuous succession of ticks until the button is pressed again, at which time the model stops running.
- **G-halt-at-tick** – an input field – enter a tick value here, and the model will automatically stop running when this tick value is reached. The "Go" button with pop out as if pressed.
- **Active Fitness Measure Is:** – a monitor – display the selection choosen by the chooser gs-fitness-measure.
- **Active Fitness Measure** – a line graph – displays a red line graph of the current fitness measure from among the three displayed in the monitors above it. Background lines show values in blue for 0.2, 0.4, 0.6, 0.8 and 1.0. A black line is shown for 0.5.

6.2   Panel 02 – Advanced System Parameters

The following controls and features are available in Panel 02:

- **"Reset Defaults"** – a button – use this button to recover the default values of all controls. Only the chooser for the scenario is not reset. It is persistent through a save/load operation, and through a reset operation.

- **Behaviour Space Usage** – a built-in feature of NetLogo, not documented here, but which uses the sliders in panels 01 and 02.
- **G-no-of-chains-at-start** – a slider – lets a user select the number of chains to be built by the "Setup" button. This is useful for debugging, to cause less data to be produced.
- **G-length-of-chains** – a slider – lets a user decide how long the chains in the library will be. This is useful for debugging, to cause less data to be produced.

- **G-drop-distance** – a slider – a key parameter for the model, associated with the internal virtual Open Atwood Machines, the height to which each mass is raised before it is allowed to fall which determines the amount of still-useful energy that can be stored in an HOAM.
- **G-acceleration** – a slider – a key parameter for the model, associated with the internal virtual Open Atwood Machines – the strength of acceleration due to gravity.
- **SPECIAL SCENARIO**:
  - Follow the instructions to the right to run one of the scenarios studied in the design of this model.
  - **Max Head Size** – a monitor – indicates the maximum size of the mass attribute of all currently active heads of all chains.
  - **G-set-max-head-size** – an input field – enter a number here if you plan to use the following button to change all of the head sizes to this number. It must be equal to or greater than the number displayed at the moment.
  - **"Make Heads All The Same"** – a button – press this button to cause the mass in all heads to be set equal to the number entered (by you) into the above input field.
  - **Min Tail Size** – a monitor – indicates the minimum size of the mass attribute of all currently active tails of chains.
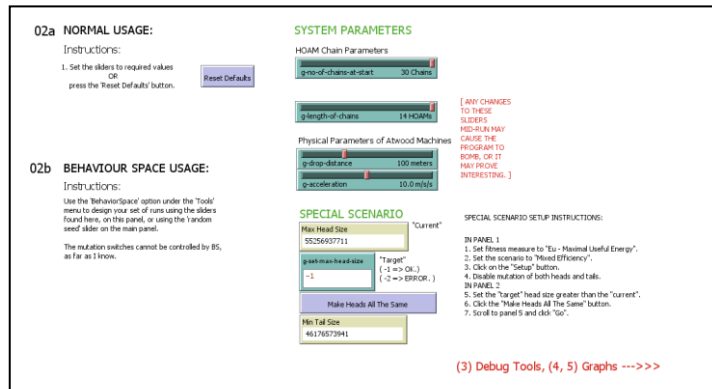
6.3 Panel 03 – Debug and Data Collection

The controls in this panel are divided into two groups:

6.3.1 Panel 03a – Debug Tools

I have left my debug tools active here in case any user wishes to modify the model. And example of debug output can be found in Annex B of this document.

- "**Toggle Debug**" – a button – use this to toggle the "LOG-TO-FILE" function on. It sends a stream of debug log data to a file on your computer, and also to the "command center" accessible via the two small carets at the bottom left of your screen.
- **Debug** – a monitor – indicates the current status of the debug feature.
- **Gs-debug-step-chooser** – a chooser – this selects which step (out of three) will cause a debug data stream to be generated when the "**One Tick**" and "**Go**" buttons are pressed. The "Setup" button always generates a data stream when the debug feature is turned on,

whether Setup is selected in this chooser or not.

- "**Setup**" – a button – This is a little different from other "**Setup**" buttons in the application. It causes the setup procedure to be run, and, if debug is turned on, causes a data stream to be sent to a debug log file and to the command center.

- "**One Tick**" – a button – this button duplicates the effect of other "**One Tick**" buttons in the application. It runs the "**Go**" sub-routine once.
- "**Go**" – a button this button duplicates the effect of other "**Go**" button in the application. It runs the "Go" sub-routine continuously until it is pressed a second time.
- "**Pre-Tick**" – a button – executes the **do-pre-tick** sub-routine once, sending a data stream to the debug log file and command center.
- "**Check-Chains**" – a button – executes the **do-check-chains** sub-routine once, sending a data stream to the debug log file and command center.
- "**Post-Tick**" – a button – executes the do-post-tick sub-routine once, sending a data stream to the debug log file and command center.
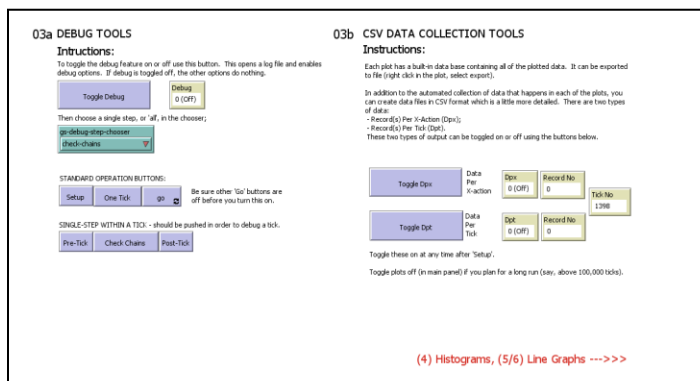
6.3.2   Panel 03b – CSV Data Collection Tools

There are at least three different ways that a user can collect data and make it available for use via MS Excel, or other data manipulation packages. These are briefly described in this panel. The third way is using the special tools I have built for this study.

- "**Toggle Dpx**" – a button – this opens a file on your hard drive into which a data stream is transmitted. This is different from the debug data file, but will appear in the same directory. Dpx is an acronym that stands for "data per transaction". For each reproduction action, a record is created dumping all of the data in the mother, and two more records – one for each of the two daughters.
- **Dpx** – a monitor – indicates the status of the Dpx CSV data file.
- **Record No** – a monitor – indicates the number of records written to the Dpx data file so far. 0 means no file is open.
- **Tick No** – a monitor – indicates the number of ticks that have been run so far in this run of the model.
- "**Toggle Dpt**" – a button – this opens a file on your hard drive into which a data stream is transmitted. This is different from the debug and Dpx data files, but will appear in the same directory. Dpt is an acronym that stands for "data per tick". For each tick, a record is created dumping all of the system-level aggregates such as geometric average of the fitness criteria.
- **Dpt** – a monitor – indicates the status of the Dpt CSV data file.
- **Record No** – a monitor – indicates the number of records written to the Dpt data file so far. 0 means no file is open.

6.4   Panel 04 – Histograms

This panel consists of four histograms and four control buttons. The control buttons are the standard control buttons for this model. The histograms are:

- **Ln(Mass) Distribution – HOAMs** – a histogram – in this histogram the number of HOAMs with a given mass is plotted against the natural logarithm of the mass. Every HOAM has a mass attribute, so the total count should equal the HOAMs monitor in Panel 01.

- **Distributions of fitness** – the other three histograms are all related to the three fitness criteria, and there is a measure for each pair of side-by-side HOAMs, i.e. for each OAM. The total count in these graphs should equal the amount in the HOAMs monitor, minus the number of tails. All three fitness measures are on the interval [0, 1]. The line graphs (in later panels) show the geometric average values, but these graphs give you some idea of the distribution of the values around those mean values.
    o **Mj Distributon** – OAMs – a histogram – distribution of the "joint" fitness measure.
    o **Mt Distributon** – OAMs – a histogram – distribution of the fitness measure based on the drop-time of the OAM.
    o **Eu Distributon** – OAMs – a histogram – distribution of the fitness measure based on Odum's definition of efficiency.
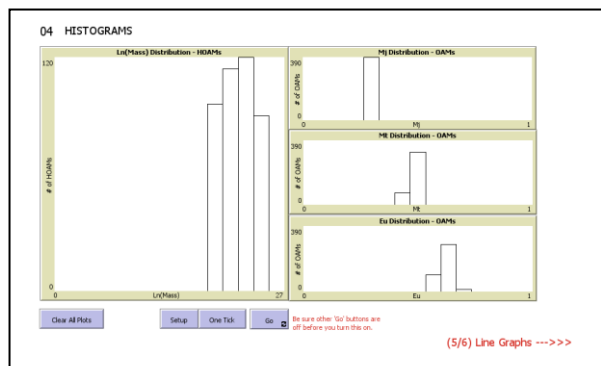
6.5   Panel 05 – Line Graphs

This and the next panel are the two key output panels. This data is not only displayed here, but can be easily dumped to CSV files for analysis using MS Excel, or other data manipulation tools. This panel has the standard four buttons for controlling the collection of data and the progress of a run. In addition, there are four line graphs.
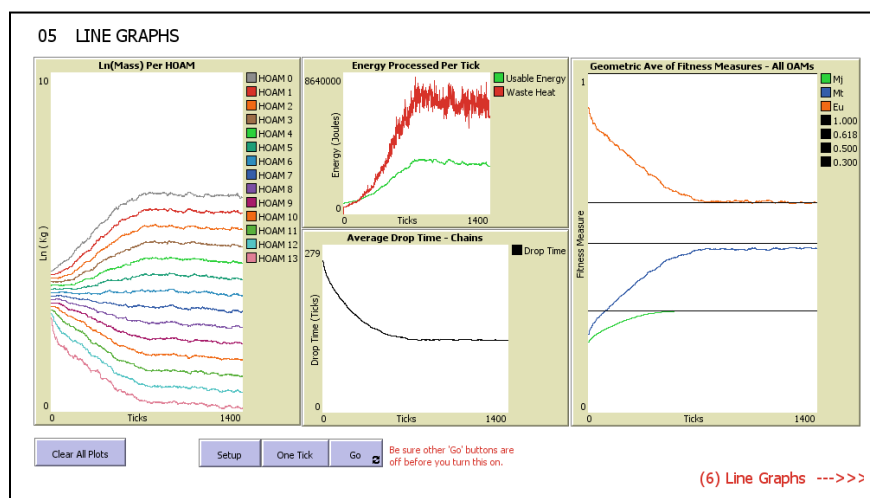

- **Ln(Mass) Per HOAM** – a line graph – this is the historical trace of the values that are plotted as a histogram in the previous panel. These are geometric averages, calculated across all HOAMs having the same position within a chain. Note that the mass attribute within a well-formed chain must exhibit a constant increase in size from tail (HOAM 13) to head (HOAM

00). In all chains, the order is maintained through all mutations. But note how the distances between averaged mass values quickly find and then maintain a regular value.

- **Energy Processed Per Tick** – a line graph – careful interpretation of this graph is fundamental to understanding how the MPP and MEPP are expressed in this model. The results vary markedly from scenario to scenario. The red line indicates the waste heat produced, calculated as a sum across all OAMs that have discharged waste heat in this tick of the model. In horse race mode, the OAMs only discharge upon completion of the simulated drop time. In the non horse race mode, there is no such simulation, and all OAMs are considered to have discharged, so this must be viewed more as a measure of the system-wide capability to capture and degrade energy. The green line is the still-useful energy that is passed from HOAM to HOAM. The difference between the two lines is the amount of energy originally primed into the head, without being passed from a previous HOAM. The rise to a maximal value, and the sustained maximal value of the production of waste heat, are clear indications that the MEPP is functioning in this scenario as a stationary state is maintained.

- **Average Drop Time – Chains** – a line graph – this shows the arithmetic average of the drop time for all chains. Note that as the system approached the stationary state the average drop time of the trophic chains stabilized.

- **Geometric Ave of Fitness Measures** – All OAMs – a line graph – there are four standard background lines in this graph, and three data lines. The four standard lines are drawn at fitness measure = 1.0, 0.618, 0.500, and 0.300. These levels all play an interesting role in the various forms of stationary state that can be demonstrated in the different scenarios. The famous "Golden Mean" of ancient Greece is τ = 1.618, so, we see here a value of (τ – 1) playing a role. This is the value that Odum and Silvert quibbled over. Odum predicted values of the Eu fitness measure less than or equal to 0.500. The role of 0.300 seems to be something new appearing in this model, and not elsewhere discussed to my knowledge. The three data lines (green, blue and red) are associated with the geometric averages displayed in the monitors in Panel 01.

6.6   Panel 06 – Fitness Measures

This and the previous panel are the two key output panels. This data is not only displayed here, but can be easily dumped to CSV files for analysis using MS Excel, or other data manipulation tools. This panel has the standard four buttons for controlling the collection of data and the progress of a
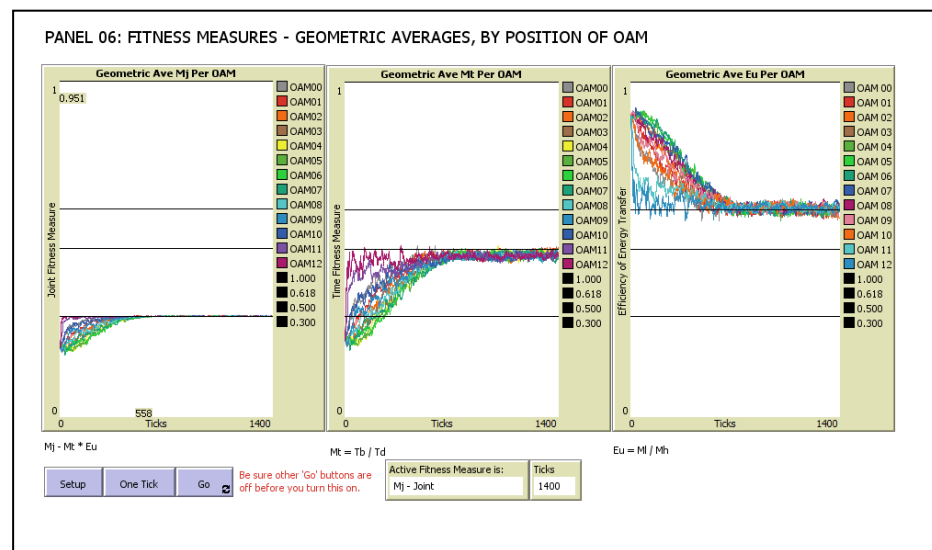
run, and two monitors indication the currently active fitness measure, and the current tick of the model. In addition, there are three line graphs, one for each of the three fitness measures that are shown in aggregate form in the previous panel. In this panel, they are broken out by OAM, where the value is a geometric average calculated on all OAMs that occupy the same position within a chain.

The four standard lines are drawn at fitness measure = 1.0, 0.618, 0.500, and 0.300. These levels all play an interesting role in the various forms of stationary state that can be demonstrated in the different scenarios. The famous "Golden Mean" of ancient Greece is $\tau = 1.618$, so, we see here a value of $(\tau - 1)$ playing a role. This is the value that Odum and Silvert quibbled over. Odum predicted values of the Eu fitness measure less than or equal to 0.500. The role of 0.300 seems to be something new appearing in this model, and not elsewhere discussed to my knowledge.

- **Geometric Ave Mj Per OAM** – All OAMs – a line graph – there are four standard black background lines in this graph as described above, and many coloured data lines – one for each active OAM position in the model. These lines are for the "joint" fitness measure.
- **Geometric Ave Mt Per OAM** – All OAMs – a line graph – there are four standard black background lines in this graph as described above, and many coloured data lines – one for each active OAM position in the model. These lines are for the "time" related fitness measure.
- **Geometric Ave Mj Per OAM** – All OAMs – a line graph – there are four standard black background lines in this graph as described above, and many coloured data lines – one for each active OAM position in the model. These lines are for the "efficiency" related fitness measure.

7 ANNEX B – Debug Output

The following is the output of the "Debug" feature.

7.1   to setup

```
observer: "OamLab_Log_170330_072933.txt opened."
observer: ""
observer: "Setup: Debug on; tick = 0"
observer: "Do-set: Scenario number     - 0"
observer: "Do-set: Scenario name       - Low Eu (Odum Efficiency)"
observer: "Do-set: Fitness test number - 2"
observer: "Do-set: Fitness test name   - Eu - Maximal Useful Energy"
observer: "Do-set: Random seed         - 7"
observer: ""
observer: "Do-set: STRUCTURAL PARAMETERS (Sliders):"
observer: "3 - Number of chains on initiation."
observer: "30 - Maximum number of chains."
observer: "3 - Length of all chains"
observer: "100 - Distance a mass falls"
observer: "10 - Acceleration due to gravity"
observer: ""
observer: "Do-set: CURRENT STATUS INDICATORS:"
observer: "0 - Current number of chains"
observer: "  Initializing: Chain 0"
observer: "    Initializing in gl-new-chain"
observer: "      Head initialized: HOAM 0"
observer: "      Body initialized: HOAM 1"
observer: "      Tail initialized: HOAM 2"
observer: "    Efficiencies being adjusted: Scenario no 0"
observer: "      Low-e: HOAM 1; mass: 160"
observer: "      Low-e: HOAM 0; mass: 1600"
observer: "  Relocated to: xcor: 14; ycor: 1"
observer: "  Initializing: Chain 1"
observer: "    Initializing in gl-new-chain"
observer: "      Head initialized: HOAM 0"
observer: "      Body initialized: HOAM 1"
observer: "      Tail initialized: HOAM 2"
observer: "    Efficiencies being adjusted: Scenario no 0"
observer: "      Low-e: HOAM 1; mass: 160"
observer: "      Low-e: HOAM 0; mass: 1600"
observer: "  Relocated to: xcor: 14; ycor: 2"
observer: "  Initializing: Chain 2"
observer: "    Initializing in gl-new-chain"
observer: "      Head initialized: HOAM 0"
observer: "      Body initialized: HOAM 1"
observer: "      Tail initialized: HOAM 2"
observer: "    Efficiencies being adjusted: Scenario no 0"
observer: "      Low-e: HOAM 1; mass: 160"
observer: "      Low-e: HOAM 0; mass: 1600"
observer: "  Relocated to: xcor: 14; ycor: 3"
observer: "Do-xxx: All aggregates updated."
observer: "Computing Energetics: Chain 0"
observer: "  Comp Energetics: Ch(0,0); OAM 0"
observer: "  CompEn: oam-time-to-drop    - 4.944132324730441"
observer: "  CompEn: age-to-discharge    - 4.944132324730441"
observer: "  CompEn: Mj-in-oam           - 0.09045340337332909"
observer: "  CompEn: Mt-in-oam           - 0.9045340337332909"
observer: "  CompEn: Eu-in-oam           - 0.1"
observer: "  CompEn: energy-to-transfer  - 160000"
observer: "  CompEn: energy-to-discharge - 1440000"
```

```
observer: "  Comp Energetics: Ch(0,0); OAM 1"
observer: "  CompEn: oam-time-to-drop   - 4.944132324730441"
observer: "  CompEn: age-to-discharge   - 9.888264649460883"
observer: "  CompEn: Mj-in-oam          - 0.09045340337332909"
observer: "  CompEn: Mt-in-oam          - 0.9045340337332909"
observer: "  CompEn: Eu-in-oam          - 0.1"
observer: "  CompEn: energy-to-transfer  - 16000"
observer: "  CompEn: energy-to-discharge - 144000"
observer: "  CompEn: Joint Fitness Measure (GeoAveMj) - Mj =0.09045340337332909"
observer: "  CompEn: Time Fitness Measure (GeoAveMt) - Mt =0.9045340337332909"
observer: "  CompEn: Energy Fitness Measure (GeoAveEu) - Eu =0.1"
observer: "Computing Energetics: Chain 1"
observer: "  Comp Energetics: Ch(1,1); OAM 0"
observer: "  CompEn: oam-time-to-drop   - 4.944132324730441"
observer: "  CompEn: age-to-discharge   - 4.944132324730441"
observer: "  CompEn: Mj-in-oam          - 0.09045340337332909"
observer: "  CompEn: Mt-in-oam          - 0.9045340337332909"
observer: "  CompEn: Eu-in-oam          - 0.1"
observer: "  CompEn: energy-to-transfer  - 160000"
observer: "  CompEn: energy-to-discharge - 1440000"
observer: "  Comp Energetics: Ch(1,1); OAM 1"
observer: "  CompEn: oam-time-to-drop   - 4.944132324730441"
observer: "  CompEn: age-to-discharge   - 9.888264649460883"
observer: "  CompEn: Mj-in-oam          - 0.09045340337332909"
observer: "  CompEn: Mt-in-oam          - 0.9045340337332909"
observer: "  CompEn: Eu-in-oam          - 0.1"
observer: "  CompEn: energy-to-transfer  - 16000"
observer: "  CompEn: energy-to-discharge - 144000"
observer: "  CompEn: Joint Fitness Measure (GeoAveMj) - Mj =0.09045340337332909"
observer: "  CompEn: Time Fitness Measure (GeoAveMt) - Mt =0.9045340337332909"
observer: "  CompEn: Energy Fitness Measure (GeoAveEu) - Eu =0.1"
observer: "Computing Energetics: Chain 2"
observer: "  Comp Energetics: Ch(2,2); OAM 0"
observer: "  CompEn: oam-time-to-drop   - 4.944132324730441"
observer: "  CompEn: age-to-discharge   - 4.944132324730441"
observer: "  CompEn: Mj-in-oam          - 0.09045340337332909"
observer: "  CompEn: Mt-in-oam          - 0.9045340337332909"
observer: "  CompEn: Eu-in-oam          - 0.1"
observer: "  CompEn: energy-to-transfer  - 160000"
observer: "  CompEn: energy-to-discharge - 1440000"
observer: "  Comp Energetics: Ch(2,2); OAM 1"
observer: "  CompEn: oam-time-to-drop   - 4.944132324730441"
observer: "  CompEn: age-to-discharge   - 9.888264649460883"
observer: "  CompEn: Mj-in-oam          - 0.09045340337332909"
observer: "  CompEn: Mt-in-oam          - 0.9045340337332909"
observer: "  CompEn: Eu-in-oam          - 0.1"
observer: "  CompEn: energy-to-transfer  - 16000"
observer: "  CompEn: energy-to-discharge - 144000"
observer: "  CompEn: Joint Fitness Measure (GeoAveMj) - Mj =0.09045340337332909"
observer: "  CompEn: Time Fitness Measure (GeoAveMt) - Mt =0.9045340337332909"
observer: "  CompEn: Energy Fitness Measure (GeoAveEu) - Eu =0.1"
observer: "Do-xxx: All aggregates updated."
```

7.2 do-pre-tick

```
observer: ""
observer: "Do-Pre-tick: Debug on.; tick = 0"
observer: "Do-pre: Halt at tick - -1; current ticks - 1"
observer: "Do-pre: routine completed."
observer: "Do-xxx: All aggregates updated."
```

7.3   do-check-chains

```
observer: ""
observer: "Do-check-chains: Debug on; tick = 1"
observer: "Chk Chain (S/N, index): Ch(1,1) "
observer: "  Checking: Ch(1,1)"
observer: "    Fitness: 0.1"
observer: "    Mj: 0.090453"
observer: "    Mt: 0.904534"
observer: "    Mu: 0.1"
observer: "    Dt: 9.888265"
observer: "    Nrg exhausted: 144000"
observer: "    Nrg transferred: 16000"
observer: "  Rep: Replication of chain ensues."
observer: "    Initializing in gl-new-chain"
observer: "      Head initialized: HOAM 0"
observer: "      Body initialized: HOAM 1"
observer: "      Tail initialized: HOAM 2"
observer: "    Efficiencies being adjusted: Scenario no 0"
observer: "      Low-e: HOAM 1; mass: 160"
observer: "      Low-e: HOAM 0; mass: 1600"
observer: "  Relocated to: xcor: 14; ycor: 4"
observer: "    D1 chain is Ch(3,1)"
observer: "    D2 chain is Ch(4,3)"
observer: "  Mutating Ch(3,1)"
observer: "    Mutating HOAM 1"
observer: "    Old mass: 160"
observer: "    New mass: 463.36109128642084"
observer: "  Comp Energetics: Ch(3,1); OAM 0"
observer: "  CompEn: oam-time-to-drop    - 6.02547594518155"
observer: "  CompEn: age-to-discharge    - 6.02547594518155"
observer: "  CompEn: Mj-in-oam           - 0.21494295796531143"
observer: "  CompEn: Mt-in-oam           - 0.7422045985555473"
observer: "  CompEn: Eu-in-oam           - 0.289600682054013"
observer: "  CompEn: energy-to-transfer  - 463361.0912864208"
observer: "  CompEn: energy-to-discharge - 1136638.9087135792"
observer: "  Comp Energetics: Ch(3,1); OAM 1"
observer: "  CompEn: oam-time-to-drop    - 4.629320865385982"
observer: "  CompEn: age-to-discharge    - 10.654796810567532"
observer: "  CompEn: Mj-in-oam           - 0.03335785634185609"
observer: "  CompEn: Mt-in-oam           - 0.9660457948461308"
observer: "  CompEn: Eu-in-oam           - 0.0345303054159759"
observer: "  CompEn: energy-to-transfer  - 16000"
observer: "  CompEn: energy-to-discharge - 447361.0912864208"
observer: "  CompEn: Joint Fitness Measure (GeoAveMj) - Mj =0.08467606694633656"
observer: "  CompEn: Time Fitness Measure (GeoAveMt) - Mt =0.8467606694633657"
observer: "  CompEn: Energy Fitness Measure (GeoAveEu) - Eu =0.09999999999999999"
observer: "  Mutating Ch(4,3)"
observer: "    Mutating HOAM 1"
observer: "    Old mass: 160"
observer: "    New mass: 125.85658159189146"
observer: "  Comp Energetics: Ch(4,3); OAM 0"
observer: "  CompEn: oam-time-to-drop    - 4.8389092850509074"
observer: "  CompEn: age-to-discharge    - 4.8389092850509074"
observer: "  CompEn: Mj-in-oam           - 0.07269816793337996"
observer: "  CompEn: Mt-in-oam           - 0.9242033052397943"
observer: "  CompEn: Eu-in-oam           - 0.07866036349493216"
observer: "  CompEn: energy-to-transfer  - 125856.58159189136"
observer: "  CompEn: energy-to-discharge - 1474143.4184081086"
observer: "  Comp Energetics: Ch(4,3); OAM 1"
observer: "  CompEn: oam-time-to-drop    - 5.081906875227585"
observer: "  CompEn: age-to-discharge    - 9.920816160278491"
```

```
observer: "  CompEn: Mj-in-oam          - 0.11187481918541682"
observer: "  CompEn: Mt-in-oam          - 0.8800113943054697"
observer: "  CompEn: Eu-in-oam          - 0.12712883027351213"
observer: "  CompEn: energy-to-transfer  - 16000"
observer: "  CompEn: energy-to-discharge - 109856.58159189146"
observer: "  CompEn: Joint Fitness Measure (GeoAveMj) - Mj =0.09018367032150527"
observer: "  CompEn: Time Fitness Measure (GeoAveMt) - Mt =0.9018367032150527"
observer: "  CompEn: Energy Fitness Measure (GeoAveEu) - Eu =0.1"
observer: "Chk Chain (S/N, index): Ch(2,2) "
observer: "  Checking: Ch(2,2)"
observer: "    Fitness: 0.1"
observer: "    Mj: 0.090453"
observer: "    Mt: 0.904534"
observer: "    Mu: 0.1"
observer: "    Dt: 9.888265"
observer: "    Nrg exhausted: 144000"
observer: "    Nrg transferred: 16000"
observer: "  Rep: Replication of chain ensues."
observer: "    Initializing in gl-new-chain"
observer: "      Head initialized: HOAM 0"
observer: "      Body initialized: HOAM 1"
observer: "      Tail initialized: HOAM 2"
observer: "    Efficiencies being adjusted: Scenario no 0"
observer: "      Low-e: HOAM 1; mass: 160"
observer: "      Low-e: HOAM 0; mass: 1600"
observer: "  Relocated to: xcor: 14; ycor: 5"
observer: "    D1 chain is Ch(5,2)"
observer: "    D2 chain is Ch(6,4)"
observer: "  Mutating Ch(5,2)"
observer: "    Mutating HOAM 1"
observer: "    Old mass: 160"
observer: "    New mass: 329.0965719739022"
observer: "  Comp Energetics: Ch(5,2); OAM 0"
observer: "  CompEn: oam-time-to-drop   - 5.50979837874555"
observer: "  CompEn: age-to-discharge   - 5.50979837874555"
observer: "  CompEn: Mj-in-oam          - 0.16694855589782498"
observer: "  CompEn: Mt-in-oam          - 0.8116696197543581"
observer: "  CompEn: Eu-in-oam          - 0.20568535748368888"
observer: "  CompEn: energy-to-transfer  - 329096.5719739022"
observer: "  CompEn: energy-to-discharge - 1270903.4280260978"
observer: "  Comp Energetics: Ch(5,2); OAM 1"
observer: "  CompEn: oam-time-to-drop   - 4.695114243063213"
observer: "  CompEn: age-to-discharge   - 10.204912621808763"
observer: "  CompEn: Mj-in-oam          - 0.04630900585965377"
observer: "  CompEn: Mt-in-oam          - 0.9525084424957129"
observer: "  CompEn: Eu-in-oam          - 0.04861794792948746"
observer: "  CompEn: energy-to-transfer  - 16000"
observer: "  CompEn: energy-to-discharge - 313096.5719739022"
observer: "  CompEn: Joint Fitness Measure (GeoAveMj) - Mj =0.08792736578183787"
observer: "  CompEn: Time Fitness Measure (GeoAveMt) - Mt =0.8792736578183786"
observer: "  CompEn: Energy Fitness Measure (GeoAveEu) - Eu =0.1"
observer: "  Mutating Ch(6,4)"
observer: "    Mutating HOAM 0"
observer: "    Old mass: 1600"
observer: "    New mass: 1623.7481519609876"
observer: "  Comp Energetics: Ch(6,4); OAM 0"
observer: "  CompEn: oam-time-to-drop   - 4.936834700592365"
observer: "  CompEn: age-to-discharge   - 4.936834700592365"
observer: "  CompEn: Mj-in-oam          - 0.0892622284013356"
observer: "  CompEn: Mt-in-oam          - 0.9058711150411767"
observer: "  CompEn: Eu-in-oam          - 0.09853744856107721"
observer: "  CompEn: energy-to-transfer  - 160000"
```

```
observer: "   CompEn: energy-to-discharge - 1463748.1519609876"
observer: "   Comp Energetics: Ch(6,4); OAM 1"
observer: "   CompEn: oam-time-to-drop    - 4.944132324730441"
observer: "   CompEn: age-to-discharge    - 9.880967025322807"
observer: "   CompEn: Mj-in-oam           - 0.09045340337332909"
observer: "   CompEn: Mt-in-oam           - 0.9045340337332909"
observer: "   CompEn: Eu-in-oam           - 0.1"
observer: "   CompEn: energy-to-transfer  - 16000"
observer: "   CompEn: energy-to-discharge - 144000"
observer: "   CompEn: Joint Fitness Measure (GeoAveMj) - Mj =0.08985584205597454"
observer: "   CompEn: Time Fitness Measure (GeoAveMt) - Mt =0.9052023275106342"
observer: "   CompEn: Energy Fitness Measure (GeoAveEu) - Eu =0.0992660307260632"
observer: "Chk Chain (S/N, index): Ch(0,0) "
observer: "   Checking: Ch(0,0)"
observer: "     Fitness: 0.1"
observer: "     Mj: 0.090453"
observer: "     Mt: 0.904534"
observer: "     Mu: 0.1"
observer: "     Dt: 9.888265"
observer: "     Nrg exhausted: 144000"
observer: "     Nrg transferred: 16000"
observer: "   Rep: Replication of chain ensues."
observer: "     Initializing in gl-new-chain"
observer: "       Head initialized: HOAM 0"
observer: "       Body initialized: HOAM 1"
observer: "       Tail initialized: HOAM 2"
observer: "     Efficiencies being adjusted: Scenario no 0"
observer: "       Low-e: HOAM 1; mass: 160"
observer: "       Low-e: HOAM 0; mass: 1600"
observer: "   Relocated to: xcor: 14; ycor: 6"
observer: "     D1 chain is Ch(7,0)"
observer: "     D2 chain is Ch(8,5)"
observer: "   Mutating Ch(7,0)"
observer: "     Mutating HOAM 2"
observer: "     Old mass: 16"
observer: "     New mass: 12.998761900123455"
observer: "   Comp Energetics: Ch(7,0); OAM 0"
observer: "   CompEn: oam-time-to-drop    - 4.944132324730441"
observer: "   CompEn: age-to-discharge    - 4.944132324730441"
observer: "   CompEn: Mj-in-oam           - 0.09045340337332909"
observer: "   CompEn: Mt-in-oam           - 0.9045340337332909"
observer: "   CompEn: Eu-in-oam           - 0.1"
observer: "   CompEn: energy-to-transfer  - 160000"
observer: "   CompEn: energy-to-discharge - 1440000"
observer: "   Comp Energetics: Ch(7,0); OAM 1"
observer: "   CompEn: oam-time-to-drop    - 4.851499590585895"
observer: "   CompEn: age-to-discharge    - 9.795631915316337"
observer: "   CompEn: Mj-in-oam           - 0.07488951274058589"
observer: "   CompEn: Mt-in-oam           - 0.9218048711531475"
observer: "   CompEn: Eu-in-oam           - 0.08124226187577159"
observer: "   CompEn: energy-to-transfer  - 12998.761900123442"
observer: "   CompEn: energy-to-discharge - 147001.23809987656"
observer: "   CompEn: Joint Fitness Measure (GeoAveMj) - Mj =0.08230438204832283"
observer: "   CompEn: Time Fitness Measure (GeoAveMt) - Mt =0.913128620961556"
observer: "   CompEn: Energy Fitness Measure (GeoAveEu) - Eu =0.09013448944536802"
observer: "   Mutating Ch(8,5)"
observer: "     Mutating HOAM 2"
observer: "     Old mass: 16"
observer: "     New mass: 19.520344151427445"
observer: "   Comp Energetics: Ch(8,5); OAM 0"
observer: "   CompEn: oam-time-to-drop    - 4.944132324730441"
observer: "   CompEn: age-to-discharge    - 4.944132324730441"
```

```
observer: "  CompEn: Mj-in-oam          - 0.09045340337332909"
observer: "  CompEn: Mt-in-oam          - 0.9045340337332909"
observer: "  CompEn: Eu-in-oam          - 0.1"
observer: "  CompEn: energy-to-transfer  - 160000"
observer: "  CompEn: energy-to-discharge - 1440000"
observer: "  Comp Energetics: Ch(8,5); OAM 1"
observer: "  CompEn: oam-time-to-drop   - 5.055511662530412"
observer: "  CompEn: age-to-discharge   - 9.999643987260853"
observer: "  CompEn: Mj-in-oam          - 0.10792383486693134"
observer: "  CompEn: Mt-in-oam          - 0.8846060010394995"
observer: "  CompEn: Eu-in-oam          - 0.12200215094642153"
observer: "  CompEn: energy-to-transfer  - 19520.344151427445"
observer: "  CompEn: energy-to-discharge - 140479.65584857255"
observer: "  CompEn: Joint Fitness Measure (GeoAveMj) - Mj =0.09880322954648345"
observer: "  CompEn: Time Fitness Measure (GeoAveMt) - Mt =0.8945145244125073"
observer: "  CompEn: Energy Fitness Measure (GeoAveEu) - Eu =0.1104545838552758"
observer: "Do-Chk: procedure completed"
observer: "Do-xxx: All aggregates updated."
```

7.4   do-post-tick

```
observer: ""
observer: "Do-Post-tick: Debug on; tick = 1"
observer: "Do-xxx: All aggregates updated."
observer: "Do-Pos: procedure completed."
```

8 Annex C – A Family of Related Models

In my study of the dynamics of sustainable economic systems I have developed a number of models that explore various aspects of systems that evolve to steady state.

8.1 PSoup

Written in C++, this model explores the nature of evolutionary forces in a purely biophysical economy. Based on a previous model called "Simulated Evolution" by Michael Palmiter, **PSoup** places a number of bugs into a primordial soup and tracks their development. Offering scenarios at many levels, it demonstrates a variety of effects of evolution from simple development of effective food search patterns in the lowest levels, to development of the five main senses, genetic cross-over and sexual reproduction. The amazing observation, for me, coming out of this model was the speed and certainty of the development of complexity. Whenever a complex option was made available in the potential genetic space of the bugs, it was quickly explored and very complex interactions between a cohort of highly varied genotypes would emerge. I also learned, from this model, that a constant flow of energy was a necessary condition for a sustainable biophysical economy, and a necessary pre-cursor for the emergence of complexity.

Many concepts from Dr Palmiter's model have been carried over into most of the models described below. In particular, the **DAT**, **RET** and **EPM** parameters from **PSoup** have been implemented in **MppLab** to manage the life functions of the heterotrophs, and the dominant steady-state search pattern called the "dodger" has been implemented to control their movements. Each heterotroph has eight cells around it, and must "decide" in each tick in which of the eight cells it is most likely to find a heterotroph. The best search behaviour is one in which 80% of the time the agent simply steps straight forward, but 10% of the time it turns 45° to the left before stepping forward, and 10% of the time is turns 45° to the right before stepping forwards. A stochastic selection of the three options leads to good performance. I did not want to confuse the effects of **PSoup**-like evolution of search patterns with the **OamLab**/**MppLab**-like evolution of **mass** genes, so I have implemented a non-evolving dodger search pattern as a baseline behaviour in **MppLab**.

8.2 ModEco

There are two versions of **ModEco**. Written in C++, the first-written version of **ModEco** is a hybrid economy consisting of a **PSoup**-like biophysical economy joined to a financial economy. In **ModEco** every transfer of matter and/or energy from agent to agent is facilitated by a reciprocal transfer of money. Again, as long as there is a consistent flow of energy, the economy evolves towards a steady-state biophysical condition. However, sustainability of the the financial economy has proven to be a very elusive property. It was discovered that economic sustainability was only possible if profit and loss were eliminated from the financial sector, and in its place an extremely precise regime of recognition and preservation of biophysical value be instituted. The scenario that exhibited sustainability under this harsh condition was called, somewhat jokingly, the "Perpetual Motion Machine", or "The PMM". In more technical terms, the equilibrium achieved in the PMM is an unstable equilibrium that must

be maintained by continuous external intervention.

8.3   ModEco and the PMM

Written in NetLogo, this model is a replication of the C++ model, but only of the single scenario called "The PMM". Again, three observations are clear from this model, and from the two previous models, when looking back over the common characteristics. First, the steady-state condition of any of these models demonstrates clear evidence of entropy rising to a maximal value, and then staying there. The distributions of alleles (in **PSoup**), or of wealth (in **ModEco** and The PMM) develop and then hold shapes characteristic of maximal entropy. Second, the emergence of complex economic organizations and inter-agent interactions seems to be an inevitable part of the evolution towards such a sustainable configuration. Third, and perhaps most important, the steady state can only be maintained by programming techniques that address the inherent instability of the equilibria associated with those steady states.

8.4   EiLab

Written in C++, this model enables a rather detailed investigation of the phenomenon of rising entropy in economic models. Inspired by the work of Dragulescu and Yakovenko (2000), it implements a capital exchange model in which I could study the origins and impact of entropy production in such models. **EiLab** stands for "Entropic Index Laboratory". I like this "laboratory" approach, because I can study many scenarios, generate lots of data, and then study the data. There were a few key observations coming out of this model. First, the study of entropy in such models is highly analogous to the study of entropy by Gibbs in his development of the concepts of "Gibbs' Free Energy". Second, in spite of the similarity to entropy, as Gibbs understood it, the entropy being investigated is not thermodynamic entropy, but a purely mathematical abstraction of it which is produced by a logical system executing logical processes distinct from chemical or heat-related effects. Third, the emergence of maximum entropy distributions was inevitable in these models, but the emergence of complexity was not, implying that there may be two distinct sets of conditions causing (a) the production of entropy, and (b) the production of complexity.

8.5   CmLab

Written in NetLogo, this model is another "capital exchange" model in the tradition of those of Benatti, Dragulescu and Yakovenko as found in the BDY models. That is to say, CmLab models the exchange of capital (of money) along with its stores and flows, but does not model the exchange of physical goods or services, nor does it model stores and flows of matter or energy. Whereas **PSoup** contains no financial subsystem, and **ModEco** is a hybrid biophysical / economic system, **EiLab** and **CmLab** contain no biophysical subsystem. This is a continuation of my study of sustainability of economic systems. The purpose of this model is to explore the analogy between the first law of thermodynamics (the conservation of energy) and the conservation of money under the regimes imposed by double-entry book-keeping and fractional reserve banking. My point would be that cash is "sufficiently-well conserved" under these two regimes that it presents an effective basis for the emergence of a purely financial version of those stochastic phenomena that are well-known and well-studied in thermodynamics. I would argue that the first law of thermodynamics is an accounting law, and the phenomenon of conservation of money is a purely financial counterpart to it. The production

of thermodynamic entropy would also then incline us to look for a similar purely financial phenomenon, which is what was found in the BDY models, and further demonstrated in **EiLab - Model I**.

8.6   OamLab

Written in NetLogo, this model is one of three developed to explore more fully the phenomenon of production of complexity in economic systems. This is a continuation of my study of sustainability of economic systems. It is the more simple senior member of a trio of models in which I explore the "Maximum Power Principle" as first proposed by A. J. Lotka and as developed by H. T. Odum. Both men argued that there is a need for a "fourth" law of thermodynamics, required to explain the persistent emergence of complexity. However, I found that Odum's ideas on this topic are difficult to decipher for a number of reasons. Ultimately, I found it necessary to restate his MPP as a set of three closely-related falsifiable hypotheses, and only then could I design models to test those hypotheses. This is the first of three such models designed to test the validity of my restatement of the MPP. The prediction was that this model would evolve to a stationary state in which the average efficiency was 0.5. Strangely, the stationary state average efficiency was 0.618, and not 0.5. This lead to the discovery of a dispute between Odum and Silvert in the early 1980s over which of the two numbers was the correct prediction. On further investigation, it turns out that there are, in fact, two valid answers, and both results are easily validated as consistent with the MPP. So, I consider that model, simple though it be, as supporting the hypotheses of the MPP.

8.7   MppLab

Written in NetLogo, this is the middle member of the trio of models exploring the validity of the MPP. Within an arena of freely roaming organisms (HOAMs) a competition for persistence ensues in which hunger and old age is the probable end of 50% of the population, and successful reproduction is the probable end of the rest. All biomechanical and biological feeding events have their dynamics modeled on the action of the AM, and in this way those aspects of time-regulation are modeled. This has very exciting results, as it is able to model a trophic web, in action, with from 6 to 10 trophic levels all operational at once. I have made a YouTube video using this model.

8.8   TpLab

Written in NetLogo, this model is intended to explore the hypothesized phenomenon that I am calling "Teleological Pruning". I argue that the beliefs and practices of any society are "pruned" and shaped by the same evolutionary pressures that shape our genes. Our societies are therefore shaped to conform to and agree with the effects of the Maximum Power Principle. This would explain why consumerism has emerged as the most destructive and persistent form of economic activity in our highly complex modern global economy. Our global economy has become the most powerful economy ever to have existed (in terms of energy consumed per year, and possibly in terms of energy consumed per person per year). Our beliefs (e.g. the necessity of endless economic growth) and our practices (materialism and consumerism) are now aligned with this destructive social trend. In **TpLab**, social beliefs are pitted against the effects of evolutionary pressures, with interesting effects.