Artificial Life Lecture 9

Gaia Theory, and Daisyworld Models

Be aware that in many scientific circles Gaia theory is seen as deeply unscientific, associated with hippies with flowers in their hair dancing naked in the woods under the full moon.

Enlightened unblinkered scientific opinion (... *You can guess how to translate that*...) considers that Gaia theory is completely serious scientific work, asking interesting questions (and proposing some answers) about aspects of life that other branches of biology have neglected.

Gaia

A ripe field for Alife-style research – *[Summer projects?]*
and strangely neglected.

Gaia = Greek for Earth Goddess

(modern Greek pronunciation is 'Yeah'!)

"Our planet is *in some sense* a living, self-regulating organism"

... but in *what* sense?

Some references

Pop: by *J Lovelock*
- Gaia, a new look at Life on Earth (1979) OUP
- The Ages of Gaia (I988) OUP

(JL now slightly disowns the first, prefers the second)
- *LE Joseph,* Gaia the growth of an idea (1990) Penguin

Not so pop:
- Dawkins, The Extended Phenotype, contains criticism
- *WD Hamilton* Gaia's Benefit, New Scientist (1996) 151, pp 62-63

New !:
- *Harvey,* Homeostasis and Rein Control: From Daisyworld to Active Perception, *Alife9, webpage.* ***[seminar]***

More references

Serious: Authoritative statement of current position of Gaia theory,
- *Tim Lenton* Gaia and Natural Selection
Nature, v394, 30 July 1998

- *PT Saunders* Evolution without Natural Selection: Further Implications of the Daisyworld Parable
J Theor Biol (1994) 166, pp 365-373 ***[seminar]***

- *S Stocker* Regarding Mutations in Daisyworld Models
J Theor Biol (1995) 175, pp 495-501

Origins of Gaia Theory

Jim Lovelock, with a background in atmospheric chemistry, was employed by JPL (Jet Propulsion Lab) in California in 1968, when NASA was looking for funding to send a rocket to Mars looking for life.

JL worked out that if he was on Mars, wondering about life on Earth,, he could just look through a telescope and see evidence that the gases in the Earth's atmosphere are in a persistent state of disequilibrium
-- driven by living organisms.

Biosphere

Conversely, looking at Mars' atmosphere, it is in a state of chemical equilibrium -- no need to waste money on rockets. Just look at the infrared signature.

He realised that the interactions between living organisms, and all the different aspects of the physical environment, within the bounded world of a planet, formed a complete biosphere in which all affected everything else

-- and then he started to notice some regularities...

The Gaian Hypothesis

Together with Lynn Margulis (a biologist who fought to get symbiosis recognised as significant to the development of life) Lovelock wrote papers in 1974 stating the original hypothesis:

"the biosphere - atmosphere, oceans, climate, Earth's crust and biota, living organisms, is regulated as a homeostatic system in conditions comfortable for the living organisms"

Context of the Original Daisyworld model

One example :- Our Sun is heating up, it was say 30% less luminous 3.8bn years ago. By rights, it should have been far too cold for life then, and far too hot now (e.g. 290^0C)

But it seems the Earth's surface temperature has been maintained at around 20^0 C for aeons. A nice temperature!

HOW ?

Scepticism

Initially there was no theory or model as to ***how*** this might work, so it received a lot of scepticism.

It was only around a decade after the first hypothesis that Lovelock and Watson created the Artificial Life model of ***Daisyworld*** that people started to take a bit more notice.

A typical story of resistance to new ideas …

Resistance to new ideas

Lynn Margulis' ideas on *symbiosis* -- that eukaryotes like plants and animals owe their origin to a symbiotic relationship between bacteria and cells -- went though the classic cycle with the neo-Darwinians:

(1) for a decade or 2 -- "nonsense, evolution is all about competition, you cant get anything serious going with such collaboration, what about cheaters?"

(2) for a decade or 3 -- "hmm, maybe your ideas might shed light on a thing or 2"

(3) eventually -- "of course we can incorporate this within our theory, we have forgotten that we ever disagreed with you".

Resistance to Gaia Theory

Resistance to Gaia theory has currently reached about stage (2), with the prime arguments against being

(A) This implies teleology, foresight, Earth Goddess (... hippies, crystals etc...)

(B) The Earth is not a unit of selection, so the Earth cannot have evolved, so how could such regulatory properties have come about?

The Teleology Problem

In earlier versions of the Gaia theory (or hypothesis), it was implied that the conditions such as climate of the Earth were regulated (around life-favourable values) *'by and for the biota'.*

This formulation suggests the *cause* of the regulation lies in the biota, the living organisms, and rang all sorts of alarm bells *'**why** did they do it, **how** did they know what level to aim for,??'.*

Worries about **CHEATS** -- if most of them 'expended some effort or energy' in doing their bit for the regulation business, how come the rest who *cheated,* benefited from the global climate without doing their share, didn't expand and wipe out the altruists?

Reformulation of Gaia

AS a consequence of these initial criticisms of Gaia theory, there was a reformulation:

It is **the system as a whole**, organisms **and** environment, that forms a closely-coupled self-regulating system

Causes for the regulation are at the level of the whole system rather than individual isolated parts.

The 'Gaia is alive' problem

When Lovelock said that '*in some sense* the Earth is a living organism' he fell foul of a whole lot of biologists with a vested interest in some particular senses of the term 'alive'.

In particular (a) scientists against woolly New Age thinking, and
(b) neo-Darwinist focusing their attention on evolutionary aspects of life.

The Earth cannot have evolved, as there is no reproduction of planets, with selection and variation.

A different core definition of life

But Lovelock was (quite innocently) taking a different, ecological, geophysiological view of 'life', seeing the whole biosphere as having these specific properties of living creatures: the homeostatic ability to self-regulate.

Having seen the fuss his earlier words made, Lovelock, and others, are now more careful in their statements

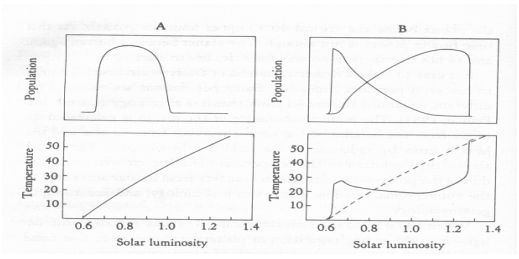
["Geophysiology" -- the orthodox name is now "Earth Systems Science"]

Response to criticism

The **Daisyworld** model was built, by Lovelock and Andrew Watson, as a direct response to the criticism of being woolly and unscientific.

It is, of course, a metaphor, a ***very simplified*** model for how any of many different life-affecting conditions on our planet can be intimately bound up in circular interactions, as both cause and effect, resulting -- so it is claimed -- in self-regulation

Daisyworld



A Grey Planet around a Sun which gets warmer over time. Black and white daisies, same limits to temp under which they can grow 5 to 40 C, with optimum 22.5 C.

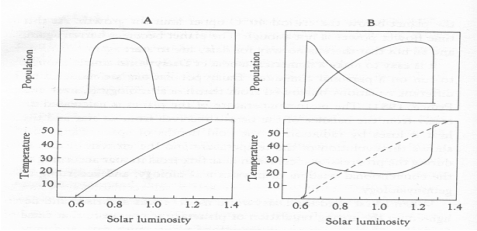
Maintenance of a comfortable temperature

When Planet is cold, any white daisies are cooler than surrounds, hinder their own growth. Any black ones absorb the sunlight, warm up their surrounds, and enhance their growth. In doing so they warm up the whole planet.

When planet is hot, the reverse happens, and white daisies dominate.

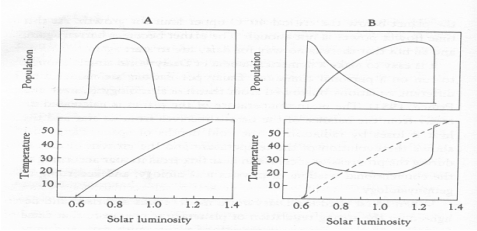
Throughout a change in solar input equivalent to 45 C, the whole planet temp is maintained within a few degrees of the optimum 22.5 C.

Different views (1)



On left, how biologists and physicists, thinking independently, would expect things to change as sun heats up: planet temp increases, and with this daisy population rises and falls as optimum growing temp is passed.

Different views (2)



On right, Gaian view, with competitive growth of dark and light daisies, which in turn affects planetary temperature.

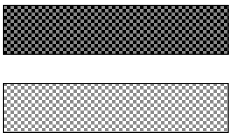
Revised Kindergarten DW version

In Jan 2004 I applied the standard rule of thumb for doing a project – "let's simplify the whole system as much as possible, retaining only the very basics"

Harvey, I., (2004).
Homeostasis and Rein Control: From Daisyworld to Active Perception
Proceedings of the Ninth International Conference on the Simulation and Synthesis of Living Systems, ALIFE'9, Pollack, J., Bedau, M,. Husbands, P., Ikegami, T., and Watson, R.A. (eds), pp. 309-314. MIT Press, Cambridge MA.

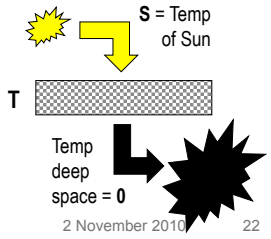
Available on my webpage

New Kindergarten Daisyworld



"Let's model the Black Daisies as in one Grey daisybed, the White in another, no longer competing for space"

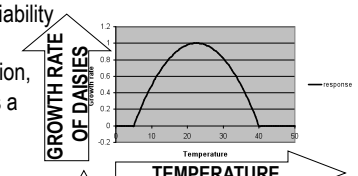
"Let's assume heat flows depend **linearly** on temp diff **(S-T)**, modulated by Daisybed albedo, and on temp diff **(T-0)** to deep space"



Hat Functions

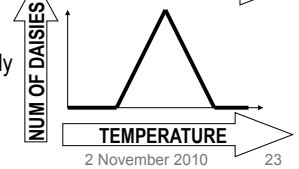
Homeostasis goes with viability

"The Daisy viability function, as temperature varies, is a Hat-shaped function."

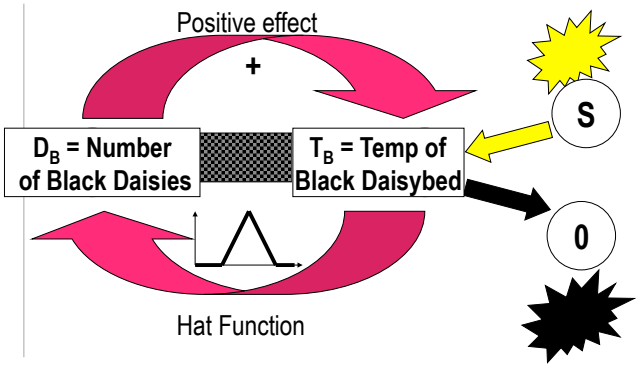


"Any Hat function will do"

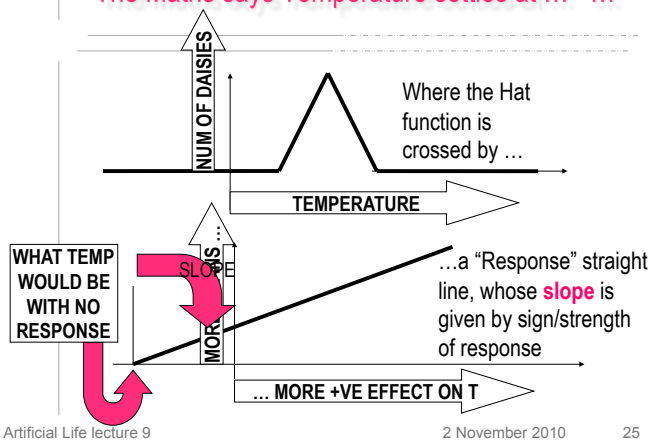
"Let's use a Witch's Hat, directly for the number of Daisies, not Growth Rate"



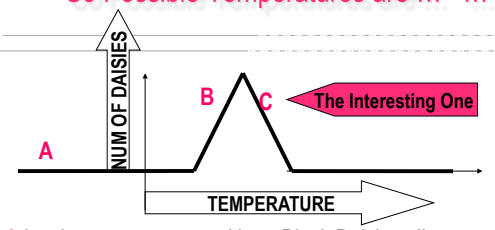
Consider just the Black Daisybed



The Maths says Temperature settles at … …



So Possible Temperatures are … …

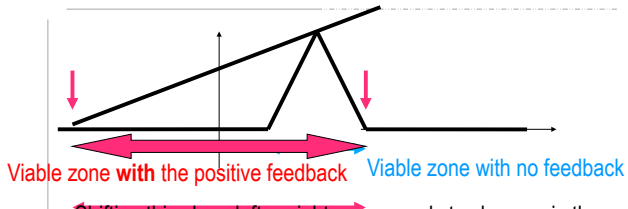


A is a low temperature, with no Black Daisies alive

B turns out to be an unstable equilibrium

C is a stable equilibrium, the +ve effect from Black Daisies brings Daisybed temperature within the viable range

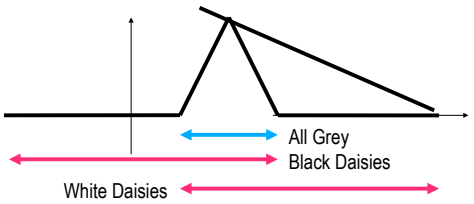
This extends the Zone of Viability



Shifting this slope left or right corresponds to changes in the external forcing of the Sun's luminosity – let's see how far it can shift and still intersect RHS of Hat Function … …

There is a bigger range of sun luminosities (extended left) that can support viable daisy temperatures, because of the positive response from Black Daisies absorbing extra heat.

White Daisies give Negative Response



Similarly, on a White Daisybed, the more White against the Grey background, the more **negative response**.

This gives a line with a negative slope, but similarly extends (now to the right) the range of viability of a White Daisybed.

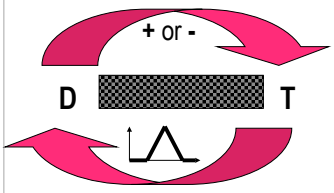
So both Positive and Negative Response works

There is no need to suppose God, or Evolution (in the real world), or some Trickery (in the Daisyworld model) has cunningly put in the **"right kind of response"** to make this homeostasis work.

Because **ANY** kind of response, positive **or** negative, when ***combined*** with a Viability Hat-function, gives this type of homeostasis :- extends the range of viability beyond what it would be without any feedback.

Terminology: "Positive and Negative Feedback"

Within each Daisybed, temperature **T** affects Daisy quantity **D** via a Hat-function. In turn, there is an effect **feeding back** from **D** to **T** that is either +ve (Black) or –ve (White daisies)



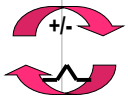
But this **doesn't** mean that this circuit as a whole is a (+ve or –ve) feedback control circuit – because the Hat-function is a crucial part !

Daisyworld ≠ Negative Feedback Circuit

Conventionally you need a "Negative feedback control circuit" for homeostasis – using a **Set Point** (eg "desired temp") and **Negative Feedback** to compensate for any Error …

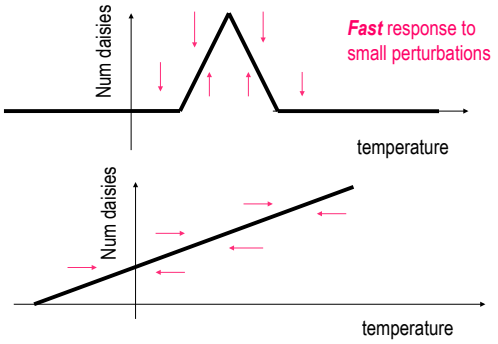
… and Positive feedback leads to instability

This Daisyworld homeostasis is very different – for a start, there is no Set Point, only a viability range !

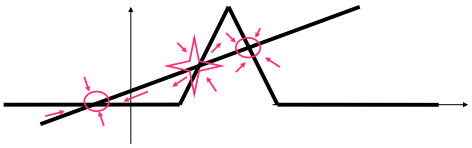


And both "Hat-plus-Positive feedback" and "Hat-plus-Negative feedback" work, to give regulation.

Different timescales



Stability



For any ***fixed*** value of the external "Big Perturbation" – ie Sun luminosity – and ***fixed*** slanting line, there will be fast negative feedback to any local noisy perturbations around the circled stable equilibrium points; and positive feedback around the starred unstable equilibrium.

But the DW feedback is at a different timescale – it is response to (slower) changes in the "Big Perturbation".

Daisyworld and Evolution

What happens if there is not just competition between black and white daisies, but potential for heritable variation, for evolution?

A common cry against Gaia Theory was 'what about cheats that disrupt self-regulation by benefiting from what others do without contributing themselves?'

Lovelock showed that a grey daisy with an energy-advantage did not destroy self-regulation.

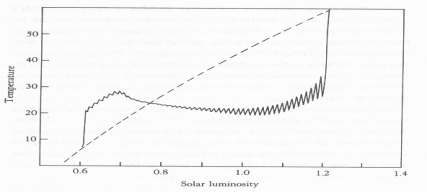
Daisyworld and Evolution (ctd)

Tim Lenton (see Nature paper) introduced an initial population of grey daisies, which could mutate in small steps to be blacker or whiter -- similar self-regulation appeared in the model.

There is scope for many further models and experiments, using Alife-style models.

Response to Perturbation

From JL 'The Ages of Gaia':



10 species of daisies evolving, range of shades. Suppose you have perturbations, periodic plagues killing 10% of all daisies.
Stability of system is dodgiest near the beginning and end of the 'horizontal' regulated range.

Ecology and Biodiversity

It is a commonly held belief that 'more biodiversity is good' for an ecology, in that it makes it more stable to perturbations. More is better?

Actually this is scientifically controversial. Robert May (recent Govt Chief Scientist) many years ago came out with widely-accepted mathematical models indicating that under very general conditions ecologies with many interacting species are **less** stable than ones with fewer.
Less is better?

Ecology, Biodiversity and Gaia ?

Possibly, the introduction of the Gaian geophysiological assumptions, that the evolution of living organisms and their physical environment should be considered together -- *possibly* this may change the picture.

Tim Lenton certainly suggests in his Nature paper (Box 3) that this may be the case -- worth further investigation.

'Damworld' model – Peter Henderson.

What practical implications of Gaia?

Without Gaia Theory, an observer visiting a planet and seeing that the plants had a preferred temperature that corresponded to the actual temperature – would assume that the plants had evolved their physiology to match a pre-ordained temperature.

But now, with Gaia Theory, there is the new possibility that cause and effect was the other way round!

Or some combination.

Takehome message

It is easy to pay lip-service to the idea that living organisms affect their environment, without really appreciating the extent and importance of this.

On Earth, our temperature, the oxygen in our atmosphere, the constituents of our rocks cycling through the ocean floor into the earth's mantle and out through volcanoes, all interact with the biota, in what seems to be in some sense a self-regulating system.

Alife models?

This is a fertile area for ALife style models, plenty of fresh research to be done, potentially bringing important new insights.

Gaia Theory is still at an early stage, by no means is all understood.

TL: *"The implications may be far-reaching; simple principles suggest that environmental regulation can emerge at all levels from the individual to the global"*

New Model

Jamie McDonald-Gibson, EASy MSc thesis 2006.

McDonald-Gibson, J., Dyke, J., Di Paolo, E. and Harvey, I. (2008). *Environmental Regulation can arise under minimal assumptions*

JTB Journal of Theoretical Biology

In this model: (1) daisies have all different 'preferred-temps' and all different +/- effects (both evolvable)
(2) Uniform temp across planet (ext perturb from 'Sun')

--- and you ***still*** get homeostasis, with punk eek

Explanation is in terms of Rein control,