

# A Precarious Existence: Thermal Homeostasis of Simple Dissipative Structures

Stuart Bartlett<sup>1,2</sup> and Seth Bullock<sup>2,3</sup>

<sup>1</sup>Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo, Japan

<sup>2</sup>Institute for Complex Systems Simulation, University of Southampton, Southampton, UK

<sup>3</sup>Department of Computer Science, University of Bristol, Bristol, UK  
stuart.bartlett@elsi.jp

## Abstract

We demonstrate the emergence of spontaneous temperature regulation by the combined action of two sets of dissipative structures. Our model system comprised an incompressible, non-isothermal fluid in which two sets of Gray-Scott reaction diffusion systems were embedded. We show that with a temperature dependent rate constant, self-reproducing spot patterns are extremely sensitive to temperature variations. Furthermore, if only one reaction is exothermic or endothermic while the second reaction has zero enthalpy, the system shows either runaway positive feedback, or the patterns inhibit themselves. However, a symbiotic system, in which one of the two reactions is exothermic and the other is endothermic, shows striking resilience to imposed temperature variations. Not only does the system maintain its emergent patterns, but it is seen to effectively regulate its internal temperature, no matter whether the boundary temperature is warmer or cooler than optimal growth conditions. This thermal homeostasis is a completely emergent feature.

## Introduction

Life is a quasi-miraculous panoply of controls, feedbacks, interactions and diversity. Every time we think we have discovered its final limits, we stumble upon hidden surprises that propel us to once more rip up the rulebook. It remains arguably the greatest intellectual challenge of our time to understand how evolutionary forces have picked, crafted and re-worked physical and chemical mechanisms such that life wins. What makes this quest so difficult is that we still struggle to define the game that life is playing, and it also seems that some players have found ways to modify the rules mid-play and perhaps even cheat.

In order to break into the vault of life's mysteries, we must seek plausible trajectories. Trajectories that life may have taken here on Earth, that it could have taken, or even could take in other scenarios, to get from dead chemistry to open-ended complexity. One of the most characteristic features of organisms is their ability to carry out regulation and stabilisation in the face of external change. The reactions and interactions that life depends on cannot take place in an arbitrary range of conditions; in fact many have strict limitations.

The idea of homeostasis conjures ideas of regulating cell salinity, glucose concentration, body temperature or cell membrane lipid composition, to name but a few. In fact, it is a fundamental and necessary feature of all living organisms that some minimal set of internal variables are maintained within viable ranges.

It is easy to imagine many forms of proto-life, early in the history of our planet (and perhaps also other worlds), which exhibited only some, not all of the characteristics of life as we know it today. For example, one could think of an early metabolic reaction set being driven by a particular geochemical gradient. Out of the space of possible such reaction sets, there are a large number which are very sensitive to the exact details of the local conditions. So if such conditions were to change, many of those possible metabolisms would cease to function.

One can also imagine early forms of life that produced some kind of waste product that was toxic in sufficiently high concentrations. In this scenario early life could have easily poisoned itself into oblivion. This of course brings to mind the example of free oxygen production by photosynthetic organisms, and the danger posed to many forms of life from that oxygen.

Broadly speaking, part of the solution that life stumbled upon was cooperation. If there is a growing excess of a particular substance and there is the possibility that a new organism can somehow make use of that substance and move the system towards being materially cyclic, then it's likely that such an arrangement will emerge and persist. To be thermodynamically consistent, the new organism may have to use a novel energy source to carry out its recycling stage, and there are many examples of this in both modern and past life.

Once there are several ecological interactions taking place between a set of organisms, there will inevitably be feedbacks. Feedbacks between population sizes, concentrations of key chemical species, environmental variables, and many other factors. Despite the fact that such feedbacks did not arise from any intentional design process, those that persisted over evolutionary time now appear to be very well

tuned. Many negative feedbacks that we can identify appear to allow organisms to survive in a range of conditions, particularly those that are normally unfavourable to their emergence or survival. We can use hindsight and place evolutionary explanatory frameworks upon these observations, making arguments such as “groups of self-regulating organisms would have had a significant selective advantage over those groups that were unable to control key environmental parameters.” However, the true chronology of life’s discovery of these clever techniques, is veiled behind a shadow of a meandering story of change, and lost historical information.

Thus we are compelled to seek systems in which such biological functions emerge spontaneously, and perhaps get a window on possible narratives for life’s ascension. Whether such sequences of events are similar to how life as we know it arose is very difficult, if not impossible to truly know. However, if we find that amongst the space of complex driven systems, a large number produce life-like dynamics, we at least can get a first foothold on the inevitability of life in the universe.

Our previous research sought to elucidate conditions in which non-living systems express life-like characteristics (Bartlett, 2014; Bartlett and Bullock, 2015; Bartlett et al., 2010), and in this work we continue in that endeavour. Having discovered systems in which non-living patterns spontaneously compete with one another for a common free energy source (Bartlett and Bullock, 2015), we questioned whether cooperation or symbiosis, might also readily emerge in simple physico-chemical systems.

Such dynamics can indeed be observed, and in this paper we will explore the spontaneous emergence of a temperature regulation mechanism in a shockingly simple non-living system.

We will first define the system in question and summarise its normal characteristic features. Then the modelling framework used to carry out our simulations will be briefly described. The next sections document the phenomenology of thermal Gray-Scott reaction diffusion (GSRD) structures and their resilience (or sensitivity) to temperature changes. We then illustrate a robust thermal homeostasis mechanism that emerges from the combined action of two sets of GSRD systems, before drawing conclusions in the final section.

## The Quintessential Pattern-Former

The original GSRD system consists of two chemical species  $A$  and  $B$ , which are free to diffuse and react within a two-dimensional domain (Gray and Scott, 1985, 1994; Lee et al., 1994; Mahara et al., 2008; Pearson, 1993; Virgo, 2011). Species  $A$  is fed into the system at all points via porous walls, at a rate equal to  $F(1 - \psi_A)$ , where  $F$  is a constant and  $\psi_A$  is the concentration of  $A$  at that location. There is a non-linear autocatalytic reaction between the two species:  $A + 2B \rightarrow 3B$ . Substance  $B$  is removed at a rate  $(F + R)\psi_B$ , where  $R$  is a positive parameter (removal rate) which speci-

fies the rate of removal of substance  $B$  (over and above the feed rate  $F$ ).

Despite its bare simplicity, this system is capable of exhibiting a myriad of dynamic chemical structures. Of course there are two trivial, non-structured attractors as well: one in which the reaction rate drops to 0 because  $B$  has all but disappeared from the system (perhaps if the reaction rate was too low to keep pace with the rate of removal of  $B$  and hence  $\psi_A \rightarrow 1$  due to the boundary conditions), and one in which the reaction occurs at a constant rate homogeneously across the domain and both species exist at finite concentrations which do not vary with space or time.

Nonetheless, under a small but finite range of conditions, and when the system is initialised in the correct way, a broad range of stable structures can be observed (structures in the concentration fields of the two species). These patterns are the emergent result of a frustration between the inward diffusion and supply of  $A$ , the transformation of  $A$  into  $B$ , and the outward diffusion and ubiquitous removal of  $B$ . If there is a point at which  $\psi_A$  is relatively low,  $\psi_B$  is relatively high, and the reaction turns  $A$  into  $B$  faster than  $B$  is lost from that region, then a small structure, or soliton, can persist. There are patterns of many different morphologies, also emerging from a similar balance of physical effects. In this paper we are interested purely in the well-known, self-reproducing spot patterns (Lee et al., 1994; Pearson, 1993; Virgo, 2011).

Traditionally, these systems are modelled under an isothermal assumption, so temperature plays no role in their dynamics. However the role of temperature in chemical kinetics could not be more essential. In recent years we have carried out a range of studies on the effects of adding thermal dependencies and interactions to GSRD systems (Bartlett, 2014).

In the investigation documented here, the system in question was a duo of GSRD systems. Having observed a competitive dynamic between GSRD spots and convection cells in our previous work (Bartlett and Bullock, 2015), we intended to go further and explore the possibility of cooperation between dissipative structures. Thus in this paper, there are two GSRD systems placed within the same domain. They are dissolved in a solvent fluid which flows and advects any passive scalars according to conventional incompressible flow dynamics. The temperature is of course also free to vary as a function of space and time. We simply need to control the temperature at the upper and lower boundaries of the system. Chemical reactions can also release or absorb a certain amount of heat (per unit reaction rate), quantified by the enthalpy change  $\Delta H$  (negative for exothermic reactions and vice versa).

The next section will describe the numerical algorithm that allowed us to re-create these model systems *in silico*.

## Modelling Framework

The simulation of non-isothermal fluids advecting chemical species, which themselves are undergoing temperature-sensitive reactions is not a lightweight undertaking. While various ‘traditional’ numerical methods (e.g. methods based on numerical integration or discretisation, such as multi-physics solvers like COMSOL) exist for the solution of the governing equations of these systems, they come with a significant computational burden and tend to lack transparency. Since we were not concerned with absolute predictive accuracy, but instead with carrying out “opaque thought experiments” (Di Paolo et al., 2000), we made use of an extended Reactive Thermal Lattice Boltzmann Model RTLBM, developed by Bartlett (2014).

The basic LBM has been extensively used and evaluated for a variety of fluid flows, and its accuracy and efficiency for simple flows is now well established (see e.g. Wolf-Gladrow, 2000; Chen and Doolen, 1998, and references therein). The LBM has also been extended to include buoyancy driven convection of non-isothermal fluids, and its effectiveness for such flows is also well established (He et al., 1998; Shan, 1997; Peng et al., 2003).

LBM capable of simulating reactive flows were less common until recent years, but these models are now steadily reaching maturity (Ayodele et al., 2011, 2013; Frouzakis, 2011). The specification, development and testing of the exact RTLBM used in this paper is described fully in Bartlett (2014); Bartlett and Bullock (2015), and hence we will not go into any further modelling details here.

Instead we will simply re-state the governing equations of the system in question. The flow field obeys the standard Navier-Stokes equations for an incompressible fluid that can experience buoyancy forces (under the Boussinesq approximation). The temperature field follows the advection-diffusion equation of a passive scalar (with sources and sinks from chemical reactions and boundary conditions):

$$\begin{aligned} \frac{\partial T}{\partial t} &= \chi \nabla^2 T - \nabla \cdot (\mathbf{u}T) \\ -Ae^{-E_a/T(\mathbf{x},t)} &(\psi_{A_1}\psi_{B_1}^2 \Delta H_1 + \psi_{A_2}\psi_{B_2}^2 \Delta H_2) \end{aligned} \quad (1)$$

Finally, the four chemical species concentration fields obey reaction-diffusion-convection equations:

$$\begin{aligned} \frac{\partial \psi_{A_1}}{\partial t} &= D_{A_1} \nabla^2 \psi_{A_1} - \nabla \cdot (\mathbf{u}\psi_{A_1}) \\ -Ae^{-E_a/T(\mathbf{x},t)} &\psi_{A_1}\psi_{B_1}^2 + F(1 - \psi_{A_1}) \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial \psi_{B_1}}{\partial t} &= D_{B_1} \nabla^2 \psi_{B_1} - \nabla \cdot (\mathbf{u}\psi_{B_1}) \\ +Ae^{-E_a/T(\mathbf{x},t)} &\psi_{A_1}\psi_{B_1}^2 - (F + R)\psi_{B_1} \end{aligned} \quad (3)$$

$$\begin{aligned} \frac{\partial \psi_{A_2}}{\partial t} &= D_{A_2} \nabla^2 \psi_{A_2} - \nabla \cdot (\mathbf{u}\psi_{A_2}) \\ -Ae^{-E_a/T(\mathbf{x},t)} &\psi_{A_2}\psi_{B_2}^2 + F(1 - \psi_{A_2}) \end{aligned} \quad (4)$$

$$\begin{aligned} \frac{\partial \psi_{B_2}}{\partial t} &= D_{B_2} \nabla^2 \psi_{B_2} - \nabla \cdot (\mathbf{u}\psi_{B_2}) \\ +Ae^{-E_a/T(\mathbf{x},t)} &\psi_{A_2}\psi_{B_2}^2 - (F + R)\psi_{B_2}, \end{aligned} \quad (5)$$

where the diffusion coefficients are  $D_{A_1} = 2D_{B_1} = D_{A_2} = 2D_{B_2}$ , the supply and removal parameters are fixed at  $F = 0.03$  and  $R = 0.061$  and  $\mathbf{u}$  is the local fluid velocity. Note that in contrast to the standard GSRD system, these equations have temperature dependent rates (incorporating the Arrhenius equation), which all share the same activation energy  $E_a = 1.7$  and frequency factor  $A = 3.1$ .

## Fragility

We are now in a position to explore the stability of a broad class of chemical patterns. Of course sustained structure formation on its own is grossly insufficient as an analogue for life. Many chemical systems show spatial structure (indeed the first that come to mind are the microscopic crystalline structures of many solid materials). However, if that structure is purely a function of external conditions, and has no means to actively respond to them, then it certainly cannot be considered life-like.

In this investigation we considered two GSRD systems in the same domain (they could only interact with each other implicitly through their thermal influence, there was no cross-diffusion or cross-reactions). We will begin at this stage with the assumption that the two reactions are neither exo- nor endothermic (they are thermally neutral, but their rates are sensitive to temperature). The steady states of such systems are shown in Figure 1 for three different temperatures. Note that in all figures, the temperature colourmaps are normalised by the same values, with red corresponding to  $T \approx 3$  and pale blue corresponding to  $T \approx 1.3$ .

We can see that at  $T = 1.5$ , the standard self-replicating spot dynamic is reproduced. However there is a strong sensitivity of the emergent patterns upon temperature. At  $T = 1.4$ , the rate of the reaction is so slow that the spots struggle to reproduce and proliferate (Figure 1(a)). At temperatures of  $T = 1.3$  and lower, the pattern formation all but ceases.

If the temperature is raised to, for example  $T = 1.6$ , a different phase of pattern emerges: more of an amorphous lamellar structure (Figure 1(c)). This is due to the thermal reaction rate enhancement causing the round spot structures to be unstable compared to the worm-like formations that arise instead.

Overall, we see that the delicate spot patterns cannot really tolerate changes of temperature and so their viable thermal range is  $\Delta T_{nt} < 0.1$ .

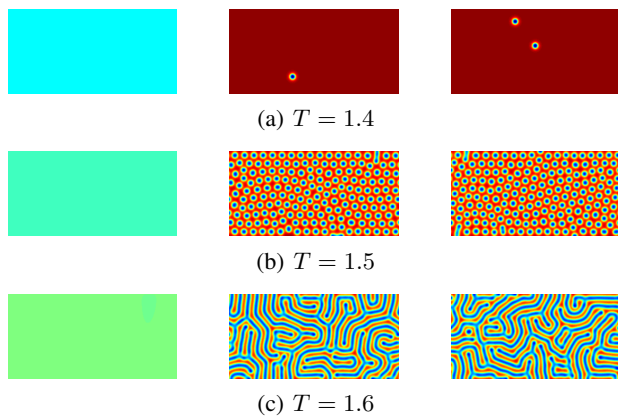


Figure 1: Steady state snapshots of the temperature (left column) and chemical order parameter fields,  $\phi_{1,2} = \psi_{A_{1,2}} - \psi_{B_{1,2}}$ , (centre column for system 1 and right column for system 2), for a double GSRD system. In these simulations, both reactions are thermally neutral ( $\Delta H_{1,2} = 0$ ).

### Self-destruction

In the previous section, we saw structures that could not exert any influence on their environment, and the result was a high degree of sensitivity to the key environmental variable: temperature. Perhaps if we add an extra coupling between the spot patterns and that crucial parameter, they will be less susceptible to thermal variations. If the reaction which drives their existence could interact with the temperature field, a self-stabilising feedback might be induced. An exothermic reaction might allow the spots to create more favourable local conditions if the background temperature was low and becoming a limiting factor. However, there is no guarantee that such a coupling would confer stability. What if it eroded the viability of the environment rather than enhanced it? This section will explore such a possibility.

As explored by our previous work (Bartlett, 2014; Bartlett and Bullock, 2015), exothermic spots exert a very strong positive feedback effect on the temperature of their surroundings. We illustrate the effect in Figure 2.

At the beginning of the simulation the spots begin to replicate as normal. However the additional heat released from the reaction begins to warm up the surroundings, which further augments the reaction rate. This then takes the system through different phases of pattern until eventually it is swamped and the temperature begins to diverge. The simulation in Figure 2 was carried out at  $T = 1.4$ . As one might imagine, higher temperatures simply reduce the time taken for the system to ‘explode’.

If the boundary and initial temperature is taken down to  $T = 1.3$ , the runaway feedback does not occur but pattern formation is also completely suppressed (the low initial temperature and concomitantly low reaction rate mean that small initial fluctuations are unable to grow into stable

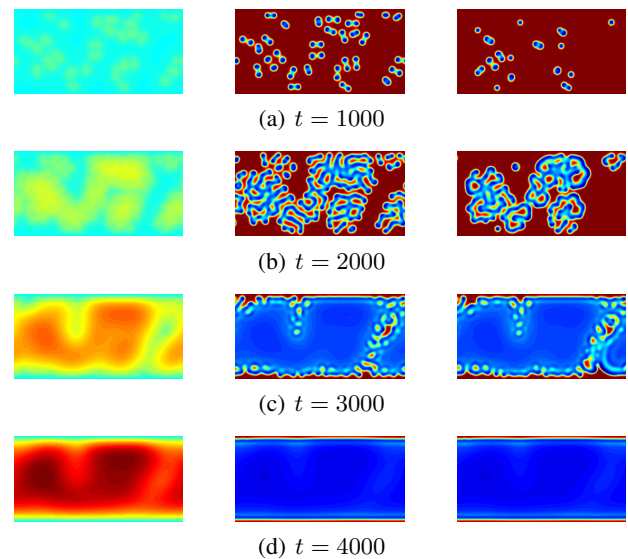


Figure 2: Snapshots of the temperature and chemical order parameter fields for a double GSRD system. One species has an exothermic reaction ( $\Delta H_1 = -20 \times 10^{-3}$ , centre column), and the other has a thermally neutral reaction ( $\Delta H_2 = 0$ , right column). The boundary and initial temperatures were all fixed at  $T = 1.4$ .

structures). Thus exothermic spots are highly unstable, in fact more so than thermally neutral spots.

What then, of endothermic spots? Our general finding has been that these patterns suffer from self-inhibition (Bartlett, 2014; Bartlett and Bullock, 2015). By reducing the temperature of their surroundings, they reduce the rate of the reaction that drives them and this often proceeds until the patterns themselves are all but extinguished. An example of this is shown in Figure 3.

We see that the endothermic spots rapidly damp themselves out. The temperature reductions are quite local so the neutral spots (shown in the central column) only experience a limited amount of destructive cooling. However as the simulation proceeds, the endothermic structures eventually cause their own demise.

At higher temperatures this self-damping still persists. At  $T = 4$ , for example (Figure 4), there is no initial pattern formation, and the reaction proceeds at a high rate homogeneously across the domain. However small fluctuations near the boundaries eventually lead to a division of the system into two layers next to the upper and lower walls, where a string of stable spots form.

Within these two layers, in the bulk of the system, the reaction ceases because the reacting layers at either boundary extract most of the thermal energy from the interior. Thus two films of spots persist, making use of the large heat flux from the boundaries to prevent their own self-destruction.

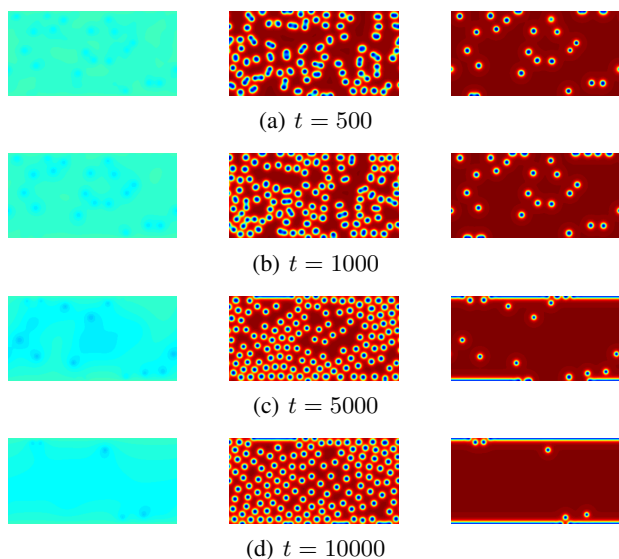


Figure 3: Snapshots of the temperature and chemical order parameter fields for a double GSRD system. One species has a thermally neutral reaction ( $\Delta H_1 = 0$ , centre column), and the other has an endothermic reaction ( $\Delta H_2 = 25 \times 10^{-3}$ , right column). The boundary and initial temperatures were all fixed at  $T = 1.5$ .

Despite this effect, the heat extraction from the spot persistence prevents them from spreading throughout the domain, so they do not proliferate. Thus even at very high temperatures, endothermic spots impose a fundamental limit on their own existence.

### Harmony

In the previous sections we illustrated the fundamental fragility of self-reproducing spot patterns in thermal GSRD systems. If the reaction neither releases nor absorbs heat, the type of emergent pattern has a strong temperature dependence, and self-replicating spots only occur within a narrow thermal window. If the reaction of one of the spot species is exothermic (and the other is neutral), there is a runaway positive feedback and the temperature diverges, taking all chemical structures with it. Conversely, when one of the two reactions is endothermic (and the other neutral), the effect is one of self-limitation. The cooling from the reaction has the effect of reducing its own rate, which in turn leads to the damping out of patterns.

At this stage we might naturally wonder whether some combination of exo- and endothermic spots might be able to mutually stabilise one another. To harmonise means to agree, to complement, and so we will now experiment with systems comprised of complementary spot systems. They will consist of an exothermic spot species with  $\Delta H_1 = -20 \times 10^{-3}$ , and an endothermic species with  $\Delta H_1 =$

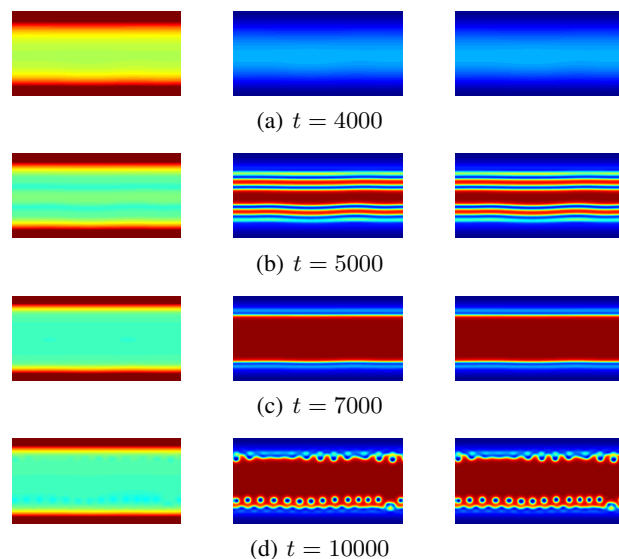


Figure 4: Snapshots of the temperature and chemical order parameter fields for a GSRD system with two different spot species. One species has a thermally neutral reaction ( $\Delta H_1 = 0$ , centre column), and the other has an endothermic reaction ( $\Delta H_2 = 25 \times 10^{-3}$ , right column). The boundary and initial temperatures were all fixed at  $T = 4$ .

$25 \times 10^{-3}$ . The slightly higher magnitude of the enthalpy change of the endothermic reaction is necessary to ensure that the exothermic reaction cannot push the system into a positive feedback cycle from a small fluctuation (e.g. a temporary period where there are a smaller than average number of endothermic spots).

If we proceed as before with initial and boundary temperatures of  $T = 1.5$ , we indeed observe stable behaviour, as shown in Figure 5(b). There is stable self-replication and the heat emitted by species 1 (substances  $A_1$  and  $B_1$ ) is compensated for by the heat absorption of species 2 (substances  $A_2$  and  $B_2$ ).

These symbiotic patterns can also provide a stable environment for themselves at higher temperatures, such as  $T = 2.0$ . After an initial transient phase, the system settles into a steady state with a stable population of both spot species (Figure 5(c)). The reason the structures survive is that they are carrying out a form of temperature regulation. Despite the boundaries being warmer than ideal, the combined spot system is able regulate the bulk temperature to  $T_{in} \sim 1.5$ . If the boundary and initial temperatures are less than  $T = 1.45$ , the endothermic spots extinguish themselves before the exothermic ones can provide compensatory heating.

In conclusion, this combined synergy of an exothermic with an endothermic spot species yields a viable temperature range of  $\Delta T_{sym} \sim 1$ , much greater than the equivalent

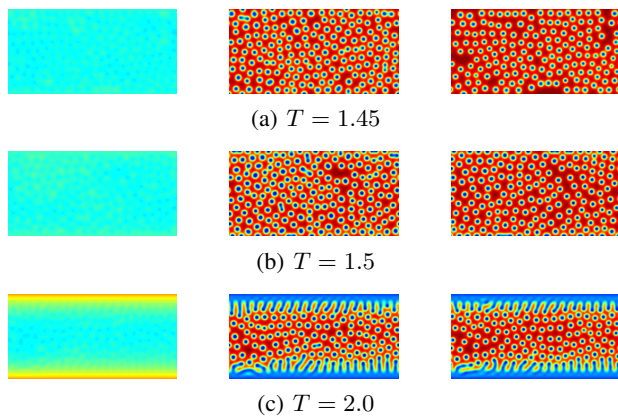


Figure 5: Snapshots of the temperature and chemical order parameter fields for a double GSRD system with three different values for the boundary and initial temperatures. One species has an exothermic reaction ( $\Delta H_1 = -20 \times 10^{-3}$ , centre column), and the other has an endothermic reaction ( $\Delta H_2 = 25 \times 10^{-3}$ , right column).

thermally neutral system (note also that when one species was exothermic or one was endothermic, there was essentially no viable range over which spots stably formed).

Having established the temperature window within which the symbiotic system can persist, we can also consider the influence of initial conditions. Perhaps it is possible that once established, a stable population could endure thermal perturbations beyond the range of static temperatures that we have already observed.

### Resilience

In this section we will carry out stress tests in which a stable population of spots are subjected to temperature variations that go beyond their viable range. Note that with initial **and** boundary temperatures outside of the range  $1.45 < T < 2.5$ , the spots are either destroyed by themselves or the phase of pattern transforms and the spots are mostly diminished. While this range is much greater than the small range of the neutral patterns, there are circumstances under which it can be extended yet further.

Here we will initialise the system at  $T_0 = 1.5$  and then vary the temperature in linear ramps over the range  $0.8 \leq T \leq 2.5$ . The results of this experiment are illustrated in **Figure 6** and can also be viewed as an animation (Bartlett, 2016).

The most striking feature of this graph is how small the variations in the internal temperature are compared to the variations of the boundary temperatures. The bulk of the system stays within the range  $1.4 \leq T_{in} \leq 1.5$ , despite the fact that the boundary temperatures range between  $0.8 \leq T_B \leq 2.5$ . It seems that the two sets of interacting chemical patterns are able to regulate their local temperature such that

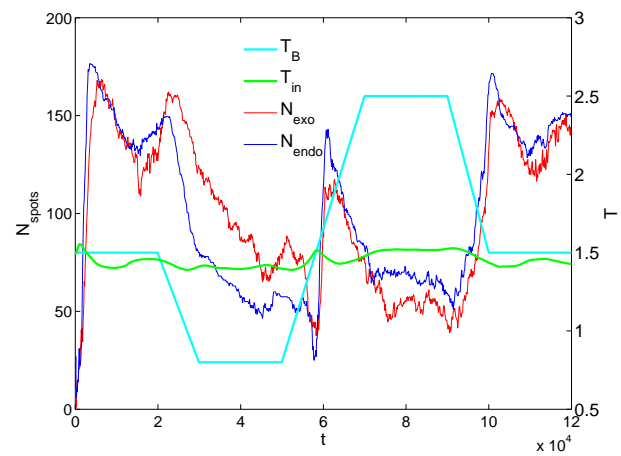


Figure 6: Population dynamics of the spot patterns within a two-species thermal GSRD system. The number of spots of the two types are shown as  $N_{exo}$  (red curve) and  $N_{endo}$  (blue curve). Also shown is the imposed boundary temperature  $T_B$  (cyan curve), and the mean bulk temperature,  $T_{in}$  (green curve). Note that this is the mean temperature of the inner region of the domain, for which  $0.2H \leq z \leq 0.8H$ .

it remains close to a suitable value for their own persistence.

From **Figure 6**, we can start to assess the mechanism behind this thermal homeostasis. When the temperature is lower than ideal, the exothermic spots tend to outnumber their endothermic counterparts. It makes sense that colder conditions make it harder for heat absorbing structures to survive but easier for those that are heat emitting.

Conversely, when the temperature is raised high enough to destroy the structures under normal conditions, we see that the endothermic spots instead have a greater population than those that are exothermic. In this case the damping effect of the endothermic spots is reduced by the warmer boundary temperature and hence they are able to increase in number, so much so that they outnumber the exothermic spots and contribute to the maintenance of the bulk temperature close to  $T_{in} \approx 1.5$ .

Note that even with ideal initial temperatures, the spot patterns cannot persist when the boundary temperatures are held below  $T_B = 0.8$ . Likewise above  $T_B = 2.5$ , the system begins to bifurcate to a different GSRD phase, and there are few spot structures left. Hence the viable range of the symbiotic system was  $\Delta T_{sym} \approx 1.7$ , when the initial temperature was close to the ideal value of 1.5.

What we have seen here is a prime example of precariousness (Virgo, 2011; Froese et al., 2013). These dissipative structures do not persist if the initial temperature is lower than  $\sim 1.45$ , but if a population is established, it can then stabilise its environment even in the face of deadly external changes.

## Conclusions

In this paper we have demonstrated how a regulatory mechanism, akin to homeostasis in living organisms, can emerge in a very simple non-living system. We carried out numerical simulations of systems with two GSRD systems. We found that when the rate constant takes on a standard kinetic dependence upon temperature, the emergent patterns in the system are readily destroyed when the temperature is perturbed away from the ideal pattern-forming value.

When enthalpy changes are introduced, making only one of the reactions either exo- or endothermic, the emergent structures are destroyed by strong positive feedback in the case of heat release, or damping in the case of heat uptake. Hence when the spot patterns have a singular influence on the temperature field, there is still no thermal resilience.

However, with a combined system in which one of the two reactions is exothermic and the other endothermic, we find that robust self-stabilisation occurs. Even when the boundary temperature was raised to  $T_B = 2.5$ , the combined action of the spot patterns maintained the internal temperature of the system very close to the ideal growth value of  $T = 1.5$ . Also in colder than optimal conditions, the two sets of structures were able to retain the ideal temperature in the midst of the system. Note that for the very low temperatures,  $T < 0.8$ , it was necessary to initialise the system at a higher temperature, such that a population of spots could first establish themselves, before surviving externally imposed temperature reductions. Overall the internal variation in temperature was only  $\sim 10\%$  of the boundary temperature variation (see [Figure 6](#)).

We observed that the regulation arose purely from changes in the number of spot patterns of the two different types. In cool conditions, the exothermic spot population rose above that of the endothermic spots. In hot conditions the opposite occurred. It is clear that with a simple set of feedbacks between a control variable and the strength of the objects carrying out the control, robust regulation of that variable can emerge spontaneously.

There are many parallels between the dynamics of our system and the characteristic Daisyworld family of models ([Harvey, 2015](#); [Watson and Lovelock, 2011](#); [Wood et al., 2008](#)). In both cases, there exist ‘active’ components of a system which somehow influence external forcings or parameters that have a fundamental impact on their persistence. In the case of Daisyworld, black daisies tolerate cold temperatures well because they have a warming effect (due to their lower albedo) and white daisies persist at high temperatures because they cause cooling. When combined together on Planet Daisyworld (described through a set of coupled, non-linear differential equations), the combined system appears to be able to regulate its temperature in the face of changes in external radiative forcing, just like our combined GSRD system.

However, there are several key differences between

Daisyworld and our GSRD world. The two species of Daisyworld do not destroy themselves when placed in isolation. In fact there is some residual stabilisation effects even when only one species of daisy is present ([Watson and Lovelock, 2011](#)). So in Daisyworld, one species confers some regulation, and two species confers much more. In the model presented in this paper, one species with thermal effects destroys structure, whereas two species with thermal effects permits strong stabilisation.

The common feature of both models is of course that two rein controls within a system allows a strong degree of negative feedback around a certain point in phase space. The original forms of our model system were not created to demonstrate the spontaneous emergence of homeostasis, as Daisyworld was. Furthermore, the parameter range over which daisies can survive is explicitly linked to the width of the (prescribed) growth rate-temperature curve. In our model, the viability range of the patterns is not prescribed, but emergent.

Observations of our system may have implications for ways in which primordial life might have been able to start to influence its own survival chances by acquiring simple feedback mechanisms with its environment. Perhaps transitions such as the prokaryote to eukaryote transition were heavily influenced by the additional feedback or control conferred on a larger organism when a smaller organism infected it. Perhaps many of the characteristic homeostasis mechanisms that we see in extant life started off as simple push-pull feedback combinations such as those illustrated in this work.

## Further Work

In this work we have explored an interesting class of dynamics in emergent pattern formation. There remain many interesting extensions to this work that could further reveal new phenomena. The reaction enthalpies of the two spot systems could be further increased. In fact it would be desirable to explore the scaling of thermal resilience as a function of the reaction enthalpy magnitudes. It could be that with extremely (thermally) strong reactions, small fluctuations could favour one or the other spot species, yielding a collapse of the system (through e.g. temperature divergence from dominance of the exothermic species).

In Section 7.4 of [Bartlett \(2014\)](#) (wherein the reaction enthalpies were lower in magnitude than those used in the current work), it was observed that pairs of thermally interacting spots (one from each species) locked together spatially. It would be useful to establish the point at which this becomes unnecessary (i.e. at what level of reaction enthalpy) for the survival of the two-spot species system. Furthermore, one could vary the diffusion constants of the two species such that, e.g. several spots of one species were embedded within the envelope of one spot of the other species. Perhaps several small exothermic spots with the correct enthalpy value can stabilise one much larger endothermic spot.

Such a dynamic takes inspiration from ideas concerning the Prokaryote-Eukaryote evolutionary transition.

**Acknowledgments.** This work was supported by an EPSRC Doctoral Training Centre grant (EP/G03690X/1) and the ELSI Origins Network of the Tokyo Institute of Technology. We gratefully acknowledge the comments of four reviewers.

## References

- Ayodele, S., Raabe, D., and Varnik, F. (2013). Lattice boltzmann modeling of advection-diffusion-reaction equations: Pattern formation under uniform differential advection. *Communications in Computational Physics*, 13:741–756.
- Ayodele, S. G., Varnik, F., and Raabe, D. (2011). Lattice boltzmann study of pattern formation in reaction-diffusion systems. *Phys. Rev. E*, 83:016702.
- Bartlett, S. (2014). *Why is life? An assessment of the thermodynamic properties of dissipative, pattern-forming systems*. PhD thesis, University of Southampton.
- Bartlett, S. (2016). Symbiotic gray-scott reaction diffusion simulation. [https://youtu.be/\\_fguKE9Xxio](https://youtu.be/_fguKE9Xxio).
- Bartlett, S. and Bullock, S. (2015). Emergence of competition between different dissipative structures for the same free energy source. In *Proceedings of the European Conference on Artificial Life 2015*, pages 415–422. MIT Press, Cambridge, MA.
- Bartlett, S., Bullock, S., and Attard, G. (2010). Challenging the robustness of simulated protocells (abstract). *Artificial Life XII: Twelfth International Conference on the Synthesis and Simulation of Living Systems, Odense, Denmark*.
- Chen, S. and Doolen, G. D. (1998). Lattice boltzmann method for fluid flows. *Annual Review of Fluid Mechanics*, 30(1):329–364.
- Di Paolo, E. A., Noble, J., and Bullock, S. (2000). Simulation models as opaque thought experiments. In Bedau, M. A., McCaskill, J. S., Packard, N. H., and Rasmussen, S., editors, *Artificial Life VII*, pages 497–506. MIT Press, Cambridge, MA.
- Froese, T., Virgo, N., and Ikegami, T. (2013). Motility at the origin of life: Its characterization and a model. *Artificial Life*, 20(1):55–76.
- Frouzakis, C. (2011). Lattice boltzmann methods for reactive and other flows. In Echehki, T. and Mastorakos, E., editors, *Turbulent Combustion Modeling*, volume 95 of *Fluid Mechanics and Its Applications*, pages 461–486. Springer Netherlands.
- Gray, P. and Scott, S. (1994). *Chemical Oscillations and Instabilities: Non-linear Chemical Kinetics*. International Series of Monographs on Chemistry. Clarendon Press.
- Gray, P. and Scott, S. K. (1985). Sustained oscillations and other exotic patterns of behavior in isothermal reactions. *The Journal of Physical Chemistry*, 89(1):22–32.
- Harvey, I. (2015). The circular logic of gaia : Fragility and fallacies , regulation and proofs. In *Proceedings of the European Conference on Artificial Life 2015*, pages 90–97. MIT Press, Cambridge, MA.
- He, X., Chen, S., and Doolen, G. D. (1998). A novel thermal model for the lattice boltzmann method in incompressible limit. *Journal of Computational Physics*, 146(1):282 – 300.
- Lee, K.-J., McCormick, W. D., Pearson, J. E., and Swinney, H. L. (1994). Experimental observation of self-replicating spots in a reaction-diffusion system. *Nature*, 369(6477):215–218.
- Mahara, H., Suzuki, K., Jahan, R. A., and Yamaguchi, T. (2008). Coexisting stable patterns in a reaction-diffusion system with reversible gray-scott dynamics. *Phys. Rev. E*, 78:066210.
- Pearson, J. E. (1993). Complex patterns in a simple system. *Science*, 261(5118):189–192.
- Peng, Y., Shu, C., and Chew, Y. T. (2003). Simplified thermal lattice boltzmann model for incompressible thermal flows. *Phys. Rev. E*, 68:026701.
- Shan, X. (1997). Simulation of rayleigh-bénard convection using a lattice boltzmann method. *Phys. Rev. E*, 55:2780–2788.
- Virgo, N. D. (2011). *Thermodynamics and the structure of living systems*. PhD thesis, University of Sussex.
- Watson, A. and Lovelock, J. (2011). Biological homeostasis of the global environment: the parable of daisyworld. *Tellus B*, 35(4).
- Wolf-Gladrow, D. (2000). *Lattice-Gas Cellular Automata and Lattice Boltzmann Models: An Introduction*. Number no. 1725 in *Lattice-gas Cellular Automata and Lattice Boltzmann Models: An Introduction*. Springer.
- Wood, A. J., Ackland, G. J., Dyke, J. G., Williams, H. T. P., and Lenton, T. M. (2008). Daisyworld: A review. *Reviews of Geophysics*, 46(1).