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Redox Homeostasis in the Emergence of Life. On the Constant Internal Environment of Nascent Living Cells

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Abstract

Two fundamental properties of life as we recognize it are homeostasis and redox chemistry. *Redox homeostasis* is defined here as the maintenance of a constant electrochemical potential and ionic concentration gradient across a cellular boundary, despite fluctuations in the electrochemical potential of the external environment and despite changing identities and activities of electron donors and acceptors. I propose that redox homeostasis originated in the iron sulphide vesicles that Russell and co-workers describe as the geochemical incubators of Earth's first living cells. Mechanisms securing pre-biotic redox homeostasis are discussed. The transition to free-living cells depends on the proto-cells' ability to maintain a proton motive force for energy conversion, providing for metabolism, for active transport, and for synthesis of informational and structural macromolecules. The persistence of regulatory circuits maintaining cellular redox state is outlined. The origin of oxygenic photosynthesis may result from failure of a redox switch that had functions in selection between different anoxygenic photochemical reaction centres. Any extra-terrestrial planet or moon with detectable free oxygen is likely to have made these transitions independently of the emergence of life on Earth.

KEY WORDS: Homeostasis, redox chemistry, chemiosmotic, photosynthesis, respiration, cell evolution, two-component regulatory system, redox sensor, redox response regulator.

1. LIFE AS HOMEOSTASIS

Living organisms are self-replicating and self-sustaining dynamic chemical systems. They obtain energy from, and information about, their environment – including its chemical, physical, geological, and biological components. A feature that distinguishes living from non-living matter was identified by Claude Bernard. This is homeostasis – the

maintenance of a constant internal environment despite changes in the external environment. A second feature of all known life, first proposed explicitly by Schleiden and Schwann, is that living things are composed of spatial compartments, called cells. Cellular homeostasis requires a system of integrated feedback and feedforward, producing adaptive responses to, and anticipation of, ultimately uncontrollable changes in the properties of the outside world. As life evolves, it extends its reach by maintaining its constant internal environment in new external environments, previously inhospitable.

2. WHAT FUELS LIVING SYTEMS? LIFE AS REDOX CHEMISTRY

In chemical reduction and oxidation, termed *redox chemistry* for short, one or more electrons move from a donor to an acceptor. In the process, the donor, or reductant, is said to become oxidised, while the acceptor, or oxidant, becomes reduced. A generalised redox reaction involving transfer of a single electron (with its unit of negative charge, –) from molecule A (the electron donor) to molecule B (the electron acceptor) can be written as follows (Equation 1).

$$A^{\ominus} + B \rightleftharpoons A + B^{\ominus}$$ Equation 1

The reaction is reversible, and the direction of net transfer reflects the approach to a dynamic equilibrium. Reading from left to right, we say that A reduces B, while B oxidises A. Free energy is released as the reaction approaches equilibrium. The initial chemical disequilibrium upon which all living things depend for energy arises from the separation of reducing and oxidising chemical species in the first place – it is a *redox disequilibrium* that allows energy-yielding redox reactions to proceed. This separation results, unaided by life, from geochemical activity, and geochemical gradients across the boundaries of inorganic compartments are now proposed as the earliest, vectorial metabolism of the first living cells, with the inside being more reducing, and the outside more oxidising – a feature maintained by all cells to this day. This separation of reducing and oxidising chemical species is also, now, achieved by life itself, using the energy of sunlight to move electrons in the opposite direction to that in which they flow spontaneously. Such light-driven electron transfer is the basis of photosynthesis, an invention of life that allows it to tap into abundant radiant energy from the Sun, so liberating it from the slower processes of unaided geochemistry.

3. HOW HAS LIFE EVOLVED FROM THE SIMPLE TO THE COMPLEX?

Maynard Smith and Szathmary (Szathmary and Smith, 1995) propose a solution to the apparent paradox of increasing complexity without there being a rational basis for the idea of evolutionary progress. The solution is the existence of transitions in levels of organisation, particularly where these involve information transfer. One such transition is the separation of the encoding of information from its translation - the emergence of the specialised roles of DNA, RNA and protein from an "RNA world" in which chemically similar macromolecules performed both catalysis and replication. The general theme of major transitions in evolution is division of labour, in which each new level of organisation incorporates specialised components which, on their own, become less versatile, but which, acting in ways that complement each other, create new possibilities for the environments that can successfully be exploited by the whole. A compelling list of examples is provided by Nick Lane (Lane, 2009), and includes the origins of life, photosynthesis, respiration, and complex cells.

4. FEEDBACK – NEGATIVE AND POSITIVE – IN METAL SULPHIDE VESICLES

Feedback occurs when an effect is partly its own cause (Figure 1). Homeostasis is secured by negative feedback, in which the magnitude of a cause is diminished by an increased magnitude of one of its effects. An example is the operation of a simple adjustable thermostat which allows the setting of a threshold temperature above which the supply of heat is switched off. Positive feedback occurs when the magnitude of a cause is increased by an increased magnitude of one of its effects. Amplification is an example of controlled positive feedback where a limit is set to the gain of the amplifier.

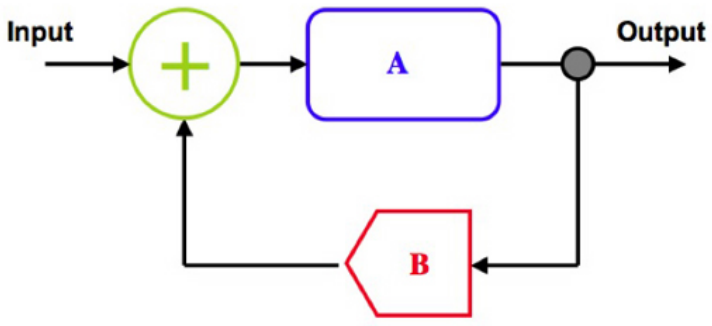

Figure 1. A block diagram for feedback. The feedback is negative if $B < 0$.

In the geochemical precursors of metabolism, reactions in which products are also substrates produced breeder reactors that concentrate reactants, by positive feedback, up to a point where their rate of production equals their rate of loss, perhaps by diffusion through porous or semi-permeable boundaries.

Autocatalysis becomes plausible if we imagine the autocatalytic cycle to be taking place in a confined space, or bounded volume, so that the concentrations of its components build up. Surface catalysis alone cannot easily explain how a reactant becomes concentrated, since the volume of the solute is, for all practical purposes, infinite, being, for example, the volume of water in all the oceans of a planet. On an unbounded flat surface, autocatalysis will be prevented, or quenched, by dilution.

Inorganic cellular compartments occur naturally, and can also be produced, in the laboratory, as a result of mixing two solutions which have solutes that react to form a froth of insoluble precipitates. Russell proposes that such structures, consisting of vesicles bounded by sulphides of iron and nickel, served as the first incubators of life by permitting, containing, and sustaining chemoautotrophic synthesis (Martin and Russell, 2003; Russell and Hall, 1997; Russell and Kanik, 2010).

A third advantage of the cells envisaged in Russell's model (Russell and Hall, 1997), is that a ready-made proton motive force can be understood to be available prior to life, as a result of hydrothermal convection into mounds of inorganic vesicles. One such vesicle is depicted schematically in Figure 2A. This convection is thought to bring relatively hot, alkaline and reducing solution into the vesicles, with a temperature, pH, and redox gradient across their boundaries being created by the cooler, more acidic, and more oxidising external environment of the ocean. Mitchell's chemiosmotic theory proposes vectorial movement of protons and electrons, establishing a proton motive force as a trans-membrane gradient of pH and electrical potential (Mitchell, 1961). The proton motive force as an intermediate in energy conversion appears to be universal for life as we know it (Lane et al., 2010; Nitschke and Russell, 2009). There are few organisms that manage with only fermentation, and with substrate-level phosphorylation. The few that do manage depend on the products of chemiosmosis in other cells, and are therefore secondary, and derived. The first living cell was surely a chemiosmotic device; a compartmentalized system of energy transduction (Lane et al., 2010; Lane and Martin, 2010; Nitschke and Russell, 2009; Raven and Smith, 1976; Russell, 2006; Russell, 2009; Russell and Hall, 1997).

So a proton motive force is another fundamental property of all living cells. Thus, hydrothermally-produced electrochemical and pH gradient across pre-existing cell boundaries might explain, in principle, where the energy comes from for early biochemical synthesis (Martin et al., 2008; Nitschke and Russell, 2009). Geothermal convection is a source of energy that is continuous and indefinitely renewable. Given cells, convection can establish a ready-made chemiosmotic system of energy transduction for autocatalysis (Figure 2B) and for coupling between oxidation-reduction, phosphoryl group transfer, and active transport.

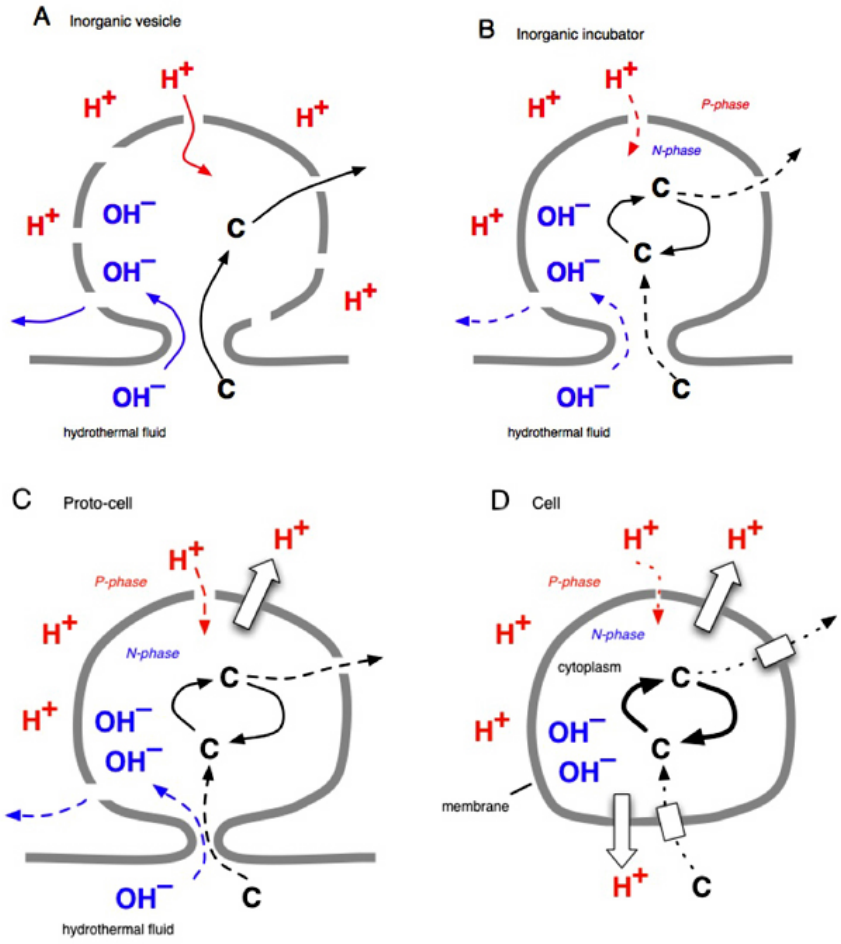

Figure 2. Steps from a porous inorganic metal-sulphide vesicle to a free-living cell. **A.** Hydrothermal fluid is alkaline, in contrast to the acidic ocean into which it flows through the boundary of a porous, catalytic, metal sulphide vesicle. **B.** The porosity of the vesicle is decreased by the intrusion of products of autocatalytic carbon reduction, symbolized by the cycle of carbon. The boundary of the vesicle begins to sustain a small gradient of hydrogen ion concentration and electrical potential difference: positive (P-phase) outside; negative (N-phase) inside. **C.** The porosity decreases further. A mechanism of negative feedback interrupts proton influx, and an active transport drives proton efflux. **D.** The vesicle is now formed from the organic intrusion alone, which presents a sufficient barrier to proton influx for the active proton efflux to generate and sustain a proton motive force. The dependency on hydrothermal fluid is lost, along with the inorganic container, though remnants of the latter remain to support vectorial electron and proton translocation.

Modern cells are bounded by lipid membranes with very low electrical conductivity, and very low permeability for hydrogen ions (protons). It might be argued that cellular compartments bounded by inorganic materials will be too leaky to protons and other ions to sustain a proton motive force, in contrast to the more familiar compartments today bounded by insulating lipid bilayers. However, an inorganic boundary needs to present only a minor kinetic barrier to free diffusion, since convection will continually replenish a reducing and alkaline internal, aqueous phase. An analogy might be that a sieve is not as good as a bucket for carrying water. However, if the mesh is fine, a sieve is better than nothing; it is a start.

A further advantage of supposing that life arises within pre-existing cellular compartments is that an internal environment is thus defined, and, as a result, homeostasis - the maintenance of a constant internal environment despite changes in the external environment - becomes possible. Without cells, nothing can be described as "living" in any sense in which we might recognise the term. Cells, pre-formed by geochemistry, not by biology, are surely a condition for the emergence of life.

5. TRANSITION TO THE FREE-LIVING STATE

If a viable concentration of reactants is achieved in leaky inorganic vesicles, a requirement for the dynamic chemical system to become separated from a replenishing influx is that negative feedback must take the place of loss of

reactants by diffusion (Figure 2C). If, as argued, the magnitude of the proton motive force is an essential variable, it may be that a simple pH-dependency enters into the negative feedback loop before transition can occur to the free-living state (Fig 2D). The alkali-stable and acid-labile phosphorylation of the amino acid histidine could plausibly provide the switch that turns off proton influx when intracellular pH decreases below a certain threshold.

Histidine protein phosphorylation is the chemical basis of a wide variety of biological environmental sensors (Wolanin et al., 2002). The effector, or response regulator, is usually another protein, one that receives the phosphate group onto an aspartic acid side chain, with a structural consequence in the exposure of a hydrophobic patch on the protein surface (Stock et al., 2000). Perhaps this system arises from a pH-stat in which phosphoryl group transfer from histidine to aspartate occurs below a pH threshold, with the effect of creating a hydrophobic plug that limits the rate of further proton influx into a nascent cell, and thus serving to maintain the alkalinity of an internal environment originally alkaline merely as a result of geochemical processes.

Maintenance of intracellular pH early in cell evolution has previously been considered (Raven and Smith, 1982), albeit within the context of a theory, now superseded (Lane et al., 2010), of the origin of life from a solution of organic compounds synthesised inorganically – a "primeval soup". The origin of chemiosmotic energy coupling from regulation of intracellular pH by electron transport- driven and ATPase-driven proton pumps has also been proposed (Raven and Smith, 1976).

Coupling between proton translocation and ATP synthesis-hydrolysis in respiration and photosynthesis is known to involve rotary catalysis by an intricate molecular motor, the F-type ATP synthase (Abrahams et al., 1994). Coupling between proton translocation and electron transfer occurs either by chemical coupling such as that seen in cytochrome b-c1 complexes (Swierczek et al., 2010) or by redox-linked conformational changes in ion channels as seen, for example, in respiratory complex I (NADH dehydrogenase) (Efremov et al., 2010).

6. REDOX SWITCHES IN MAJOR TRANSITIONS OF EVOLUTION

A redox switch in the context of biological evolution is a signal transduction event or pathway that places gene expression under the regulatory control of the redox state of an electron carrier. Two broad classes of redox switch can be discerned today.

6.1. Redox Sensors, Redox Response Regulators. Two-component regulatory systems, comprising sensor kinases and response regulators, are ubiquitous signal transducers in bacteria, and today usually control gene expression, often at the level of transcription. The sensor is usually a membrane protein and becomes phosphorylated in response to the environmental signal. Its substrate, the response regulator, is typically a DNAbinding protein that initiates transcription of a specific gene or genes by interacting, in its phosphorylated form, with an RNA polymerase. Entirely different environmental inputs can each determine specific outputs, all using this conserved chemical mechanism of signal transmission (Skerker et al., 2008). I proposed the terms redox sensor for any electron carrier that initiates control of gene expression upon oxidation or reduction; and redox response regulator for the corresponding DNA-binding or RNA-binding protein that modifies gene expression as a result of the action of a redox sensor (Allen, 1993a; Allen, 1993b). Any redox sensor together with its corresponding redox response regulator comprises a two-component redox regulatory system (Allen, 1993a; Allen, 1993b). A consensus view of such a system in a negative feedback loop is shown in Figure 3. Today ATP appears to be the universal donor of the phosphoryl group to any histidine sensor kinase. In view of its proposed role as a precursor of ATP in energy coupling (Martin and Russell, 2007; Russell and Martin, 2004), I suggest that acetyl phosphate serves as the phosphoryl group donor to a histidine of an oligopeptide redox sensor in nascent cells (Figure 3),

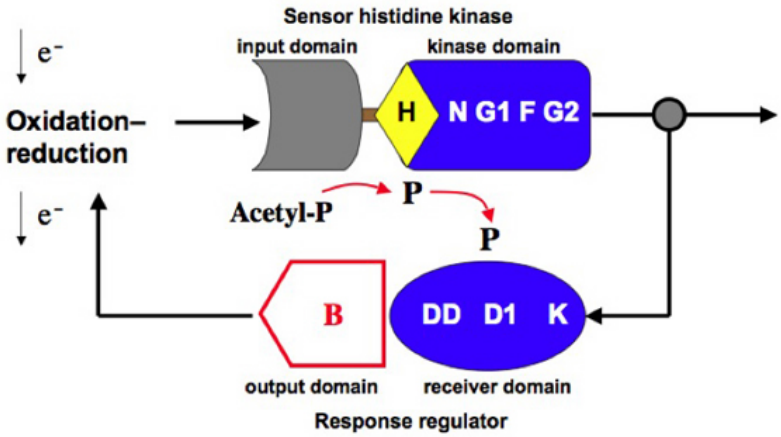

Figure 3. A generalized feedback loop (compare Figure 1) involving the elements of a twocomponent redox regulatory system.

6.2. Redox Activators, Redox Repressors In contrast to a two-component system based on phosphoryl group transfer (Figure 3), activator or repressor proteins exist in which sensor and response regulator domains are present in a single protein and connected functionally by a change in protein structure. Such systems are exemplified by the catabolite activator or repressor protein (CAP or CRP). An example is the *Escherichia coli* FNR protein which represses the enzymes fumarate and nitrate reductase under aerobic conditions and other conditions of high redox potential. The respiratory electron transport chain is thereby re-configured to use oxygen as a terminal electron acceptor in place of fumarate or nitrate, according to availability. This re-configuration of modular energy-transducing systems is widespread, perhaps ubiquitous, in biology, and exemplifies the versatility of respiration and photosynthesis in adaptation and fine-tuning to altered environmental conditions. FNR is a helix-turn- helix DNA-binding protein with an amino-terminal segment containing cysteines that ligate a redox-active iron atom (Spiro and Guest, 1990). Reduction of the iron from Fe^{III} to Fe^{II} is thought to cause a protein structural change that regulates transcription. From effects of poising the growth medium at different potentials on expression of a reporter gene for *frd* (encoding fumarate reductase), the standard mid-point potential (*Em7*) of the FNR response has been estimated at + 400 mV (Unden and Bongaerts, 1997). An overview of a such redox-responsive system in a negative feedback loop is shown in Figure 4.

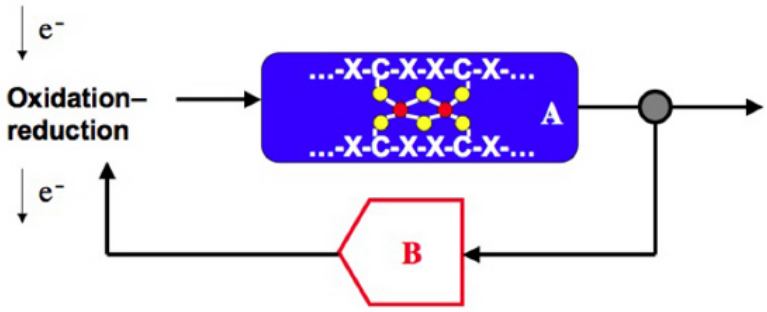

Figure 4. A generalized feedback loop (compare Figure 1) involving the elements of a redox repressor or activator incorporating an iron-sulphur centre in a polypeptide.

7. REDOX HOMEOSTASIS IN THE ORIGIN OF LIFE ON EARTH

Living things exhibit the property of homeostasis. If, as described in section 1, life is redox chemistry, then redox homeostasis must have been a primary requirement of the precursors of the first living cells. Paraphrasing Claude Bernard, redox homeostasis may be defined as the maintenance of a constant electrochemical potential and ionic concentration gradient across a cellular boundary, despite fluctuations in the electrochemical potential of the external environment and changing identities and activities of electron donors and acceptors - of electron sources and sinks. So far, this fundamental feature of the emergent living cells seems not to have been considered, despite dramatic progress in understanding the potential of inorganic incubators for early biochemical synthesis (Russell, 2006; Russell, 2009).

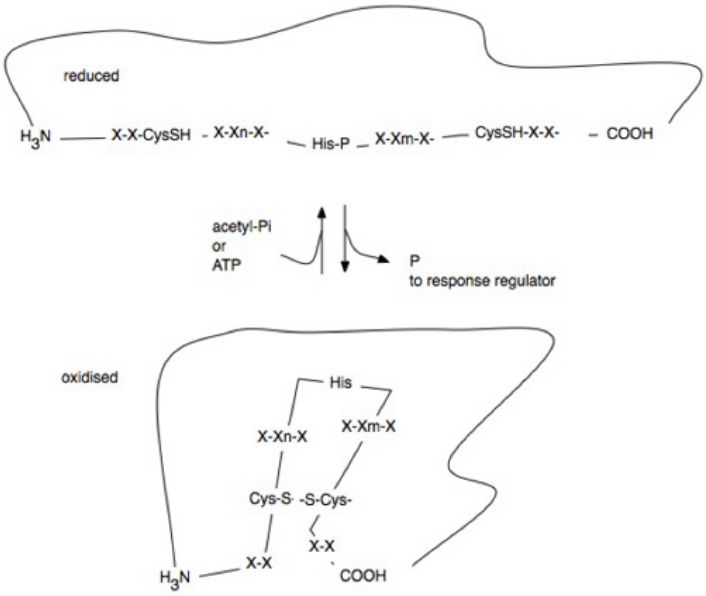

Figure 5. Proposed model for a synthetic redox sensor kinase. A simple peptide chain is depicted, one containing a histidine that may accept a phosphate group from acetyl phosphate, ATP, or carbamoyl phosphate. When neighbouring cysteines are in their reduced (sulphhydryl) forms, phosphorylation is promoted by exposure of the histidine on the surface, as a phosphate acceptor. When the cysteines become oxidised, the cysteines form a disulphide bridge, burying the histidine within the folded chain, prohibiting phosphorylation. This peptide will have the property of a prototype electron, or redox, sensor, with redox sensing causing a conformational change that controls its phosphorylation. Other variations are plausible. For example, an equally likely connection is for oxidisation of the peptide to expose the His for phosphorylation, rather than bury it, producing a reversed sign for the switch (i.e. oxidation equals "on"; reduction equals "off"). Maquettes of synthetic peptides as analogues of natural redox proteins (Koder and Dutton, 2006) can be considered and incorporated into the experimental design.

A Chemical Model For Pre-Biotic Redox Homeostasis The origin of redox homeostasis can be considered and perhaps approached experimentally by devising chemical model systems using building-blocks thought to have been present in the inorganic, transition metal sulphide incubators proposed by Russell. One of a number of possible devices may be described as follows (Figure 5). A simple peptide chain could be synthesised, one containing a histidine that may accept a phosphate group from acetyl phosphate. When neighbouring cysteines are in their reduced (sulphydryl) forms, phosphorylation is promoted by exposure of the histidine on the surface, as a phosphate acceptor. When the cysteines become oxidised, the cysteines form a disulphide bridge, burying the histidine within the folded chain, prohibiting phosphorylation. This peptide will have the property of a prototype electron, or redox, sensor, with redox sensing causing a conformational change that controls its own phosphorylation.

A cognate prototype response regulator could also be constructed, containing an aspartate residue whose phosphorylation results from phosphate group transfer from just one of the two forms of the sensor – initially its reduced form, with the histidine exposed for phosphoryl group transfer. A chemical feedback system of this type can be devised and synthesised. A negative feedback loop (Figure 1) is expected to arise as a consequence of coupling phosphorylation of the response regulator to re-oxidation of the sensor, so preventing the sensor's phosphorylation, and thus maintaining a constant internal environment despite changes in applied redox potentials. This simple model might serve as a reference for studies of autocatalysis in what are now thought to be chemical analogues of the nascent living cells.

8. THE RETENTION OF REDOX SIGNALLNG IN COMPLEX LIFE

Two-component regulatory systems, comprising sensor kinases and response regulators, are ubiquitous signal transducers in bacteria. A two-component regulatory system, centred on the electron carrier plastoquinone, also controls gene transcription in chloroplasts – the photosynthetic subcellular organelle of plants and algae (Puthiyaveetil et al., 2008). The genes for the two components themselves are universal in photosynthetic eukaryotes (Puthiyaveetil and Allen, 2009). I have proposed that bacterial redox regulatory systems survive, in modified form, in both mitochondria and chloroplasts (Allen, 1993b). These regulatory systems connect electron carriers with DNA promoter binding sites. They have been refined by natural selection in order to provide coupling between information processing and redox chemistry. This coupling extends to the eukaryotic nuclear-cytosolic system. It is suggested that complex life requires sequestration of energy-transducing membranes from the cell's boundary membrane (Lane and

Martin, 2010). A single, centralised genetic system may run, in consequence, at much greater energetic efficiency per gene (Lane and Martin, 2010). A residual genetic system in each subcellular, energy-converting compartment is then required to give co-location of gene and gene product for redox regulation of gene expression – the CORR hypothesis (Allen, 2003a; Allen, 2003b; Allen et al., 2008; Allen et al., 2005).

The name "two-component regulatory system" is used to describe a class of signal transduction pathways found in eubacteria (Grebe and Stock, 1999). Each one is made up of two protein components with conserved domains. These two conserved protein components are a sensor kinase and a response regulator. In response to a specifi c environmental signal the sensor kinase or histidine kinase undergoes autophosphorylation at a conserved histidine residue. The phosphate group is then transferred to an aspartate residue in the response regulator or effector. The resulting structural change causes an appropriate physiological or genetic response to the signal detected by the sensor kinase. Since response regulators are often DNA-binding transcription factors, the regulatory response mediated by a two-component system usually involves control of initiation of transcription.

Two-component regulatory systems originated in bacteria and have spread throughout the eukaryotic domain of life through endosymbiotic, lateral gene transfer from the bacterial ancestors and early evolutionary precursors of chloroplasts and mitochondria. Until recently it was believed that two-component systems of the ancestral cyanobacterial symbiont are no longer present in chloroplasts (Grebe and Stock, 1999). It is now known that two-component systems have survived in chloroplasts as products of nuclear genes (Puthiyaveetil and Allen, 2009; Puthiyaveetil et al., 2008), to add to the persistence of response regulator-like genes in chloroplasts of some non-green algae (Duplessis et al., 2007).

9. FEEDBACK AND FEEDFORWARD. EXPECTATION OF ENVIRONMENTAL CHANGE

Feedforward results from a reference or target output being compared with the actual output, and from feedback being controlled accordingly. There is no intention, but comparison between reality and the output of an internal chronometer or time reference produces an expectation of what will be appropriate response at a certain time. As in science itself, the living cell learns – refines its model of the world – by comparison of the observed with the expected (Allen, 1998; Popper, 1972). Biological clocks themselves seem to have their origin in two-component regulatory systems (Simons, 2009) and rhythmicity is a property of simple model systems exhibiting negative feedback. Perhaps an early, periodic environmental change induces a rhythmic adaptation that becomes free-running, thus providing the internal chronometer to which reference can be made for anticipation of an appropriate response (Allen, 1998).

10. THE REDOX SWITCH HYPOTHESIS FOR THE ORIGIN OF FREE OXYGEN

10.1. Photosynthesis Photosynthesis is the conversion of radiant energy into electrochemical potential and its subsequent storage in the form of chemically reduced carbon compounds. These reduced storage molecules are food, and release of the energy they contain occurs by their stepwise oxidation in respiration. Respiration thus requires an electron acceptor from the environment. For aerobic respiration upon which most complex (and multicellular) life depends, the electron acceptor is oxygen.

10.2. Anoxygenic Photosynthesis Anoxygenic Photosynthesis was studied and formally described by Cornelis van Niel, who correctly proposed that all photosynthesis is a light-driven redox reaction. In the van Niel equation (Equation 2), electron transfer is equivalent to hydrogen atom transfer (H in bold) from the donor to carbon dioxide (CO_2):-15

$$2\mathbf{H_2}A + CO_2 + \text{light} \rightarrow \mathbf{CH_2}O + H_2O + 2A \qquad \text{Equation 2}$$

donor acceptor reduced carbon oxidation product

"H_2A" may be any of a variety of organic or inorganic electron donors, specific examples being succinate (organic), hydrogen sulphide, molecular hydrogen (where "A" is nothing), or ferrous iron (FeII). When these electron and hydrogen donors are substituted into the above equation, specific, known cases of anoxygenic photosynthesis are accurately described.

10.3. Oxygenic Photosynthesis Oxygenic Photosynthesis has been described by Falkowski as "the last of the great inventions of microbial metabolism, and it changed the planetary environment forever" (Leslie, 2009). An insight of van Niel was the appreciation that oxygenic photosynthesis, too, is accurately described as a special case of the van Niel equation. On Earth, at not less than 2.4 Gyr (gigayears; 10^9 years) before present, an anoxygenic photosynthetic organism hit upon a mechanism to use water (H_2O) as H_2A), the electron and hydrogen donor for energy capture and storage (Equation 3).

$$2H_2O + CO_2 + \text{light} \rightarrow CH_2O + H_2O + O_2 \qquad \text{Equation 3}$$

donor acceptor reduced carbon oxidation product

The equation (Equation 3) simplifies to the better-known equation for photosynthesis (Equation 4).

$$H_2O + CO_2 + \text{light} \rightarrow CH_2O + O_2 \qquad \text{Equation 4}$$

This last formulation is mechanistically misleading since it hides the all-important hydrogen (electron) transfer, and suggests, incorrectly, that the action of light is to split CO_2 with subsequent hydration the carbon atom. It was demonstrated in the 1940s that the oxygen comes from water, not from CO_2. Thus oxygenic photosynthesis is indeed the product, too, of light-driven electron transfer. Oxygenic photosynthesis is found in all plants, algae, and cyanobacteria, and it produces the oxygen that transformed life on Earth and now occupies 20 % by volume of its atmosphere, supporting aerobic respiration that sustains complex life, and producing the ozone UV shield that allows terrestrial life.

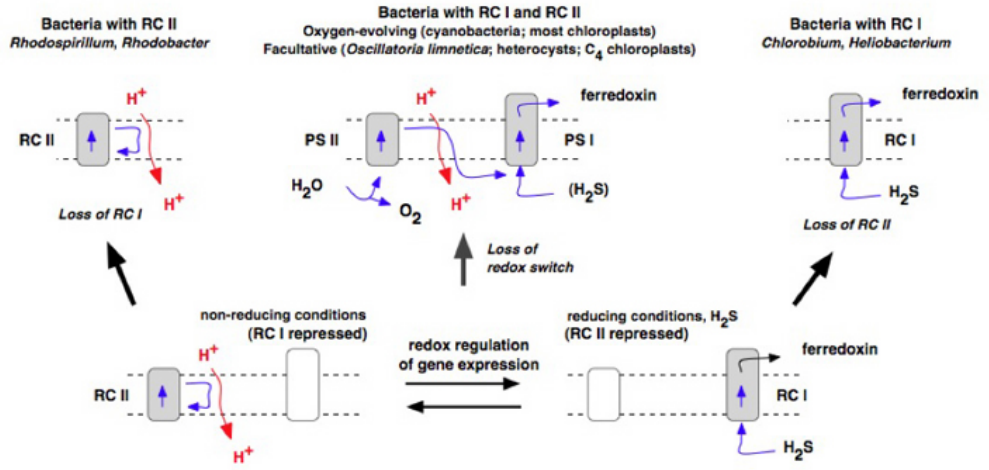

Figure 6. Retention of type I and type II photosynthetic reaction centres, selected by a redox switch.

Type I (RC I) and type II (RC II) reaction centres separate, allowing specialisation and eventual loss of the redundant reaction centre in photoautochemotrophic (type I-containing) lineages (e.g. *Chlorobium, Heliobacillus* spp.) and in photoheteroorganotrophic (type II-containing) lineages (e.g. *Rhodobacter, Rhodospirillum* spp.). However, a versatile, facultatively chemoautotrophic photosynthetic bacterium retains genes for both type I and type II reaction centres. In this hypothetical ancestor of cyanobacteria and chloroplasts, expression of type I centre genes in the presence of H_2 is accompanied by silent type II genes, which are themselves induced under non-reducing conditions, when type I genes become repressed. Subsequent loss of regulatory control allows co-existence of type I and type II reaction centres, with complementary functions. In place of H_2S, the type II centre, as photosystem II (PS II), oxidises water, liberating oxygen, and donating electrons to the type I centre, as photosystem I (PS I). Adapted from Allen (2005).

10.4. The Redox Switch Hypothesis for the First Cyanobacterium, and for the Origin of Free Oxygen The Redox Switch Hypothesis (Allen, 2005; Allen and Martin, 2007) is depicted in Figure 6. It predicts the existence of an anoxygenic photosynthetic bacterium retaining genes for both type I (photosystem I) and type II (photosystem II) reaction centres (Bryant and Frigaard, 2006). These genes are never expressed at the same time – instead, they cater for a versatile and flexible metabolism that allows the bacterium to grow either with (type I) or without (type II) H_2S as the electron donor for photosynthesis.

10.5. Free Oxygen as a Planetary Signature of Life The relevance of the redox switch hypothesis (Figure 6) to astrobiology is that the abundant, free, diatomic molecular oxygen in Earth's atmosphere indicates unambiguously that the surface of our planet is maintained far from thermodynamic, redox equilibrium. Spectroscopy of extra-solar planetary atmospheres may soon approach a resolution at which abundant free oxygen will be detectable, if it is present (Cockell et al., 2009a; Cockell et al., 2009b; Javaux and Dehant, 2010). If evidence is found for extraterrestrial or extra-solar redox disequilibria, it will be reasonable to take it as evidence that life has arisen there (Cockell, 2008) and evolved there, at least to the point where Earth was in the late pre-Cambrian when oxygen finally reached the atmospheric concentrations seen today, as a consequence also of sequestration or dumping of fixed

carbon (Equation 4) in both inorganic and organic form.

11. TWO VIEWS OF LIFE AND ITS ORIGIN: ENERGY AND INFORMATION

In section 1, I proposed a description of living organisms as self-replicating and selfsustaining dynamic chemical systems, obtaining energy from, and information about, their environment – including their chemical, physical, geological, and biological components. There is also a valid perspective on life from evolutionary genetics. According to this view, self-replication arises from the complementarity of sequences of monomeric subunits that together comprise informational macromolecules. However, this perspective is insufficient, since it fails to account for the source of the energy that is required for synthesis and replication of information macromolecules themselves, just as much as it fails to account for metabolism and transport.

Living things are self-sustaining because the information thus encoded is utilised selectively, placing its carriers in the path of spontaneous dissipation of thermodynamic disequilibria, harnessing free energy as well as assimilating chemical substrates to build more cells, and cellular components. Thus life diverts energy from chemical and geochemical gradients to itself, and uses this energy to perform work in assimilation and in synthesis of the same informational macromolecules that encode the machinery for tracking and exploiting their sources of energy and raw materials. Infidelity in self-replication – mutation – then represents misinformation that occasionally, by chance, improves the dynamic, living system's ability to track and exploit sources of energy and materials. Thus arises a third fundamental property of living things, recognised by Charles Darwin and by Alfred Russel Wallace – a living system has the capacity to evolve by means of natural selection of chance variation.

I suggest that this new and emerging synthesis will, perhaps by 2020, unite these geochemical and evolutionary-genetic perspectives. The separate disciplines of genetics, evolutionary biology, and biochemistry are contemporary points of view – no more. Life itself, as we know it and are part of it, forms a self-sustaining planetary biofilm, the origin and properties of which we will be able to see in a new way when we understand the dynamic link between redox chemistry – the basis of energy metabolism – and information transfer in gene expression and replication. The major impact of this synthesis of traditional disciplines may be that it will offer a new and better understanding of life on Earth, thereby to sharpen our focus its essential features and on the features by which we may recognise life on other planets or moons in our own solar system, and, eventually, elsewhere in the Universe.

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