The Origins Center, in which Dutch scientists work together to answer questions submitted to the National Science Agenda about the origin of the Universe and life, had its formal kick-off during the Fundamentals of Life in de Universe symposium. Two days of challenging presentations and stimulating discussions whetted the appetite for a research program that crosses disciplines and both temporal and spatial scales on an unprecedented level.

What is the origin of Earth and life? Can we predict biological evolution? Is it possible to build life from molecules to biosphere? What can we say about extraterrestrial life and how do we bridge the huge temporal and spatial scales from quantum mechanics through living matter to galactic superstructures?

These five questions govern the tentative research program of the Origins Center, and are inspired by the general public in The Netherlands. It was therefore fitting that the official opening symposium of the Origins Center at the University of Groningen was built around these five game changers. During two days (30 August and 1 September 2017), 19 presentations covered different aspects of the five questions.

The program was however started by a video message by the Minister of Education, Culture and Science Jet Bussemakers, who wished the scientists well on their quest. She stressed that science need the backing of the general public, and challenged the Origins Center to interact with this public, which after all submitted the questions of the National Science Agenda.

To kick off the scientific program, **John Hernlund**, who holds a PhD in Geophysics & Space Physics talked about his own experience of interdisciplinary research into 'Big Questions' at the Earth Life Science Institute (ELSI) of the Tokyo Institute of Technology in Japan. ELSI is one of a number of new institutes created by the Japanese government in order to stimulate an international research environment in the country. There's a budget of USD 1 billion available, typically USD 10 million per institute per year.

ELSI is tackling similar questions as the Origins Center, i.e. how our planet was formed and how its early environment allowed for the rise of initial life and its subsequent evolution to complexity. Hernlund is one of fifteen PI's at the institute.

Working at such an institute is a challenge, Hernlund explained to the audience. 'Traditional research is centered on one discipline, which fits in one person's mind. But for big questions you need different disciplines, so you have to bring different brains together to form a kind of collective intelligence.'

For this process, flexible scientists are needed, which often means young people. 'The people are the key ingredient!' Next, these people need time to adopt the big questions, they often need to change the direction of their work when entering an institute like ELSI. 'Trust is the key, give them the right incentives. For example: don't reward output, but collaboration.'

Doing a regular 'health check' is also important to keep all members focused. 'Does everyone still know how the institute works?' And money is an issue. When scientists have to get a lot of external grant money, this might loosen their ties to the central program. But if everything works, an institute like ELSI work as a 'lens' to focus the PI's on the big question.

One example from ELSI which Hernlund mentioned was the idea of 'Deep Time Biochemistry': 'Just leave beakers standing for six months and see what happens!' As it turned out, slow processes did happen which would not have been observed in normal chemical experiments.

Session 1 Origin of the Earth and of Life

What does it take to craft a planet capable of supporting life as we know it? **Geoff Blake**, Professor of Cosmochemistry and Planetary Science and Professor of Chemistry (Caltech, US) discussed what we know from astronomy about the origin of Earth-like planets.

Taking the restrictive view of a 'solar system' such as our own, several characteristics, like a 'gatekeeper planet' such as Jupiter and of course a rocky planet in the habitable zone, are important. Even if less than 0.01 percent of sun-like stars have this configuration, this would add up to 10^7 such systems in our galaxy. Stars and planetary systems are born in molecular clouds and start with talcum-powder sized dust. The gas in these clouds already contains organic molecules, even including chiral molecules, long before planetary surfaces are assembled.

To study planet formations itself it is necessary to study the tiny regions of dense clouds that are making stars, and with new telescopes it has recently become possible to see roughly which processes take place at different distances from the center of a protoplanetary disk and assess the distribution of water, CO and small organic molecules. Blake: 'This way, we can learn to understand the processes which occur at different distances in the disk.'

Blake described how Earth has a low carbon and nitrogen content compared to the initial conditions. This begs the question: What is the importance of the amount of carbon/nitrogen for life on the planet? Furthermore, most of the carbon on Earth is located in the deep earth, certainly the mantle and quite possible the core. And as collisions – like the one that probably spawned the Moon – would have blown away any organics on the surface, this could mean that a late exogenous delivery of carbon and nitrogen is important, Blake concluded: 'You need this late delivery to get carbon and nitrogen in the atmosphere, rather than in the core or mantle, or being blown away.'

Once you have all the pieces in place – a rocky planet in the habitable zone, the right atoms and molecules – what happens next? You will get chemical reactions, explained Earth scientist **Bob Hazen** (Carnegie Science, US), and life is based on chemical reactions. Hazen's work is focused on the role of minerals in the origin of life. He argued that minerals can facilitate such a wide range of reactions that on a planetary (time) scale, unlikely processes become inevitable.

Minerals can act as catalysts, but may also form protective containers or selective scaffolds. In this way, they can create geochemical complexity that is hard to emulate in the lab. The amount of minerals likely to occur on Earthlike planets is huge: some 2,000 have a likelihood of nearly 100 percent, while another 20,000 will probably be present on at least one Earth-like planet somewhere in our galaxy.

'Each mineral species represents a chemical reaction', explained Hazen. Given the surface area of clay minerals and average reaction times, Hazen calculated that 10^{54} chemical reactions could have occurred during the roughly 600 million years before the start of life on Earth. 'This means that chance versus necessity is a false dichotomy.' But, someone from the audience asked, doesn't the origin of life need a chain of different reactions? Hazen agreed, but saw possible solutions: 'For example, some minerals grow from other minerals.'

Chemist **John Sutherland** (Medical Research Council Laboratory of Molecular Biology, Cambridge, UK) discussed the chemistry that could have started life from a different angle. Biological life is very complex, so something much simpler must have arisen first, something that could eventually produce subsystems like RNA, metabolism, membranes and proteins. Sutherland started his search for a common pathway that would produce the necessary building blocks for these systems with just a one-carbon feedstock, hydrogen cyanide (HCN). 'This can be reduced to form carbon-carbon bonds.' Furthermore, UV-driven reductive chemistry would be a good starting point the create C2 or C3 molecules, which form a product tree that includes a lot of amino acids. Ferrocyanides and other salts could produce further building blocks.

Geochemical scenarios that would produce these reactions include impact shocks that produce HCN from meteoric carbon and atmospheric nitrogen, but also heating and evaporation in a small stream. And H_2S produced alongside SO_2 from volcanism would act as a reducing agents.

Once building blocks are formed, polymers like RNA could be made. Most of these molecules would be inactive, but recycling of the components coupled to selection would drive RNA evolution, as long as there is an input of energy in the cycle of RNA creation, breakdown and re-assembly.

Paulien Hogeweg (Utrecht University, the Netherlands) introduces the final lecture in this session with a question: how did we get from a simple beginning, to life as we know it? In the early 1970s she coined the term bioinformatics together with Ben Hesper, describing the study of informatics processes in biological systems. Using this bioinformatical approach she considers the question on the evolution of life on earth.

How do you get from a simple self-replicating molecule (a replicator) to an elephant? Many people assume that once the first replicators appeared, Darwinian evolution will take over and inevitably lead to more and more complex lifeforms. Basic evolutionary theory accounts only for maximizing replication rate, not for the increase of complexity. In fact there are well known obstacles to the increase of complexity, both at the level of the individual replicators as on the level of ecosystems.

Hogeweg showed in models of the RNA world (the hypothesized replicators at the origin of life) how evolutionary dynamics can overcome these obstacles. In spatial models new levels of evolution emerge through self-organization. The presence of parasites (viruses/cheaters) play an important role in this self-organization process and therewith help rather than hinder the evolution of complexity. Hogeweg showed that in a variety of multilevel evolution models division of labor between information storage and information usage evolves. For example DNA as information storage molecule can evolve in the RNA world. This division of labor evolves despite rendering reproduction less efficient. Instead, the unidirectional information flow ('Cricks dogma') renders the evolutionary process more efficient and open ended.

Session 2 Predicting the evolution of Life

All our knowledge about biospheres is based on Earth. So, Earth system scientist **Tim Lenton** (University of Exeter, UK) simulated 'virtual biospheres' to increase our understanding of the interaction between life and planet. Lenton is inspired by Lovelock's Gaia hypothesis and wants to know what selection mechanisms could help life to shape the biosphere.

There are different gases present on a planet with life, compared to a lifeless planet. Biospheres need to recycle materials to 'build bodies', as Lenton put it. He showed 'one pot' simulations in which nutrient recycling loops appear in a robust way. By coupling flasks in the simulation, he observed how communities that regulate their environment tend to spread at the expense of those that degrade theirs. This works in particular with heterogenous environment variables. However, on Earth many variables like oxygen or carbon dioxide concentrations are well-mixed. In this case, other mechanisms should drive the interaction between life and the biosphere.

At the planetary scale, sequential selection could occur when life affects the environment. If this leads to a stable situation, it will persist. But often, unstable situations occur, leading for instance to a snowball Earth. This 'resets' the system and as long as some life persists it will eventually lead to new effects on the environment and the chance of a stable outcome.

The simulations show different types of outcomes: a situation where life always survives, a 'bottleneck' scenario with early abrupt dying or long-term survival, a critical scenario where random extinction times are found and an outcome where life always perishes. This could provide some guide to what we may expect to detect on potentially habitable exoplanets around other stars.

As for the future of Earth, Lenton noted that humanity causes changes to the environment, but is now able to observe the consequences and alter them, thus creating self-aware planetary self-regulation.

Molecular biologist **Tetsuya Yomo** of East China Normal University took up the challenge to build a life-like network from biomolecules. He used a system where RNA and RNA replicase were present in liposomes. When he added other liposomes with energy and building blocks, they fused and produced new RNA strands. Fission of the vesicles (using a freeze-thaw method) produced a new 'generation'. In this system, the size of the vesicles remained stable over some ten cycles.

Conducting the daily passage experiment of more than 500 generations with mutations during RNA replication, Yomo studied whether his system would show Darwinian evolution. Short strands of RNA evolved to act as 'parasites', as they are copied faster. But the parasites were suppressed over several generations, as the affinity of the RNA replicase for the short strands diminished. Thus, there was Darwinian evolution present. Yomo concluded that a simple proto-cell of less than 10 µm diameter could have evolved a gene replication network and show life-like characteristics.

Once evolution has started, is it possible to predict its course? This question was tackled by evolutionary ecologists **Marcel Visser** (Netherlands Institute of Ecology, NIOO-KNAW, the Netherlands) and **Jacintha Ellers** (Free University Amsterdam, the Netherlands). In their talk, they also discussed three misconceptions about evolution. The first is that evolution is something from the past. ‘Our planet changes, so life changes’, Visser explained. Long term studies of the great tit show that in response to climate change, the birds start breeding a week earlier than 25 years ago.

So can evolution come to the rescue of species faced with global warming? Visser: ‘Misconception number 2 is that evolution is too slow. But that is not always the case.’ He gave several examples of species adapting to e.g. urbanization or climate change. However, there are also many species which don’t seem to adapt. The big question is whether we can predict this. ‘That is one of the game changer questions in the Origins Center’, explained Visser. This question is a dot on the horizon they hope to reach in perhaps 20 years.

Evolution acts on the phenotype, but it changes the distribution of genotypes. This brought Visser to misconception number 3: that genotype predicts phenotype. In fact, the path from genes to phenotype is very complicated and many environmental factors play a role. In the great tits mentioned above, the genotype shapes the phenotype much more in warm years than in cold years.

One thing we do already know is that we can speed up evolution by increasing variability in the population. The classic method is connecting populations, but other, albeit less practical, approaches are inducing non-genetic evolution (e.g. by training birds to fly certain migration routes) or genetic modification by using Crispr/cas9 (e.g. via gene drives).

Finally, paleobiologist **Phil Donoghue** (University of Bristol, UK) presented data on when the last common universal ancestor (LUCA) of all current life must have lived. The fossil record won’t answer this question, so Donoghue used the molecular clock, based on mutations in genes that were present in LUCA. He used a panel of 29 nine genes common to all life, analyzed in 102 species. He factored in the fact that the rate of mutations is not always constant over time, lineage and genes. The genetic data were combined with ‘hard dates’ for the last sterilization event on Earth, first dated life forms and the oldest known eukaryotes.

The result is that Donoghue placed LUCA at 4.5 billion years BP, the Archaea/Bacteria split at 3.4 billion years and Eukaryotes at 1.8 billion years. ‘These are fairly robust results’, he concluded. However, his results did contain a few surprises: the Great Oxidation Event (GOE), traditionally linked to the rise of photosynthetic cyanobacteria was no longer connected to this evolutionary innovation. Also, in his data the diversification of Eukaryotes is placed long after the GOE. As he stated at the beginning of his talk, the time scale of evolution and the evidence for the start of life on Earth are still in flux.

Session 3 Building and directing life from molecule to biosphere

‘What I cannot create, I do not understand’ is a famous quote by Richard Feynman, found on a blackboard after his death. Building life can help us to understand it better. That is what the Dutch consortium BaSyC is doing – and they recently got a multi-million euro grant to do it. Biochemist **Bert Poolman** (University of Groningen, the Netherlands) is part of this consortium.

‘Our challenge is to construct all parts of a cell from molecules‘, said Poolman. This is quite a task, as the number of proteins in an *Escherichia coli* bacterium is roughly equal to the number of parts in a Boeing 747. Poolman himself is tasked with creating a metabolism from simple examples found in nature with the goal to sustainably supply the cell of fuel.

Making a synthetic system is more than just getting a few molecules from a real cell and putting them into an artificial vesicle. ‘Cells are not random bags of enzymes, but dynamic structures’, Poolman emphasized. There are many interactions of all the molecules crowding inside cells. Getting the amount and interactions of proteins and other molecules similar to that of a real cell inside a vesicle is in itself already a huge challenge.

Poolman sketched the metabolic pathway he has chosen to test in an artificial system. It produces ATP by converting arginine into ornithine. The nice part is that the arginine importer is driven by ornithine export. A not so nice part is that the system, unexpectedly, increased the acidity in the vesicle, so this required some extra compensatory systems. But it does show that we can learn by building artificial systems.

Poolman also showed an ATP driven ionic strength-gated ABC transporter that he can now power with the fuel generated in the synthetic cell, and the current system is capable of controlling the volume of the cell. A colleague of his at the University of Groningen is creating a synthetic lipid synthesis system, and others construct additional modules. Eventually, the participants of BaSyC must combine their systems to ultimately create a cell that can sustain itself, grow and replicate.

The next speaker, nanoscientist **Cees Dekker** (TU Delft, the Netherlands) is also part of the BaSyC consortium. He aims to produce an artificial system for cell division. For a proper cell division, you need a duplication of parts, spatial separation and finally division. This division is often guided by a protein ring structure.

Over the past years, Dekker studied the processes involved in cell division, in for example cells that were forced into strange shapes like triangles, circles or squares. ‘We wanted to understand the biochemistry behind it all’, he explained. This led to insights in how the cell decides were to divide, and which proteins are involved in positioning the division ring. Oscillations up and down the cell of the Min protein guided the FtsZ proteins that form this ring. But as yet, in vitro and in vivo systems are still different, so more work is needed.

Ultimately, Dekker wants to add division machinery to a vesicle, and induce it to divide. This is still some way off: ‘We are taking baby steps towards the goal of synthetic cell division.’

The keynote lecture which rounded off the first day was given by University of Groningen organic chemist **Ben Feringa**, who was awarded the 2016 Nobel Prize for chemistry for his work on molecular motors, together with Sir James Stoddart and Jean Pierre Sauvage. He explained how his molecular motors are in part inspired by moving biological systems and also that ‘inspired’ can mean the end result is quite different – just like a Boeing 747 that flies but doesn’t resemble a bird.

Chemistry, Feringa explained, can build a lot of wonderful things, but it is not very good at building moving parts. Nevertheless, he succeeded in creating light-driven molecular rotary motors as well as switches. And of course, he combined four motors to create his now famous nanocar. The switches can be used to create self-assembling objects that respond to light. Feringa also made photo-switchable drugs which promise high-precision treatment.

But apart from this work, Feringa has throughout his career been involved in chiral chemistry and more specific, the question of the origin of homochirality in life. ‘This is one of the really big questions.’ There are plenty of ideas on how enantiomeric excess could have arisen. For example by stochastic fluctuation (i.e. mere chance), parity violations or circularly polarized light. Feringa showed the latter could create 0.06 percent enantiomeric excess. A tiny amount, but coupled to an amplification mechanism, it might be enough. Crystallization (favoring one enantiomer) or sublimation could act as such. Feringa expressed his hopes that the Origin Center might create the right community to answer important questions about the emergence of life on our planet.

The third session continued on the second day with ecologist **Han Olff** (University of Groningen). His work bridges scales from molecules through ecosystems to the biosphere. Olff started out be stating that a reductionist approach – only trying to understand how a system works by studying its components – doesn’t work in biology: ‘the elemental composition of a baby doesn’t explain a working baby.’ Instead, the interactions between different components and levels of organization in biological systems are important. Biology is made out of ‘complex interacting systems’, with emergent properties.

He illustrated his point by focusing on autocatalysis. This is found at many levels from chemical reaction sets to ecosystems, though not always under the same name. ‘We need to clarify terminology in order to understand similarities across levels.’ Olff sketched a simple system in which grass forms litter on which microbes live, producing nutrients that can be used by grass. In this feedback loop, the introduction of, for example, earth worms, or herbivores, enhances the mutual benefit of all species, boosting their growth rates. Olff’s research in savannahs has so far shown that large herbivores locally compact the soil, thereby creating conditions favorable for the type of vegetation they eat. But on other patches, earthworms loosen the soil, making it better for them. Thus, competing autocatalytic loops may coexist at the landscape scale.

Expanding on this, Olff went on to develop a mental model which should facilitate thinking and talking about causation across even larger scale differences, down from (sub-)atomic to planetary and astrophysical scales. He made the important point that dealing with complexity across levels of organization requires an approach visualized as a stack of ice-cream cones. At each level of organization, it is important to reduce complexity to a simple set of emergences which form the mechanisms to explain complexity at the next level of organization. This keeps complexity manageable, compared to for example explaining the functioning of the whole ecosystems from the set of all biochemical reactions in all the cells of all organisms that together form such an ecosystem.

To round off this session, biophysicist **Dieter Braun** (LMU Munich, Germany) showed how molecules can be concentrated by simple physical processes. Inducing heat flow and thereby establishing a small-scale temperature gradient results in a non-equilibrium system that might have occurred in for example the volcanic rocks of Iceland. In a fluid-filled container which is heated on one side, convection and cooling will create a system in which molecules accumulate on the cold side.

Bigger molecules will accumulate better than small ones. In this way, for example RNA precursors might accumulate without the need of compartmentalization in vesicles. Indeed, lipids are also concentrated by this system and lead to the formation of vesicles.

The next step Braun took was to look for molecular evolution. When polymerase is added, DNA strands replicate. Interestingly, longer DNA strands are selected over short DNA. The next step is to see if the system can host chemical replication systems without the polymerase and obtain similar results in prebiotic conditions. Braun showed more examples of replication and selection, and different ways of creating a selective flow inside a container or on a surface. He also pointed out that the system that his laboratory developed for temperature-induced molecule accumulation has been the base for an innovative start-up Nanotemper.

Session 4: Life in extraterrestrial environments

Life on Earth is found in the most inhospitable environments. And as we find ever more exoplanets (now approximately 3700 and counting) in great diversity, it seems quite plausible to search for life on these alien worlds. But how do we do this? Astronomer **Giovanna Tinetti** (University College London, UK) explained how the atmosphere of exoplanets have been studied.

Tinetti started her talk by briefly discussing the variation in size, composition and orbit of the current sample of exoplanets. Statistics are limited, and the types of exoplanet we have found so far is strongly determined by the method used to detect them.

It is now possible to take spectra from the atmosphere of exoplanets when they transit their star (as viewed from Earth). But this technique is limited to planets in an orbit close to their parent star which transit at short intervals, as this allows for multiple measurements. Planets in wider orbits could be studied by direct observation, masking the parent star.

Readings from exoplanet atmospheres have in some cases shown water vapour and carbon-bearing molecules. But what kind of signature would point to life on such a planet? Life will impact the composition of the atmosphere, explained Tinetti, and it will trigger a chemical disequilibrium. But our knowledge of biospheres is limited to Earth. Our planet shows near- infrared reflection from photosynthetic pigments. But on other planets, those pigments might be different – depending on the light emitted by the parent star.

‘The definition of a biosignature has not changed since the 1970ies’, Tinetti said, and is mainly based on our knowledge of life on Earth. ‘So far, the definition of habitability is based on a very simple concept: you need liquid water.’ In the next decade, she would like to do a census of the atmospheric chemistry of non-habitable planets, with a variety of temperatures, sizes and mother stars. Only then we should be prepared to tackle planets in the habitable zone, to get more statistics on which to base a biosignature of life on other planets.

In our own solar system, we can actually go and look for life on other planets (or moons). Astrobiologist **Inge Loes ten Kate** (University of Utrecht, the Netherlands) discussed the possibility of life on Mars. Ten Kate has worked on the Curiosity Rover program. Based on what we know of the conditions under which life evolved on Earth, she listed the requirements for life: a solvent, the right physicochemical conditions (e.g. temperature, acidity), presence of major elements and trace elements needed for life, organic compounds and available energy.

All the conditions she listed should be met in one place (location?) for life to emerge. On Earth, hydrothermal vents are interesting candidates, as are shallow pools. Hydrothermal vents are studied as one-pot-synthesis scenario: all conditions in the same location and all the necessary molecules synthesized locally. Shallow pools rely on getting part of the necessary molecules through external delivery by for example comets or meteorites. Additionally, the latter would be flooded with UV radiation from the young Sun. Next, Ten Kate compared her list with studies performed in three Martian locations by different Rovers: Endeavour crater and Meridiani Planum (both visited by Opportunity) and Gale Crater (visited by Curiosity).

Out of these three candidates, only Gale Crater ticks all the boxes. In this crater, formed some 3.7 billion years ago, a shallow pond or an impact crater with some hydrothermal activity might have spawned life. But, how likely is this scenario? ‘It’s not looking too bad’, Ten Kate concluded. She is currently running simulations within the context of the Origins Center, to investigate the role of extraterrestrially delivered organic compounds using her PALLAS Athena simulation facilities. She will also test the ‘one pot origin of life’ hypothesis using the Origins Simulator to be developed by one of the Origins Center fellows.

One thing we do know about Mars is that it is not teeming with life. But that might be a normal situation, explained astrobiologist **Charles Lineweaver** (Australian National University) – it could very well be the case that once life gets started, abiotic planetary feedback systems will wipe it out (the Gaian bottleneck).

Even though life is present in the most inhospitable corners of the Earth, our planet still harbors lots of deserts, where there is too much heat, not enough nitrogen, carbon or other vital elements. And of course, life is limited to a very thin layer of some 10 kilometers. Based on our knowledge of Earth, we have defined ‘habitability’ for other planets. Lineweaver explained that it is not just the temperature which defines whether life can exist, but also the history. The now famous TRAPPIST planetary system has no less than seven planets in the habitable zone. ‘But these planets have been scorched by their star for a billion years.’

Furthermore, apart from a planetary orbit in the ‘habitable zone’, the entire planetary system may have to be in a habitable ‘Goldilocks’ zone of the Galaxy, where stars have high enough metallicity and the number of supernovae is small enough for emerging life to escape roasting. And the habitable conditions shouldn’t disappear.

Disappearance is probably likely, Lineweaver argued. Ice formation increases the albedo of a planet, which increases the reflection of sunlight and thus decreases the temperature. This could lead to runaway ice-albedo. On the other hand, a runway greenhouse effect like the one that occurred on Venus is also likely. It is possible that some life can change the atmospheric conditions, preventing the abiotic positive feedback and thus keep the planet habitable. Lineweaver: ‘So to remain habitable, a planet may need to be inhabited.’ And to remain inhabited, mutations are needed that jointly prevent runaway processes towards ‘too cold’, ‘too hot’ or other inhospitable circumstances. ‘All this could be very rare.’

Thus, if this Gaian Bottleneck scenario is correct, the origin of life could be common, but on most planets life would quickly disappear before advanced life could evolve. This could be a solution to the Fermi Paradox (the question why no advanced life form has yet contacted Earth). If there is a Gaian Bottleneck, we should not expect lots of planets with advanced life.

After talking nearly two days about the origin of life, chemist **Lee Cronin** (University of Glasgow, UK) stated that we might be better off to abandon all definitions of life. We just don’t have enough data for a good definition, he argued. He favors the approach to focus on what life does: ‘Evolution creates objects or artifacts that are so complex, they wouldn’t exist without life.’ For example it is possible to imagine molecules that are simply too complicated to originate from abiotic processes in any abundance.

Cronin introduced the concept of ‘pathway complexity’, the number of steps needed to create an object, as a tool to threshold which artifacts are created by living processes. It would make the search for life on other planets simpler: ‘This way, you don’t need to find a life form, just a complex artifact.’ Preliminary studies show a correlation between measured physical properties correlate with pathway complexity. In this way it is possible to target which objects are alien artifacts and the product of alien life.

Session 5: Emergence and bridging of temporal and spatial scales

The final words in the presentation by **Peter Sloot** of the Institute of Advanced Studies, University of Amsterdam (Netherlands) were a quote by Benedict de Spinoza (1665): ‘Every part of Nature agrees with the whole and is associated with all other parts’. It summed up his presentation on the quantum nature of biology and life.

Life is full of noise-resilient networks encoding information. Noise even increases the efficiency of these networks. The networks span different levels where ‘new levels of organization are built out of elements at a lower level … they have a physics of their own’ (Paul Anderson, 1958). It is a form of ‘naive reductionism’ to argue that causation would reside at a particular scale. Causal interactions work up and down the different levels of organization.

These levels are what matters and not the scales, Sloot argued. Causality can be seen as how much one level predicts about another or how much the past predicts about the future or how much information is shared by different biological levels. In a classical system, you can look for the minimal information about the past needed to store (or encode) in order to optimally reproduce the future. The amount of organization in a process is defined by Statistical Complexity ($C\mu$), which delineates the levels in a system.

Sloot then tackled the question whether quantum processes play a role in the up-down and circular causality biology. There are trivial effects stemming from quantum processes, like the color of blood or binding affinities. However, Sloot also identified at least two biological systems that are based on non-trivial (i.e. coherence, entanglement or tunneling) quantum processes. The first is photosynthesis. It was shown in 2007 that long lasting coherence occurs between two electronic states in a photosynthetic purple bacterium.

The second example is navigation in birds. They appear to sense small fluctuations in the Earth’s magnetic field using a cytochrome in the retina. In this sensing mechanism, the electron spin (a quantum phenomenon) is involved. And finally, Sloot speculated that stochastic processes across biological levels may gain from Quantum information processing efficiency.

A totally different approach to ‘scales’ was presented by **Alexander van Oudenaarden**, director of the Hubrecht Institute (KNAW). He investigates how a single cell can become a full-grown organism. Inspired by the Nobel-prize winning work of John Sulston, who tracked the fate of every cell in a developing *C. elegans* nematode worm, he devised a method to induce ‘scarring’ in the DNA of cells in developing zebrafish embryos.

The scars were made in a series of Green Fluorescent Protein genes engineered into the fish, so they would not interfere with the normal development. By comparing the scar pattern in cells from different tissues, Van Oudenaarden is able to observe how many different progenitor cells contribute to them. For example, blood cells in the kidney marrow originate from six early progenitors, while resident macrophages in the fin have different clonal origin than macrophages in bone marrow. The preliminary results show the method Van Oudenaarden devised is powerful indeed.

The conference was wrapped up by **Stan Gielen**, director of Dutch science funding organization NWO, who explained the changes in the funding landscape and the place of the National Science Agenda in it.

Some 180 participants enjoyed two days of stimulating presentations and discussions. During a speed-date, they got to know five total strangers and during the poster sessions, many more participants were able to present their own work. The organizers look back on a very successful symposium at the start of a fascinating and extremely challenging research program.