Synthetic Biology Workshop

Process and Results

ACADEMY OF FINLAND

Index

1. Synthetic biology foresight workshop

1.1. Aim of the foresight workshop

The Academy Programme Synthetic Biology (FinSynBio)[1] took place in 2013–2019. The programme funded 15 research projects and 32 researchers. Currently the final evaluation of the FinSynBio programme is under preparation. As a part of the final evaluation process, a foresight workshop was organised for the researchers funded by the FinSynBio programme. The invitation was also extended to others interested in synthetic biology research. The workshop was organised by the Academy of Finland and VTT Technical Research Centre of Finland. It took place in Helsinki on 19 March 2019.

The aim of the foresight workshop was to gain insights into the possible futures of synthetic biology: which possibilities may synthetic biology offers in the future, which research guidelines can be traced, which ethical issues might be faced and how we can prepare ourselves to these changes.

The results of the foresight workshop will be a part of the final evaluation material, based on which the evaluators will assess the success of the programme, the attainment of desired objectives, the impact of the programme, and the future of the field of synthetic biology, as well as the technical and ethical challenges. In addition, the results can be utilised when planning new research funding programmes related to synthetic biology. Research institutes and individual researchers planning their future research interests can also take advantage of the insights elaborated in the foresight workshop.

Furthermore, the foresight workshop presented a collective, future-oriented ending to the FinSynBio Academy programme, where many of the researchers funded by the programme met for the last time.

1.2. Workshop process

The half-day foresight workshop took place on 19 March 2019. The participants included 15 researchers from six Finnish universities and research institutes. In addition eight representatives from Academy of Finland participated in the discussions, facilitated the group work and kept a memo of the group discussions. Three researchers from VTT, Research Scientist Minna Halonen, Researcher Scientist Minna Kulju and Research Team Leader Jussi Jäntti, planned the workshop in collaboration with the Academy of Finland. Minna Halonen and Minna Kulju together with the staff of Academy of Finland facilitated the workshop. The language of the workshop was English, since roughly a half of the researchers were not native Finnish speakers.

The workshop aimed at focusing the participants' attention on future developments and possibilities of synthetic biology. Prior to the workshop a survey related to the final evaluation of the FinSynBio programme was conducted among the FinSynBio-funded researchers. The survey also included a future-oriented part, where the respondents were asked to identify 1) challenges synthetic biology may have to face in the future and how to overcome them and 2) solutions synthetic biology may have

[1] http://www.aka.fi/fi/tiedepoliittinentoiminta/akatemiaohjelmat/toiminnassa/finsynbio/

to solve global challenges. The topics elaborated in the foresight workshop were selected based on the results of the survey. The workshop topics were:

- **Which solutions synthetic biology may have to global challenges?**
- **How to build valuable collaboration network?**

The participants were divided into three groups in order to enhance collective discussion and active participation. In the end the participants were asked to give their written feedback[2] on the workshop. Below, the workshop assignments and results are discussed in detail.

2. Synthetic biology-based solutions to global challenges

Synthetic biology is expected to be the central technology when we tackle global grand challenges such as resource sufficiency and climate change using biological solutions. Furthermore, technologies enabled by synthetic biology are increasingly used in diagnostics and treatment of diseases. These technologies require new engineering approaches, measurement tools, computational solutions, including data management and artificial intelligence. Therefore, efficient utilisation of synthetic biology will depend on highly interdisciplinary approaches. This challenges the appropriateness of current educational programmes and funding tools[3].

The workshop task was based on the previous statement. It focused on the critical role of synthetic biology in the future. The workshop groups were asked to elaborate solutions based on synthetic biology to global challenges in fields of energy, well-being and industry in the next 5–10 years. Each group worked on one of the topics by filling in a template[4] according to the instructions. The groups had an hour to work on the assignment, after which twenty minutes were reserved for finding out what the other groups had produced and commenting on and giving additional input to the topic.

[2] The feedback is presented in the attachments of this report.
[3] Statement formulated by Dr Jussi Jäntti, VTT Technical Centre of Finland.
[4] See the template in the attachments of this report.

2.1. Energy

Rapid transformation of all the sectors that are emitting greenhouse gases is needed to limit the global warming below 2ºC. Billions of mechanical devices, buildings, vehicles and industrial processes need to be changed, retrofitted or renovated to improve energy efficiency and to decrease emissions. Emergence of numerous integrated consumers and producers, called prosumers, recreates energy markets.[5]

Local, distributed biology-based systems that enable home-generated energy were identified as a ground-breaking solution which helps to achieve oil-free society in heating and transport sector. The solution could consist of a living solar panel and battery, which generates, captures and stores electrons. It would harvest solar light with inbuilt control systems to keep mechanism stable. As a side product it would produce water, not carbon dioxide. The living solar panels could be placed in containers anywhere as long as there is light (on vehicles, buildings). Using microbe-containing wall paint and roofing to generate electricity was speculated as a possible future scenario.

The group identified the following enablers as necessary for the realisation of such home-grown energy systems: the regulation of synthetic biology development by political decisions, consumer behaviour and customer push; new business models need to be developed by the energy sector; the support from funders.

Both local and global actors are needed. As discussed in the other workshop assignment, synthetic biology requires interdisciplinary innovation. The joint effort of engineers, designers, physicists, biologists, architects, city planners and specialists in commercialisation is also needed.

In order to succeed commercially, the public interest has to be sustained by diverse means of communication such as storytelling, education, terminology and marketing. Also visible measuring of energy generation is needed. It should be easy to quantify and visualise the input/output of the system.

ENERGY

IS IT POSSIBLE TO GENERATE ENERGY FROM MICROBES IN MOVEMENT?

The Energy group started their assignment from the idea that movement can be converted to heat, but the process is very inefficient.

Can we think of a combination of different cells that work together? Yeast that collaborates with algae! This combination could generate a fuel that does not need to be burned or combusted and its by-product is water. The energy could be stored in a battery in form of electrons in movement.

Can you scavenge the electrons from a ‘bug’ without killing it by removing electrons and causing an imbalance? It would be like a living battery! There are electron conductive bacteria that spit out electrons. Make electrons, store them and get them out to use them!

[5] Excerpt from the workshop assignment.

The group discussing legislative and ethical aspects mentioned the organisms going rogue and/or replacing other plant life and taxing of oil-based products. The importance of increasing young people's understanding of synthetic biology was also mentioned.

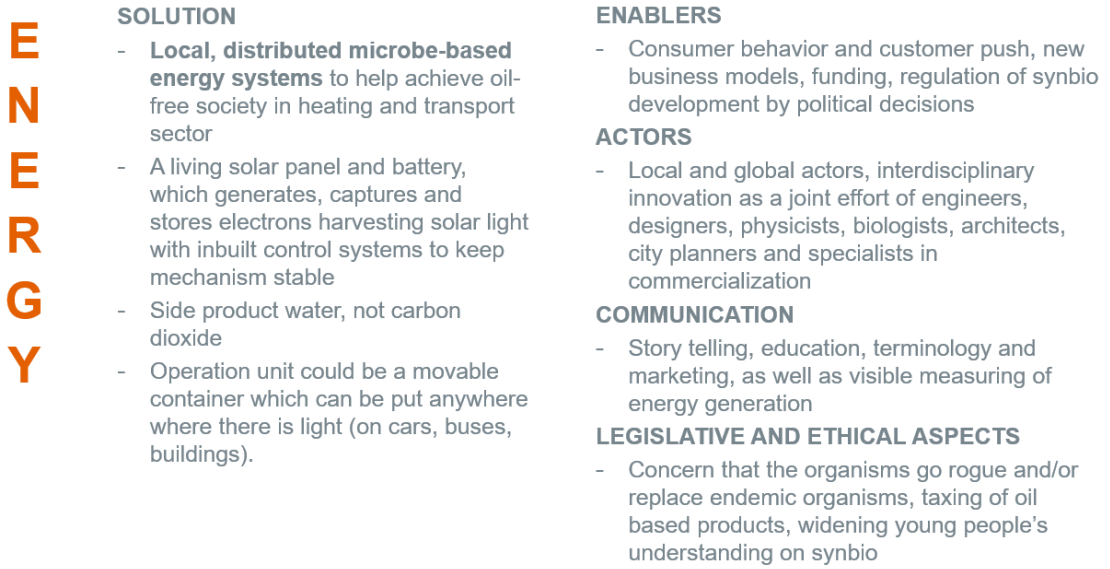

Figure 1. Summary of the Energy discussion.

2.2. Wellbeing

Growing healthcare costs together with the aging population require a paradigm shift for prevention of non-communicable diseases and a new kind of participatory healthcare. Disruption of work – robotisation beyond factories is making many current jobs obsolete. The overload of human-technology relation, manifesting itself clearly in the gadgets we use in our work and free time, is increasing stress when it should make life easier. Urbanisation and strained infrastructures put pressure on the design of our living environment.[6]

New synthetic biology-based solutions for medicine in the fields of drug development, probiotics and prevention were identified as the future change-makers of wellbeing in society. Their impact was considered to be manifold: these solutions give hope and improve the quality of life of the humankind. These new solutions could provide more indivualised treatments, decrease side effects of the traditional medicine, and also decrease treatment expenses for some diseases. Improved state of health could result in increased productivity. These solutions would also generate opportunities for new businesses.

WELLBEING

ETHICAL QUESTIONS TO BE ANSWERED

- Who will be treated, if everyone cannot be treated?
- Which diseases should be treated first?
- How will the regional equality be guaranteed?
- What about the treatment of aging? Is aging a disease?
- If aging can be treated, how will we tackle the problem of overpopulation? Who will be permitted to gain a very long life or even immortality?

The group named these technologies enablers of development in these novel medical solutions: CRISPR-Cas and similar techniques, phage therapy, bioinformatics and vast amount of sequencing data. More general pathways and/or processes are also needed for drug testing and validation. The group identified the following players as actors in charge of the development of new solutions for medicine: researchers, funding agencies and investors, health care system, legislative decision makers and pharmaceutical companies and their alternatives. Accelerator programmes engaging researchers and pharma were also considered topical. There was discussion about the drugs being produced by public and/or international institutions to tackle the high cost of these medicines both for patients and the society.

New techniques and regulations are more easily accepted in medicine than, for example, in crop production. Nevertheless open communication with the public and between the players was considered crucial. Transparency of science is a prerequisite for open communication, even if it entails difficult tasks such as the publication of negative results, or the conflict between open science and the interests of pharmaceutical companies. The educational aspect was considered a key success factor comprising the basic science education at schools, the education of decision makers and the education of medical doctors who in turn educate their patients.

Difficult legislative and ethical questions were raised in the group discussion: who will be treated, if everyone cannot be treated? The lack of regulation concerning

[6] Excerpt from the workshop assignment.

new systems and the level of public understanding and acceptance of such novel medicines are aspects which have to be taken care of urgently.

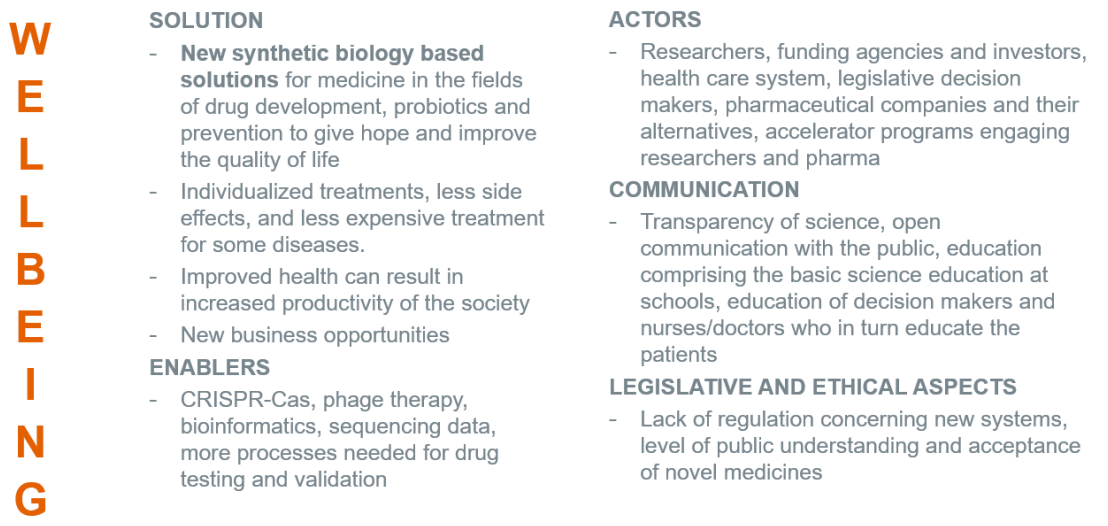

Figure 2. Summary of the Wellbeing discussion.

2.3. Industry

Tomorrow's smart products and services are created in new industrial ecosystems supported by a globally connected platform economy. Opportunities will emerge from the collaboration, service subscriptions and use of data. Robotisation, flexible automation and artificial intelligence offer opportunities for enhanced production. High dependence on resources (energy, materials, water) can be overcome by applying solutions of circular economy.[7]

New sustainable materials are the solution identified by the industry group. These materials should be techno-economically feasible and sustainable solutions for industry. This means Proof-of-Concept type of solutions with a high Technology Readiness Level (=4), since the time span considered is quite short (5–10 years). These solutions could be e.g. sensor materials, high-value chemicals (bioplastics, biopolymers, polymers in-vivo), conductive materials, plant-related compounds, pigments, living materials (real biomaterials produced by living organisms).

The anticipated impact is to save the world by using resources and energy more efficiently and reducing carbon emissions. No more harmful solvents or catalysts. It has to be noted that this will happen only if the industry succeeds in the area of synthetic biology products.

Funding was seen as the most important enabler in developing synthetic biology products for the industry. Development takes time and needs many (interdisciplinary) resources. The interdisciplinary approach is also challenging, as it entails finding and establishing mission-driven collaboration with other researchers (goals and understanding of other areas) as well as creating beneficial networks. Sufficient investments in infrastructures in universities and other research organisations are important to enabling high quality research and development of synthetic biology.

General acceptance and awareness of synthetic biology is an essential enabler. Utilisation of synthetic biology products will not progress without public support. Public discussion on synthetic biology as well as good cooperation between media outlets

INDUSTRY

PRELIMINARY CONSIDERATIONS

1. Industrial growth requires efficient utilisation of available resources (incl. energy, by-products, reutilisation of end-products). In particular, product manufacturing has to be sustainable, consuming less energy and being carbon neutral or even negative. At the moment, industry is investing in the improvement of existing sustainable systems and in the development of new systems.
2. Chemistry is needed in biotechnology: we are transforming simple things to more complex systems where novel materials are used as building blocks. In biotechnology, synthetic biology will replace organic chemistry.
3. There are three ways to see synthetic biology enhancing industry:
   - Improving existing systems, making them more efficient
   - Using existing systems for creating new products
   - Inventing entirely new, ground-breaking production systems

[7] Excerpt from the workshop assignment.

enlightening synthetic biology research is important. In addition to these, for synthetic biology to be a competitive edge for the industry, we must ensure that we have highly skilled professionals with a high level of academic and applied science education.

Industrial companies are in a key position for the development of synthetic biology. The challenge is how the companies find researchers and how they become aware of the opportunities synthetic biology offers in their field[8]. Other identified actors were: researchers, startups, funders (AoF, EU, foundations), venture capitalists, ministries, EU project coordinators (deep understanding), communicators (media relations), policy and decision makers[9], general public and supporters (institutes).

The media plays an important role in the communication between the scientist and the general public about the solutions and possibilities of synthetic biology. TV and radio programmes can have a huge role as a communication channel. An example of this is “Suomen tulevaisuuden menestystekijät” (“The future success factors of Finland”), a TV series produced by YLE, the Finnish public service broadcasting company. In addition, social media is gaining an ever-increasing role in presenting research results both to the scientific community itself but also to the citizens (open science and publications).

Based on current information, the most important legislation which has to be considered while developing synthetic biology products is the GMO (genetically modified organisms) legislation.

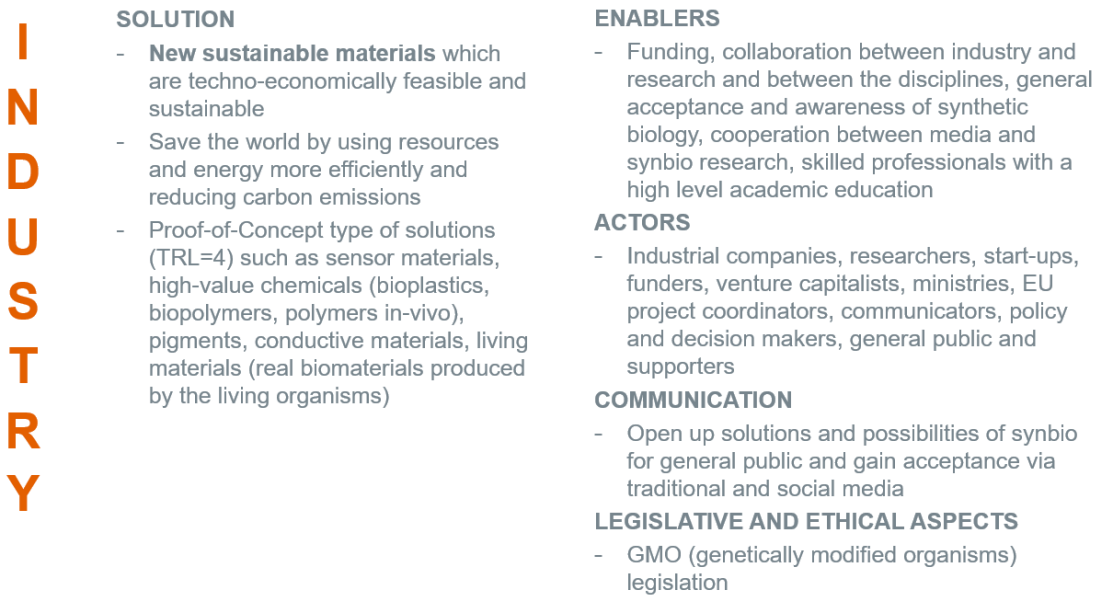

Figure 3. Summary of the Industry discussion.

[8] Newly established SynBio Power House (https://www.synbio.fi/) will have an important role in acting as a communication channel and actively promoting interactions between researchers and industry partners.
[9] Research white papers and policy briefs that present perspectives on topical issues and are addressed for political decision making may ease the communication between research organisations and policy makers.

3. Ways to build valuable collaboration networks

The rationale behind this task lies in the answers given in the Academy's post-programme survey, which pointed out the need for collaboration outside of the researchers' own fields. The interdisciplinary collaboration and networking opportunities appeared to be the most significant added value of participating in the FinSynBio programme compared to having been funded as an ordinary Academy project.

> *"The programme encouraged to establish collaboration which probably would have not been realised in an ordinary Academy project."*
>
> *"It became clear during the project that the potential impact of our methods is broader than we initially thought."*
>
> *"Collaborations were started both with research in a closely related field (biotechnology/synthetic biology) as well as in a more remote research area (computational modelling of processes)."*[10]

In the workshop, each of the three groups selected a field of synthetic biology to be covered in the discussion. The proposed fields were: 1. Understanding the code, 2. Design of impact-driven synbio products, 3. Enzymes in bioprocessing/on a metabolic pathway, 4. Improved enzymes, cells, organs. Then the groups answered to the following questions from the point of view of the selected field of research:

1. Which partners and collaborations are needed in this field? Think beyond the obvious!
2. Which actions are needed to carry out these collaborations?
3. Who are the actors required and what should they do?
4. What will you/your project group/organisation do to accelerate valuable collaborations in Finland and abroad?

CONSIDER THIS

Synbio is an extremely interdisciplinary field of knowledge:

Artificial intelligence (AI), machine learning, modelling, biology are the most obvious disciplines for collaboration.

The regulatory issues and the public acceptability of synthetic biology require expertise in social sciences, legislation, communication, language, philosophy, theology, and social sciences. Material sciences and design are also important disciplines for collaboration.

- ❖ Important to collaborate with the industry

Funding bodies play an important role:

Funding bodies have the power to push research towards interdisciplinary collaborations by requiring it in the project proposals

- ❖ Utilise EU project preparations as networking opportunities

[10] Examples of answers to the post-programme survey.

The groups had one hour to do the assignment utilising a template. The main findings were discussed in a plenary session.

3.1. Proposed solutions

Regardless of the selected starting point for the collaboration discussion, it became clear that the ways of collaboration discussed apply to all fields of synthetic biology. The groups came up with very similar suggestions for improving interdisciplinary collaboration. They also shared the desire to form collaborations. What varied was the **combination of disciplines and actors** needed to study a certain topic. Collaborative networks in engineering biology/synthetic biology are emerging. One good example is the Engineering Biology Research consortium (EBRC, https://ebrc.org/) for universities, research institutions and industry in the USA. This network is also reaching out to have a global role in coordinating synthetic biology related activities. VTT in Finland is a member of the EBRC.

When discussing the topic 'Understanding the code', the participants underlined that small pieces of DNA can be synthesised, but for many proteins "we don't understand their functions, their multiple components, and how these functionalities interact." Therefore a great investment in computation is needed. "Technically we manage, we can synthesise DNA in cells, but we don't understand the code." Artificial intelligence (AI), machine learning, modelling and biology are the most obvious disciplines for collaboration. However, the so-called filtering sciences such as philosophy, language studies, social sciences are increasingly important in synthetic biology. In the design of impact-driven synbio products understanding the code is not necessary. "We can make new synthetic proteins or pick existing proteins from nature and with these proteins we can make new materials." Here, the knowledge of material sciences, design and communication are the most important disciplines for collaboration.

Collaboration is needed when one partner has the skill the other one lacks, which is often the case in synthetic biology because of its interdisciplinary nature. In addition, the regulatory issues and the public acceptability of synthetic biology require expertise for example in legislation, communication, language, philosophy and theology.

Collaboration with the industry is crucial for innovation in synthetic biology. The newly established SynBio Powerhouse (https://www.synbio.fi/) accelerates synthetic biology-based business growth in Finland in cooperation with a growing international network. It is important that synbio researchers take full advantage of the network.

CONSIDER THIS

Utilise different ways to accelerate internationalisation

- Take advantage of Finnish research infrastructure and invite researchers from countries lacking these facilities
- Attract top people from abroad by inviting young international researchers in Finland for lectures or big synbio events
- Send doctoral students to top laboratories abroad
- Take full advantage of the existing synbio networks
- Establish an international university network

It was also stated that collaboration has two sides: one is creating collaboration and the other sustaining it. The second part is as important as the first one. It was also recognised that communication between different fields of knowledge is challenging and takes time and effort, although it is not impossible. An example of a long-term, interdisciplinary network is described in the attachments of this report.

The role of **funding bodies** was considered crucial. On the one hand, there is not any research without funding[11]. On the other hand, funding bodies have the power to address the research towards interdisciplinary collaborations by requiring that in the project proposals. In fact, EU project preparations were recognised as excellent networking opportunities. EU research calls are opportunities for networking and brainstorming where both research and industry partners are needed.

International collaboration was considered especially important for the development of synthetic biology in Finland. A number of actions to accelerate the internationalisation were mentioned:

- In Finland we have an excellent research infrastructure. Finnish synbio research units should invite researchers e.g. computational experts from countries lacking these kinds of facilities, such as Estonia or Poland.
- Finnish synbio research units need to attract top people from abroad. One way to do this is to invite young and bold international researchers in Finland for lectures, big synbio events, and let them talk about their success stories in synthetic biology. This could generate longer term co-operation between international top researchers and Finnish research units.
- It is also important to send doctoral students from Finland to top laboratories abroad. Students or young researchers have the opportunity to create their own networks for their own good, and to the benefit of their home research unit. Sending young researchers to the international top laboratories requires previous contacts between senior research staff and cannot rest upon young researchers own efforts.
- Besides taking full advantage of the existing synbio networks such as the above-mentioned SynBio Powerhouse, it would be useful to establish an international university network (see also EBRC above). The network could organise summer schools and support exchange of staff and students like the ULLA network

[11] A lack of investors who understand the biosciences was recognised as a key problem in Synthetic biology as an enabler of sustainable bioeconomy - A roadmap for Finland (2017), p 33. https://www.vtt.fi/inf/julkaisut/muut/2017/syntheticbiologyroadmap_eng.pdf

(https://ullapharmsci.org/), which is a European university consortium for pharmaceutical sciences between eight partners. Its main activities include organising summer schools, workshops and lectures, coordinating joint EU applications, and supporting exchange of staff and students.

In general the **education of young generations** was considered extremely important for the success of synthetic biology. One way to raise awareness of and knowledge on synthetic biology could be to involve master students in research projects. They can be "naïve" enough to be bold and thus think much more broadly. Senior researchers are likely to think more narrowly and be stuck to their old habits and methods. For young people a sufficient "carrot" can be just to be involved.

Another way to educate young researchers is to offer them mentoring to support their career development following the example of the Spark Finland programme (https://sparkfinland.fi/about-us/) which "is designed to increase the maturity of academic and clinical discoveries towards practical solutions in the life science and health tech space. Programme supports also career development by educating scientists, students and clinicians on drug and health tech discovery and development, and building the understanding of business aspects related to the discoveries."

The discussions in the workshop also involved children. There are several underexplored opportunities to demonstrate school-age and even pre-school-age children how exciting science can be. Synthetic biology could be taught in schools, as a part of the curriculum. In fact, interesting pilot projects on technology education in schools and kindergartens have already been implemented in Finland[12]. There are also two newly established professorships in technology education[13]. A children's non-fiction book and/or a computer game on the possibilities of synthetic biology could be one viable option to reach even younger children. Synbio researchers should communicate about synthetic biology more actively with the public, especially with high school students. Experience has shown that public events and contacts with high school students sparks also the researchers' thinking. This can be done via existing services and networks such as:

- Tutkija tavattavissa https://nuortentiedeakatemia.fi/tutkija-tavattavissa/ which is the Finnish version of the global Skype a Scientist service https://www.skype-ascientist.com/

CONSIDER THIS

There are several ways to educate young generations

- Involve master's students in research projects
- Offer mentoring to young researchers
- Demonstrate children how exciting science can be

Digital tools enhance collaboration

- Create a data sharing repository for sharing information regarding unsuccessful research
- Create a synbio cross-disciplinary dictionary

[12] See, for example, the Innokas network https://www.innokas.fi/en/ specialised in training teachers in collaborative innovation education.
[13] Assistant professor in technology education Kaiju Kangas, Helsinki University; Professor of Practice in technology education Maria Clavert, Aalto University

- BioGarage service of SynBio Powerhouse https://www.synbio.fi/biogarage

Going back to the researchers of today, the use of **digital tools** would enhance collaboration in synthetic biology. A data sharing repository for sharing information regarding unsuccessful research would prevent different scientists from doing the same mistakes again. A synbio interdisciplinary dictionary or translator would facilitate the interaction and the communication between scientists and experts of different fields and between research community and the public. A limited Bio-dictionary in Finnish exists e.g. in the web pages of the Advisory Board on Biotechnology (http://www.btnk.fi).

Synbio infrastructure could be developed e.g. according to the model of structural biology (https://www.helsinki.fi/en/infrastructures/integrated-structural-cell-biology/about-instruct-fi) that makes high-end technologies and methods available to researchers. Steps towards improved access to high-throughput engineering and testing infrastructures is taking place within the IBISBA consortium (https://www.ibisba.eu/), which is in the preparatory phase to become a European research and innovation infrastructure (ESFRI) that will support industrial biotechnology and synthetic biology.

CONSIDER THIS

Arenas for sharing scientific data and networking

- ❖ Participate in science competitions

Need for better synbio infrastructure

- ❖ Benchmark what has been done in structural biology

More business from synthetic biology

- ❖ Accelerate startup company development via startup incubators and other innovation services

Conferences and competitions are classic arenas for sharing scientific data and building new contacts. There is a demand for an annual interdisciplinary conference in synthetic biology in Finland. Synbio researchers could also become more active in science competitions such as the Helsinki challenge (https://challenge.helsinki.fi/) which presents an interesting platform for collaboration: science meets business, decision makers, non-governmental organisations and representatives of public sector. Academy of Finland and VTT Technical Research Centre of Finland could become more active in startup events such as Slush /https://www.slush.org/)[14]. A highly important forum within the synthetic biology is the iGEM competition (https://igem.org). Every year a large number of student teams from all over the globe meet up to present their synthetic biology projects. A Finnish team of students has participated already in several competitions. There is also a team for 2019 (http://www.aaltohelsinki.com). More teams should be encouraged to participate from Finland as this forum offers an outstanding possibility for future scientists and entrepreneurs to network and share ideas on synthetic biology.

The last category of collaboration recognised and discussed in the workshop was how to create **business from synthetic biology**. The lack of spin-offs was considered a challenge in Finland. There is a need for startup company development via startup incubators and other innovation services such as HIS Helsinki Innovation Services LTD (https://www.helsinki.fi/en/research/innovation-services) which help

[14] Synthetic biology as an enabler of sustainable bioeconomy - A roadmap for Finland (2017, p. 33) suggests utilising the competence of the Slush events to organise an international "Bio-Slush" event. https://www.vtt.fi/inf/julkaisut/muut/2017/syntheticbiologyroadmap_eng.pdf

researchers commercialise their research results. Universities should provide researchers more information about potential developer companies. VTT type of partners are needed to upscale between academy and the industry.

4. Future developments and possibilities of synthetic biology

As a part of the final evaluation process of the FinSynBio programme, a foresight workshop was organised by the Academy of Finland and VTT Technical Research Centre of Finland in Helsinki on 19 March 2019. The workshop aimed at focusing the participants' attention on future developments and possibilities of synthetic biology. The workshop had two main topics: a) the solutions synthetic biology may offer in the fields of energy, well-being and industry in the future, and b) interdisciplinary collaboration networks in synthetic biology.

The participants came up with innovative solutions to global challenges in the fields of energy, wellbeing and industry by means of synthetic biology. The given time span was the next 5-10 years. In the field of energy, **local distributed energy system based on microbial systems** was identified as a potentially ground-breaking solution which can help to achieve oil-free society in the heating and transport sector. The solutions could consist of distributed systems that are based on microbial systems that can generate, capture and store electrons. Such systems could operate in closed containers placed for example on vehicles and buildings.

New synthetic biology based solutions for medicine in the fields of drug development, probiotics and prevention were identified as future change-makers of well-being in society. These solutions can provide more individualised treatments and decrease side effects of the traditional medicine e.g. in the form of highly improved interpretation of genomic information. Furthermore, synthetic biology enabled production system for medicines can decrease treatment expenses for some diseases and, as seen in the case of the CAR-T cell therapies, generate new ways to fight cancer.

In the field of industry, **new techno-economically feasible and sustainable materials** were identified as an innovative solution to go for. This can mean Proof-of-Concept solutions, for example sensor materials, high-value chemicals (bioplastics, biopolymers, polymers in-vivo), conductive materials, and living materials (biomaterials produced by living organisms). The anticipated impact is to mitigate the expected future resource and energy insufficiency more efficiently and to reduce carbon emissions. This will happen only if the industry succeeds in the area of synthetic biology products. A recently publicised Headphones Korvaa (https://www.synbio.fi/korvaa-microbial-headset) is an excellent example on the possibilities different natural or engineered biological systems have to replace oil-based materials such as plastics and foams.

In the workshop, the participants identified various ways to foster collaboration across disciplines and between research and industry, both at the national and international level. International collaboration is important and necessary for any high-quality research. For synthetic biology it is vital because of the interdisciplinary nature of the research field. Especially in smaller countries it is difficult to cover all required scientific or other disciplines at a sufficient level. International collaboration

was considered especially important for the development of synthetic biology in Finland. The role of young researchers backed up by the seniors' networks was highlighted. The role of funding bodies was also considered crucial because of their power to point research towards interdisciplinary collaborations by requiring that in the project proposals.

Another focal point was found in the education of the public in general, and the young generations (starting from school children) in particular, in order to gain public acceptance for synthetic biology-based solutions and to secure highly skilled professionals to create those solutions in the future. Today's synbio professionals do often possess the knowledge to do educational work, but they usually do not have resources allocated for educational activities.

Discussions about scientific education of and communication with the public, and the young generations in particular surfaced frequently throughout the workshop. This topic was considered important in order to guarantee the public acceptability of synthetic biology-based solutions and to inspire future problem solvers through engineering biology[15]. The researchers felt that they should engage themselves more in these activities but also that insufficient resources are available. Effective communication about the impact of synthetic biology-based solutions on society would benefit from collaboration with communication and marketing experts.

In the future, it is central to the development of new biological production systems to introduce methods that enable significantly improved translation of information contained in the rapidly growing amount of DNA sequence data (code of life) into biological understanding and functionalities and engineering of biology-based solutions to global challenges. This requires integration of gene engineering technologies with much more extensive use of automation and robotics to modify and build biological systems that provide new features suitable for e.g. industrial applications.

For such efforts to be truly impactful globally, we need improved collaboration and coordination of work and resources. The recently established Global Biofoundry Alliance (https://www.biofoundries.org/) addresses this need partly. This network (in which VTT was recently accepted) aims to accelerate and enhance research in engineering/synthetic biology, build a robust engineering/synthetic biology industry with broad public benefits and to promote and enable the beneficial use of automation, high-throughput equipment, and new workflows and tools in engineering/synthetic biology.

Several companies that base their business idea for automated microbial gene engineering are already operating in the United States and have raised hundreds of millions of dollars in investor funding. It is expected that engineering biology will increasingly make use of computation directed modelling and design of biological systems that are then engineered using automated high-throughput systems. Related to these developments, increasing efforts are put in research that aims to use DNA as a computing platform. This work is supported by the high information density of DNA, its ability to endure long periods of time and the robust biological systems that exist for DNA sequence replication. This paves way for the fusion of semiconductor science and biology and is likely to generate a large body of innovations and business in the future.

[15] The importance of public discussion on the ethics and ethical methods of synthetic biology is a widely recognised requirement for the progress of new, science-based technologies. See e.g. Synthetic biology as an enabler of sustainable bioeconomy - A roadmap for Finland (2017), p. 33. https://www.vtt.fi/inf/julkaisut/muut/2017/syntheticbiologyroadmap_eng.pdf

Finally, the participants found it important that Finland which has a high level of biomass for industrial biotechnology and high know-how and technologies for synthetic biology solutions remains at the forefront of these developments. The significant impact synthetic biology is expected to have on the realisation of bioeconomy and circular economy has been highlighted in two recent, comprehensive roadmaps (https://www.vtt.fi/inf/julkaisut/muut/2017/syntheticbiologyroadmap_eng.pdf and https://roadmap.ebrc.org/). Solutions for the use of biomass for biotechnology are global and have a large export market. With sufficient investment, Finland has the opportunity to develop new globally attractive solutions and high-value export products. Funding bodies, such as the Academy of Finland, hold a key role in addressing the research calls in a way which supports the generation of fruitful collaboration networks.

5. Attachments

5.1. Programme

Agenda		
9.30 – 10.00	Coffee	
10.00 – 10.10	Welcome	Sara Illman AoF
10.10 – 10.45	Key note speech: Future Visions of Synthetic Biology	Merja Penttilä VTT
10.45 – 12.00	Workshop 1: How to build valuable collaboration networks?	Minna Halonen & Minna Kulju VTT
12.00 – 12.45	Lunch	
12.45 – 14.20	Workshop 2: What kind of solutions synthetic biology may offer to solve global challenges?	Minna Halonen & Minna Kulju VTT
14.20 – 14.30	Feedback and closing words	Sara Illman AoF

Venue: Congress centre Paasitorni, Helsinki

5.2. Feedback

At the end of the workshop we asked the participants to fill in a simple feedback form. The participants were asked to specify the reason why they participated in the workshop, how the workshop met their expectations, and what their overall assessment of the event is. A space was also given for additional comments. All except one participant gave feedback.

The participants were motivated by the subject of the workshop itself, the opportunity to meet others working in the field of synthetic biology and the possibility to discuss future research in synthetic biology. Other reasons to participate were also to get new ideas for teaching, to hear about future funding opportunities and educate oneself more broadly on synthetic biology.

Table 1. The reasons to participate in the workshop

	Totally agree	Somewhat agree	Somewhat disagree	Totally disagree
The subject of the workshop was interesting	7	8	0	0
To meet and network with workshop participants	10	4	0	0
To get new research ideas	2	7	2	2
To promote my research project(s)	0	5	7	1
To address the future research of synthetic biology	8	6	0	0

Most of the participants were satisfied with the workshop. The workshop met the expectations of four participants definitely, and the expectations of six participants out of fourteen mostly. Two participants were very satisfied with the event, seven were satisfied and four were neutral. One participant was unsatisfied with the event.

Eight participants wrote an additional comment. Some of the comments wished for deeper and more concrete and better framed discussions. More time for commenting other groups' work was also asked for. Others were grateful for the event and proposed to repeat a similar event on an annual or biannual basis, hopefully with more participants.

5.3. Assignment templates

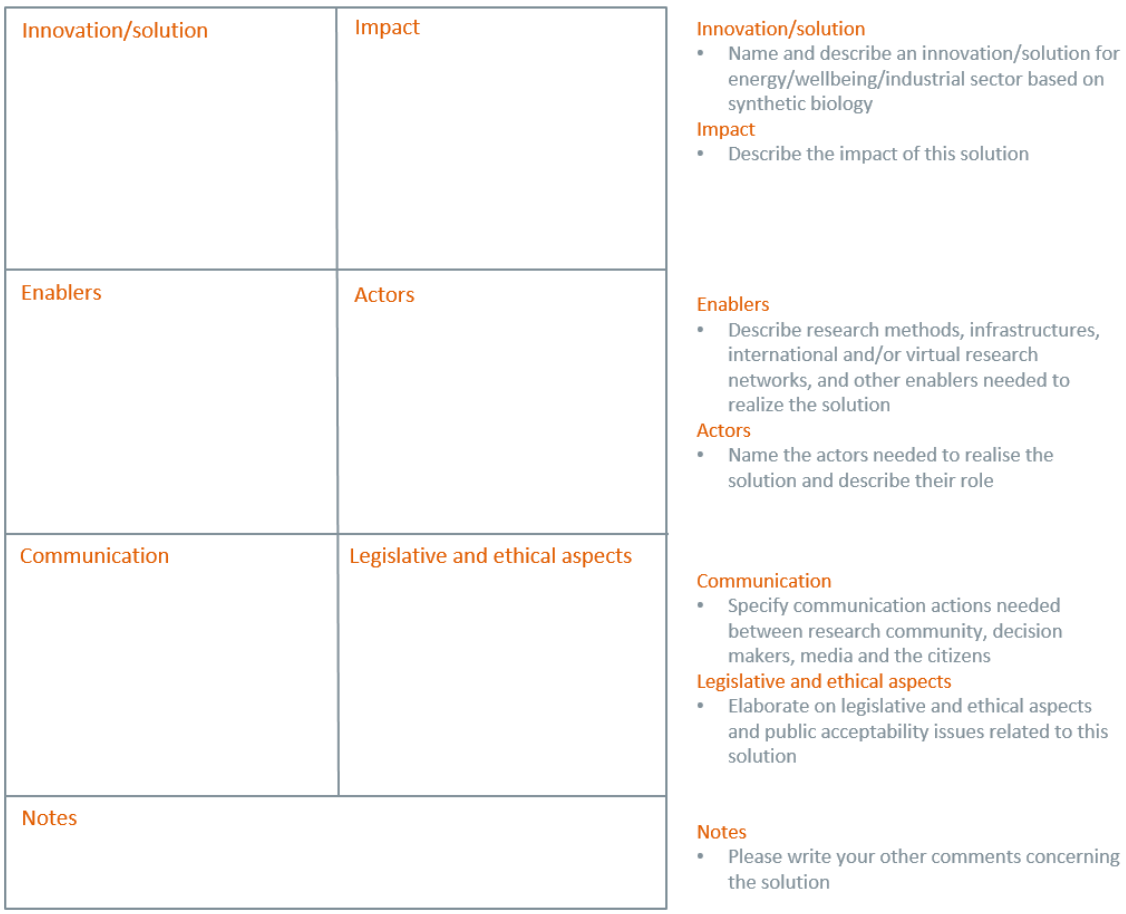

Figure 4. Template to describe possible new solutions.

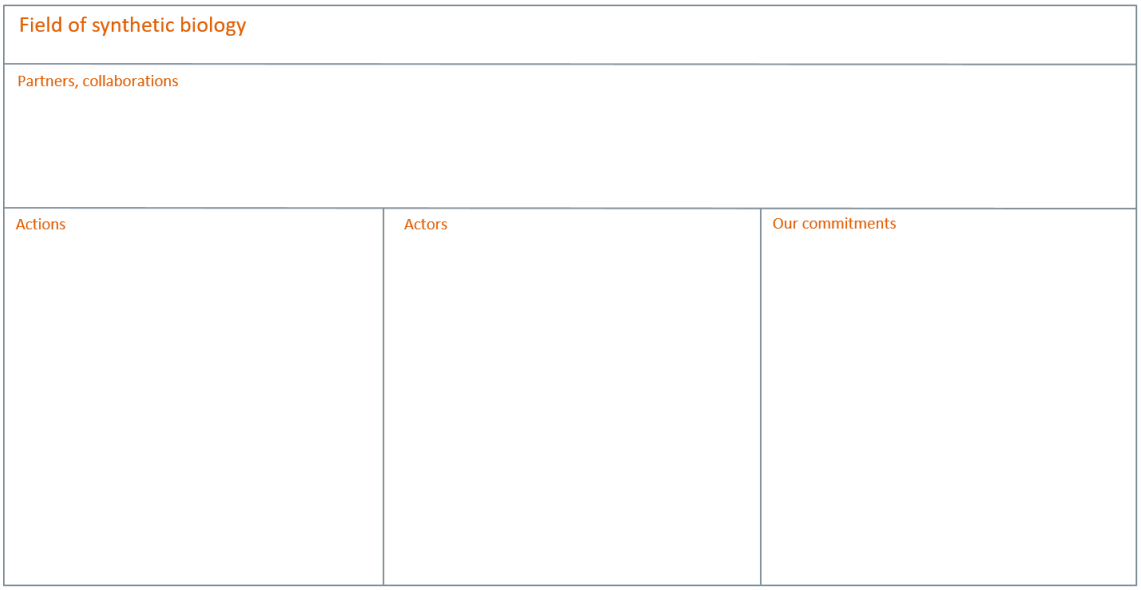

Figure 5. Template to discover ways to enhance collaboration.

5.4. Benchmarking Studia Stemmatologica research network

BENCHMARKING

STUDIA STEMMATOLOGICA

Studia Stemmatologica is an international, interdisciplinary research collaboration network bringing together researchers from humanities (e.g. history, anthropology, musicology) computer science and natural sciences (molecular biology, mathematics, statistics, biochemistry).

The network has made significant methodological breakthroughs in computer-aided stemmatological research and many perennial questions have finally been answered.

Today, the network has increasingly shifted its emphasis to include research areas outside the stemmatology of literary culture, e.g. music, orally transmitted stories and calendars.

After an initial grant the network has preferred not to apply for funding. The bi-annual workshops are organised on a voluntary basis of committed researchers. The network has a significant role in the researchers' scientific community.

In the workshop, participants highlighted that synthetic biology needs interdisciplinary or even crossdisciplinary, innovation-driven research collaboration where experts from different areas, such as biology, chemistry, engineering, computer science, mathematics, philosophy, behavioural science and communication, will together study and develop new solutions based on synthetic biology. The interdisciplinary approach was seen as challenging in finding and establishing mission-driven collaboration with other researchers, finding common goals and understanding other disciplines as well as creating beneficial, long-standing networks. In the following we describe a successful example of an interdisciplinary research collaboration network named Studia Stemmatologica, which was originated from the crossroads of humanities and computer science.

Studia Stemmatologica network (http://cosco.hiit.fi/stemmatologica) has done significant methodological breakthroughs in computer-aided research on how historical texts, music and other cultural phenomena have been developed and spread over time. Dr Tuomas Heikkilä (currently a professor of church history at the University of Helsinki) felt necessary to upgrade the outdated research methods of medieval history and contacted a professor of computer science for help. This collaboration led up to the development of an entirely novel algorithm, which introduced computer-aided research methods in the toolbox of humanities researchers. In addition, this source-based approach has led into the second branch of digital humanities: the digitisation of sources and the construction of databases. The fruit of the collaboration was a method, now used around the world, which leans, on the one hand, on techniques from the field of evolutionary biology and packing algorithms familiar to every computer-user and on the other, on an interpretation of original medieval source material.

The Studia Stemmatologia network was initiated with a grant which was used to arrange six international workshops between 2010 and 2012. The aim of the initiative was to solve problems in stemmatology, textual development and genealogy pertaining to disciplines like historical research, theology and literary studies. The workshop participants represented numerous disciplines ranging from molecular biology, mathematics, statistics, computer science and biochemistry to history and anthropology. Nowadays the workshop is organised bi-annually with voluntary

work by the participants (they have not applied for any funding since the first grant) and it brings together around 50 top scholars from a dozen scientific disciplines and from over ten countries and five continents. The desire to learn new things and come up with new ideas brings the researchers together again and again. This community allows the emergence of completely new insights that would not have happened without this kind of network.

The network has faced some challenges over the years. Particularly in the early phase there were problems in finding a common language between researchers from different research areas. However, it was even more difficult to communicate with researchers outside the community. The problem was solved by creating a common terminology bank (https://wiki.helsinki.fi/display/stemmatology). Another challenge has been individual negative statements towards the methods developed by the research community. Especially the old school researchers have criticised these new methods and their reliability against the old methods.