Metaphor usability for clarifying synthetic biology in upper secondary education

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3 July, 2015

Abstract | Synthetic biology is a new and rising scientific field in which multiple disciplines are involved. This field will, in the near future, give rise to new applications and implications in society and in personal life. In a democratic society, the public should be aware of such major implications, so that they are able to make well-informed decisions. In order to engage the public and clearly communicate what synthetic biology entails, the use of metaphors is required, due to its abstractness and invisibility. Previous studies showed what specific synthetic biology metaphors are most used at this moment, however not which metaphor(s) are most useful to clarify this complex and abstract field of research. This study aims to determine which synthetic biology metaphor(s) are most useful for clarifying synthetic biology to upper secondary school students. In order to accomplish this goal several methods were used, (i) scientific literature and civil society organization publications were reviewed, (ii) five experts on synthetic biology were interviewed and (iii) a questionnaire was administered among secondary school students (N = 212) of which some students were thereafter interviewed for more in-depth information (N = 14). The literature study showed that the three most used synthetic biology metaphors are the book, industry and computer metaphor. The expert interviews determined which categories of synthetic biology are most important for education of upper secondary school students. Besides this, the experts advised caution with the use of metaphors in general and mainly the book metaphor. However, no differences between student associations between the three metaphors were found. However, students preferred the use of the book metaphor greatly and had a relative preference to the metaphor it was first presented to. Therefore, at this moment, it seems wise to use univocal communication with the book metaphor for education in upper secondary schools.

Key-words: *Synthetic biology; metaphor; scientific literacy; upper secondary school; student associations*

Research performed at: Freudenthal Institute for Science and Mathematics Education (FIsme) | Faculty of Science | Utrecht University | Utrecht, the Netherlands
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Possible journals for publication: International Journal of Science Education, Journal of Biological Education and Science Education

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This is a 45 ECTS master thesis (AS-SEC423) for Science Education and Communication (SEC), Freudenthal Institute for Science and Mathematics Education (FIsme), Utrecht University, Utrecht, the Netherlands.

Table of Contents

Introduction

Synthetic biology is a new emerging scientific field that aims to design and engineer biologically based parts, novel devices and systems as well as redesigning existing, natural biological systems (Kitney et al., 2009). It is a field with great potential and, according to synthetic biology specialist prof. dr. Joachim Boldt (2010), synthetic biology will take the same flight as synthetic chemistry. Some applications of synthetic biology are already available, like the cost-effective production of an anti-malaria drug precursor via bacteria (artemisinin) (Endy, 2005; Keasling, 2007). Although, these applications are not yet massively present in everyday life, expectations are that within just a few years the public could face many implications of this new scientific field in their daily lives.

The developments in the field of synthetic biology can create a revolution in food and pharmaceutical processing, energy production and refinement, and industrial manufacturing (Boldt, 2010; Hellsten & Nerlich, 2011). Many positive consequences may arise – such as higher efficiency or even new technological possibilities –, however, negative consequences originate simultaneously. These possible negative implications can either be hard (predictable, objective) or soft impacts (subjective, unpredictable). Soft impacts might also have positive implications, New biotechnologies give rise to new controversial issues that relate to science, so called socio-scientific issues (SSI). In order for the public to make well-informed decisions about these SSI's related to synthetic biology on both personal and societal level it is important to inform and engage the public (Sadler, 2004). On top of that, it is argued that general scientific and technological knowledge is required for an effective workforce participation in the twenty-first century. Synthetic biology is most likely to become part of this general knowledge. In order to create scientific literate citizens, education is a good way to reach a large audience (Roth & Lee, 2003). Currently, synthetic biology is not a part of the secondary school biology curriculum in the Netherlands (*College voor Examens*, 2012, p. 8). Therefore, it is important to find a way to adequately introduce synthetic biology in the curriculum.

In order to do so, it is important to find a way to communicate synthetic biology as clearly as possible to students. However, synthetic biology is a complex topic. It is founded on the base of genetics, which is a difficult field of science due to its abstractness and invisibility to the naked eye. Lay people tend to have little knowledge of this field (Richards & Ponder, 1996). Due to the complexity of synthetic biology, tools can be used for clarification. One of these tools is the metaphor. It is acknowledged that metaphors can play an salient role in the understanding and learning of scientific concepts (Aubusson, Harrison & Ritchie, 2006). Metaphors can be used to clarify difficult topics by using expressions to connect the unfamiliar to the familiar and thereby creating an image of the unfamiliar (Cameron, 2002). For example, 'the human genome is our blueprint', which creates an image of the genome with the use of something familiar, the blueprint. However, a metaphor can also create an image that is incorrect. Therefore, it is important to be careful with the use of metaphors and observe the associations the learner makes with the metaphor (Chew & Laubichler, 2003).

Some research has already been conducted on communicating synthetic biology. Most of this research was on ethical aspects of synthetic biology (e.g. Boldt & Müller, 2008; Dabrock, 2009; Kaebnick, Gusmano & Murray, 2014; Van der Belt, 2009; Yearley, 2009). A minor part of these studies reviewed synthetic biology metaphor use in German-language media articles (Cserer & Seiringer, 2009) and in English-speaking press coverage (Hellsten & Nerlich, 2011). In these media articles and press articles a great amount of metaphor use was found. However, the usability for the purpose of education of these metaphors has not yet been studied.

Therefore, this study aims to describe what metaphors can successfully be used to clarify synthetic biology to secondary school students. These results might be used to inform school textbook writers, science teachers, and science communicators – such as Civil Society Organisations (CSO's) – on what metaphors are most suitable to use for synthetic biology communication.

Theoretical Background

In this section the key concepts of this study will be discussed in more detail. Firstly, a more in-depth description of synthetic biology, its current state, applications and implications will be provided. Thereafter, the need for scientific literacy is discussed. Lastly, the use of metaphors in general, and in science – and more specifically in synthetic biology – will be analysed.

Synthetic biology

Ever since the discovery that DNA is the carrier of genetic information in 1953, interest in DNA has increased tremendously. This discovery induced a new field of biology; molecular biology (Dahm, 2004). After the origination of molecular biology, this field expanded and eventually new biotechnologies arose, e.g. recombinant DNA technology. With use of this technology a part of the DNA from one organism can be inserted into another organism, thereby creating new traits. The first successful uses of recombinant DNA technology were reported in the early 1970's (Hughes, 2001). From this point on, DNA could more selectively be modified and new DNA combinations of already existing DNA could be created. Nowadays, the use of biotechnologies is quite common, for example in healthcare and criminology (Dahm, 2004).

Synthetic biology is a new field of science that uses biotechnology. There is currently no consensus about a single definition of synthetic biology. Recently, the European Commission and the Scientific Committees on Consumer Safety (SCCS), on Health and Environmental Risks (SCHER) and on Emerging and Newly Identified Health Risks (SCENIHR) launched a campaign to create consensus on the synthetic biology definition (Vermeire et al., 2014). This led to a new definition of synthetic biology:

> **SynBio** (synthetic biology) **is the application of science, technology and engineering to facilitate and accelerate the design, manufacture and/or modification of genetic materials in living organisms.** (p. 5)

This definition implies that synthetic biology is a new field in which biology is engineered, which means it is driven by several different fields, among others biology, chemistry and engineering (De Vriend, 2006; Endy, 2005; Benner & Sismour, 2006; Heinemann & Panke, 2006; Polizzi, 2013), but also mathematics (Heyer & Poet, 2014).

For biotechnologists synthetic biology is a new way to organise and structure genetic engineering (Schwille, 2011). The main difference between genetic engineering and synthetic biology is that genetic engineering involves the transfer of individual genes from one species to another, while synthetic biology envisions the assembly of novel microbial genomes from a set of standardised genetic parts.

The assembly of these parts can be done in two-ways, namely top-down and bottom-up. In the bottom-up approach, scientists aim to create a cell *de novo* (from scratch) by constructing a membrane-bound compartment and then adding components. This is what chemists and physicists focus on mostly (Schwille, 2011). In the top-down approach, scientists begin with living cells (*in vivo*) and then modify functions of these cells (Porcar et al., 2011; Purnick & Weiss, 2009; Tucker & Zilinskas, 2006). In the next few decades bottom-up and top-down synthetic biology will increasingly blend and become harder to distinguish (Bedau, Parke, Tangen & Hantsche-Tangen, 2009).

Applications

There have been several successful synthetic biology studies, mostly using top-down methods (Hodgman & Jewett, 2012). Chemical engineer Jay Keasling redesigned *Escherichia coli* in order to synthesize a precursor for the antimalarial drug artemisinin. Due to this 'new' *E. coli* the malaria medicine became less expensive and is now more suitable for widespread use (Ball, 2004; Keasling, 2007; Tucker & Zilinskas, 2006). Synthetic biology pioneer Craig Venter and his team assembled a virus in just three weeks that infects bacteria. They are also working on bacterial cells that fulfil functions they cannot fulfil in nature (Ball, 2004).

Besides that, researchers are looking for the smallest amount of DNA that is essential for maintaining cell viability. Tom Knight, researcher at Massachusetts Institute of Technology (MIT), studies one of the simplest organisms known: *Mesoplasma florum*. This bacterium consist of only 682 genes – in comparison, the human genome contains 20.500 genes – and contains very little non-essential DNA. Knight tries to simplify the bacterium even further, he states that 'an alternative to understanding complexity is to get rid of it' (Ball, 2004, p. 625). If the minimum essential bacterial DNA is found, it can then be used to add parts of standardised DNA that are preferred (De Vriend, Van Est & Walhout, 2007; Pleiss, 2006). These standardised parts are called 'BioBricks', which is, ironically, a metaphor itself. BioBricks are standardised DNA parts that are interchangeable, functionally discrete and capable of being combined in a modular fashion (Calvert, 2010; Bedau et al., 2009). Using these techniques will increase the pace of innovation in comparison to previous techniques (Erickson, Singh & Winters, 2011).

BOX 1 | Potential applications of SynBio

Biomedicine
- Complex molecular devices for tissue repair/regeneration
- Smart drugs
- Biological delivery systems
- Vectors for therapy
- Personalised medicine
- Cells with new properties that improve human health

Synthesis of biopharmaceuticals
- Complex natural products

Sustainable chemical industry
- Environmentally friendly production of chemicals

Environment and energy
- Bioremediation
- Production of energy
- GMO safety

Production of smart materials and biomaterials

Security/ counter-terrorism

(Balmer & Martin, 2008)

The main reason to use the bottom-up method is to understand life and thereby the origin of life. Theoretical physicist Feymann once famously said, 'What I cannot create, I do not understand' (Van der Belt, 2009, p. 258). In other words, in order to comprehend something to its full extent we should be able to effectively construct and deconstruct it (Ruiz-Mirazo & Moreno, 2009). However, the bottom-up method has so far not led to useful applications, but might play an important role in the future by creating new possibilities.

To put all of these possibilities in perspective, the European Union's New and Emerging Science and Technology (NEST) programme studied the potential applications of synthetic biology. They found several fields to which synthetic biology could contribute in the near future (BOX 1) (Balmer & Martin, 2008). Ultimately, the goal of all of these synthetic biology methods is to create applications which will benefit society (Kitney et al., 2009; Yadav, De Mey, Lim, Ajikumar, Stephanopoulos, 2012).

Implications

Like any other technology, applications of synthetic biology will have lots of implications on daily life and society (Andrianantoandro, Basu, Karig, Weiss, 2006). These implications can either be benefits or downsides.

Benefits

The benefits are closely related to the applications of synthetic biology, since these applications have the potential to bring epochal changes in medicine, agriculture and industry and thereby stimulating economic growth (Lowrie, 2010; Tucker & Zilinskas, 2006). More concretely this means auspicious new possibilities or higher efficiency in food and pharmaceutical processing, energy production and refinement and industrial manufacturing (Boldt, 2010; Pei, Schmidt, Wei, 2011). Synthetic biology already holds many accomplishments to its credit, e.g. Venter's work on new functions for bacteria, Keasling's work on artemisinin producing *E. coli* and Knight's work on simplifying bacteria. The possibilities of synthetic biology are enormous, as Ball (2004) stated:

> *…if synthetic biology is successful, it may become possible to treat a variety of diseases by repairing defective cell functions, targeting tumours of stimulating growth and regeneration of specific cell types. Other researchers are hoping to engineer bacteria to make complicated drugs or to use sunlight to generate clean-burning hydrogen for cars and power plants.* (p. 625)

Along with changes in technological possibilities, comes the possibility for new choices. Due to current DNA technologies, for instance, people are able to test for hereditable diseases. A similar change can be expected due to the developments in synthetic biology. For example, if the technologies as suggested above (Ball, 2004) become reality, people could choose for alternative treatments and energy sources which are more efficient, less expensive, completely new or any combination of these three. Synthetic biology could improve our life in the same way as engineering has done so far (Serrano, 2007).

Downsides

Besides all the benefits, we should always be aware of any negative impacts, since engineering also brought us sophisticated bombers and tanks (Schmidt, 2008; Serrano, 2007). These impacts can be divided into two categories; hard impacts and soft impacts. Hard impacts are basically neutral and objective and soft impacts are unpredicted side effects of technological developments on society and individuals (Boerwinkel, Swierstra & Waarlo, 2012).

Lowrie (2010) studied possible downsides of synthetic biology developments and created a list of six main concerns.

(1) The release into the environment of novel, genetically modified organisms potentially resulting in harmful consequences for ecological systems and/or human health.
(2) The increasingly routine nature of many synthetic biology procedures, which makes them more readily accessible to those without specialized training.
(3) The possible misuse of synthetic biology for bioterrorism–including the construction of modified or novel microorganisms with lethal or incapacitating effects.
(4) Patenting strategies, potentially creating monopolies that could inhibit basic research and restrict product development to large companies.
(5) Trade and global justice issues, such as preventing the exploitation of indigenous resources by enabling the chemical synthesis of valuable products in industrial countries.
(6) Claims that synthetic biology is involved in creating artificial life, raising philosophical and religious concerns.

The first three can be seen as hard impacts, since consequences can be directly noticed. Numbers 4 till 6 can be seen as soft impacts, due to their unpredictability. The soft impacts are closely related to ethical issues, such as values of justice and respect for life (Tatje, 2013).

The 'Hart Research Associates' (2013) studied the main concerns regarding synthetic biology among citizens of the United States of America. More than a quarter of the studied group thought of bioterrorism as the greatest concern (28%). This is quite logical, according to Ball (2004), since it is a real possibility that bioterrorists could use synthetic biology to create even more dangerous organisms – including Ebola, smallpox and anthrax – perhaps enhancing them with resistance to antibiotics.

The second concern in this study (Hart Research Associates, 2013) is creation of artificial life. Approximately a quarter (27%) of the interviewed condemned it as morally wrong to create artificial life, and therefore thought of this as the greatest concern. This topic has been widely discussed in literature (e.g. Boldt & Müller, 2008;

Dabrock, 2009; Petersen, 2001; Sadler, 2004; Van der Belt, 2009; Yearley, 2009), and is often compared to the story of Frankenstein. The creation of Frankenstein's creature, Adam, was seen as monstrous and unethical. Questions were raised, such as; what is the meaning of life if it is manufacturable? Van der Belt (2009) claims that the creature would not have been seen as such a monster if dr. Frankenstein would have communicated more openly about its creation and created a safe environment, as Craig Venter did when he started his research. Therefore, thoughtful communication with the public should be one of the earliest concerns on the agenda for social and ethical responsible synthetic biology research (Ruiz-Mirazo & Moreno, 2013). This study aims to find guidelines for communicating synthetic biology towards the public.

Scientific literacy

There are many expected implications on everyday life of synthetic biology applications. Since people should be able to make well-informed decisions about these implications it is important to be informed about synthetic biology. In other words, scientific literacy should be promoted among the public. Scientific literacy can be defined as; '…the knowledge and understanding of scientific concepts and processes required for personal decision making, participation in civic and cultural affairs, and economic productivity' (National Science Education Standards, p. 22 as cited by Van den Hoogen & Tatje, 2013). Moreover, general knowledge about scientific and technological topics is essential for an effective workforce participation in the twenty-first century (Roth & Lee, 2003), because it is science which will pose the political and moral dilemmas of the twenty-first century (Osborne, 2007).

According to Shamos (1995) there are three forms of scientific literacy, i.e. 'cultural scientific literacy', 'functional scientific literacy' and 'true scientific literacy' (Laugksch, 2000). Cultural scientific literacy is the simplest form and represents the level of scientific literacy held by most educated adults who believe they are reasonably literate in science. Functional scientific literacy means that an individual is able to use this knowledge to function in society by talking, reading and writing about science in a meaningful way. And true scientific literacy is the highest form, which is unachievable for most members of society (Boerwinkel, Veugelers & Waarlo, 2009; Laugksch, 1999; Slegers, 2014). The focus in this study will be on functional scientific literacy, because this is the amount of knowledge that is necessary to talk, read, write and think properly about a certain topic. In order to reach scientific literacy on a certain topic, some basic knowledge is required. In this article this is what is determined as 'essential knowledge'.

Functional scientific literate individuals are able to make well-informed decisions on scientific topics that affect their daily lives (Sadler, 2004). In order to make these kind of decisions, the public needs to possess proper knowledge and skills. However, this is currently not the case. Research by Hart Research Associates (2013) showed that in 2013, 75% of the surveyed population in the United States of America had heard little or nothing about synthetic biology. In 2010, a survey by Gaskell (2011), already showed that 83% of the Europeans had never heard of synthetic biology. Despite this knowledge gap among the public, many of the interviewed claimed that they want public involvement in decision-making when ethical and societal issues are involved (Gaskell, 2011). Therefore, scientific literacy should be promoted more extensively on synthetic biology.

But how to promote more scientific literacy among individuals? One way to communicate science is through informal education. According to Calvert & Martin (2009) there is a changing role for scientists, converting them more and more into social scientists, meaning they should contribute to or collaborate with members of society. It is also claimed that Civil Society Organisations (CSO's) might play an important role in transparent education and communication about synthetic biology (Stemerding, De Vriend, Walhout & Van Est, 2009). Other platforms are the yearly international Genetically Engineered Machines (iGEM) competition – in which high school teams produce genetically modified useful organisms (Hellsten & Nerlich, 2011; Mitchell, Dori & Kuldell, 2011) –, the pClone – a synthetic biology tool for biology students (Campbell et al., 2014) – and discussion platforms for secondary school students (Kennislink, 2014).

Another way to improve scientific literacy is via formal education (school). During their education students should learn to become functional scientific literate individuals. They should learn certain skills which will enable them to explore scientific issues that might arise in the future (Ratcliffe & Grace, 2003). On top of that, the Dutch government indicates that schools should spend time on "active citizenship and social integration" (Bron, 2006). Citizenship consists of three competences; (1) being able to collect and critically assess information, (2) being able to form a well-informed opinion or make a well-informed decision, and (3) act based on an opinion or decision (Boerwinkel et al., 2009). These competences connect closely to functional scientific literacy (Slegers, 2014). Citizenship education should, therefore, lead to more scientific literacy among these students, which is important to enable them to live and act with reasonable comfort and confidence in a society that is highly influenced by science (Osborn, 2007). This study aims to find a way to promote scientific literacy among young citizens on the topic of synthetic biology.

Metaphors

Introducing and clarifying an abstract and complex topic, such as synthetic biology, is difficult. Due to this abstractness and complexity, tools can be used to provide a solution for clear explanation. One of these tools is the metaphor. In this section metaphor use in general, in science, and more specifically in synthetic biology is elaborated.

Metaphors in general

Metaphors, and its close relatives analogy and simile, have been used since the earliest writings of man. For example, Plato's dialogues (e.g. the cave metaphor to describe several levels of knowledge) and the bible (e.g. body of Christ [bread], Christ as shepherd) are filled with metaphors (Ortony, 1975).

A metaphor is an expression that consists of multiple parts which are linked together to form a new understanding. The product of metaphor comprehension is a complex interaction between the 'Topic' and the 'Vehicle' concepts (Kovecses, 2000; McGlone & Manfredi, 2001). For example, in the common used genome metaphor, 'the human genome is our blueprint', the 'human genome' is the Topic and 'blueprint' is the Vehicle. The underlying idea is that the Topic is perceived in terms of the Vehicle. In this case the human genome (Topic) is perceived in terms of a blueprint (Vehicle).

Metaphors are not always directly used, or even noticed. Often a concept is metaphorically structured. An example is *argument is war*, in which sentences as 'I *demolished* his argument' and 'your claims are *indefensible'* imply the metaphorical association of war (Lakoff & Johnson, 1980). In this kind of metaphor a stretch of language creates the possibility of activating two distinct domains. Similes and analogies can be included in this stretch of language. Through this text, the Topic and Vehicle domains are connected (Cameron, 1999; Cameron, 2002).

Metaphor use is enmeshed in everyday language. Lakoff & Johnson (1980) state that metaphors are the main mechanism through which we comprehend abstract concepts and perform abstract reasoning. However, the use of metaphors for explanation may have complications. Incorrect use of metaphors can cause the creation of an erroneous image, thereby missing the target of comprehension. This may even cause premature conclusion about the topic or the vehicle (Boudry and Pigllucci, 2013; Chew & Laubichler, 2003).

This Topic-Vehicle relation is illustrated in Figure 1, the Topic (T) is understood in terms of the Vehicle (V). However, not all concepts of the Topic are understood via the use of one Vehicle and each Vehicle may cause associations that are not related to the Topic. The use of multiple metaphors might provide a solution for complete topic explanation (Ceccarelli, 2004).

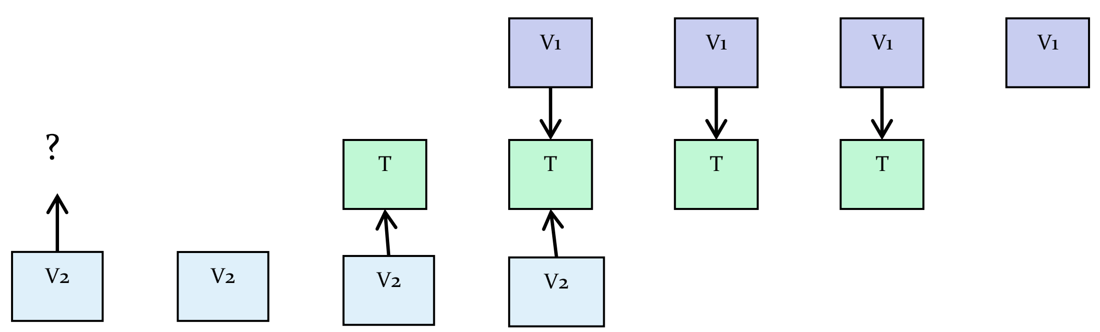

Figure 1. Relation between concepts of the Topic (T) and the Vehicle (V)

Due to these possible misunderstandings, metaphor use should always be done carefully. The transfer between the Topic and the Vehicle should be understandable. If done properly, a link between both of them is created. However, if not done properly the learner cannot create a proper link between Vehicle and Topic and might be left in confusion (Gernsbacher, Keysar, Robertson & Werner, 2001).

Despite all of these points of awareness, Ortony (1975) claims (cited in Heijkoop, 2013) there are three reasons why metaphors are actually functional in education. 'First, metaphors can tell more in less words. Second, metaphors provide a way to explain something when there are no proper words. Third, metaphors are closely related to the imagination, because they are lively and easy to visualize' (Heijkoop, 2013, p. 6).

Following these three reasons it seems only logical that nowadays metaphors are used for explaining and bonding different concepts (Avise, 2001). Especially abstract and complex concepts require the need for metaphor explanation (Muscari, 1988; Duit, 1991), because these concepts require visualisation to make them comprehensible (Ortony, 1975).

Metaphors in science

These complex concepts often arise in science. Niebert, Marsch and Treagust (2012) even argue that it is not possible to teach, think about and understand science without metaphors and analogies. Brown (2003) agrees with this and says: 'None of the scientist's brilliant ideas for new experiments, no inspired interpretations of observations, nor any communication of those ideas and results to others occur without the use of metaphor' (p. 15). Thus, science communication strongly relies on metaphors, which is also illustrated by school textbooks. The 8th edition of the book *Biology* (Campbell et al., 2008), for example, uses a *war metaphor* to explain the immune system: 'Although the body *responds* to HIV with an *aggressive* immune response sufficient to *eliminate* most viral infections, some HIV invariably *escapes*' (Niebert et al., 2012).

BOX 2 | Well-known science metaphors

- Greenhouse effect: the atmosphere is like a hotpot (Arrhenius)
- Planetary motion: comparison to a clock (Kepler)
- DNA: Double helix structure analogy of a twisted ladder (Watson & Crick)
- Light: Light moves like a wave (Huygens)

(Adapted from Niebert et al., 2012)

Besides very complex, scientific topics (e.g. genetics and chemistry) are often invisible to the naked eye (Duncan & Reiser, 2007). Metaphors can be used for clarification by creating an image and thereby visualising the Topic in terms of the Vehicle (Ortony, 1975). By visualising a concept, metaphors can help to explain and popularize complex scientific information (Nelkin, 2001).

There have been various studies on the effectiveness of metaphor use in genetics (e.g. Condit & Condit, 2001; Heijkoop, 2013; Martins & Ogborn, 1997; Richards & Ponder, 1996; Van Berkum, 2013). However, these studies have not yet been conducted specifically for the new scientific field; synthetic biology.

Metaphors in synthetic biology

In the field of synthetic biology metaphor use is currently widespread. Several studies have reported on the use of synthetic biology metaphors. Cserer and Seiringer (2009) studied the most frequent used metaphors in German media between January 2004 and December 2008. Hellsten and Nerlich (2011) studied synthetic biology metaphor use in English-speaking press coverage between 2008 and May 2010. They suggest that there are three main synthetic biology metaphors – books, engines and computers –, which are linked to three historical revolutions, respectively printing, industrial and information revolution.

In the use of synthetic biology metaphors one main concern is often discussed. This main concern has to do with the gap between the realistic image versus the image created by metaphors. This concern seems greatest in the use of 'machine' metaphors. Synthetic biology connects closely to molecular biology and machine metaphors (both computer and industry metaphors) are often used in synthetic biology.

There is, however, no consensus about the use of these machine metaphors, or any other metaphors, in synthetic biology. There are both proponents and opponents for the use of machine metaphors. The proponents (e.g. Scott, 1997) claim that 'even if the machine cannot function purely as a machine we still have to explain, and to have a language for explaining, why it so often appears to do so' (p. 573). In other words, education about difficult concepts requires a way for explanation, which might not be perfect, but is still the best way. The opponents (e.g. Piglucci & Boudry, 2011; Boudry & Piglucci, 2013), state that the idea of machines conflicts with the idea of living beings – since living beings are subjects of Darwinian evolution and extremely context-dependent (Deplazes & Huppenbauer, 2009; Porcar et al., 2011) – and therefore the metaphor would not be accurate enough. Due to this inaccuracy misconceptions may arise.

In summary, metaphors can be used to clarify complex and abstract topics and concepts – such as synthetic biology –, however, metaphor use should be done carefully, in order to avoid or minimize complications and maximize understanding.

Research question

The aim of this study is to describe what metaphors can be successfully used to clarify synthetic biology to secondary school students. Thereby, more insight can be gained in the use of metaphors, as well as in how science educators can adequately communicate synthetic biology to young citizens. The research question in this study is:

Which metaphor(s) are most fruitful to clarify synthetic biology adequately in upper secondary biology education?

In order to answer this research question three sub-questions must be answered:

In order to determine which metaphor(s) are most fruitful, first it has to be determined what the most frequently used synthetic metaphors are. (S1) *What are the most frequently used synthetic biology metaphors?*

In order to determine what is considered most fruitful it is important to find out what is considered essential information. (S2) *What is the essential knowledge secondary school students should know about synthetic biology?*

To determine what metaphor use is adequate in secondary biology education it is important to answer the following question. (S3) W*hat reactions do most used synthetic biology metaphors evoke in upper secondary school students?* Herewith, 'reaction' is twofold; associations and preference.

Method

This study is divided in two phases to maintain an clear overview and structure. During the first phase, an inventory of metaphor use in literature was conducted and experts on synthetic biology were interviewed to determine the essential knowledge upper secondary school students should have about synthetic biology. In the second phase, it was determined what reactions upper secondary school students have with different metaphors.

Phase 1

Metaphor inventory

In order to get an overview of the most used synthetic biology metaphors (sub question 1), scientific articles on synthetic biology were reviewed and publications on synthetic biology from websites of several Civil Society Organisations (CSO's) were analysed.

Since the goal was to determine what metaphors are currently used for explaining synthetic biology the used search term was "Synthetic biology is". This search term was used in three search engines, namely Google scholar, Web of Science and ERIC, and hits were sorted by 'Relevance'. These searches were conducted on November 6, 2014. The first ten articles of each search engine were included. Articles that did not explain synthetic biology and duplicates were manually filtered and the next article in line was included. Of these articles the introduction was analysed for synthetic biology metaphor use. Using this approach, a total of 23 articles were included, since ERIC only showed three relevant articles (see Appendix A). In these articles the use of the three most common synthetic biology metaphor source domains, according to Hellsten and Nerlich (2011), were analysed. This was done with the use of the list of words that correspond to each metaphor, as presented in Box 3.

Since Hellsten and Nerlich's (2011) review analysed literature until May 2010, another analysis was conducted, in which metaphor use between June 2010 and February 2015 was analysed, in order to determine whether the most used synthetic biology metaphors have changed since Hellsten and Nerlich (2011). The used search term was again "Synthetic biology is" and the same three search engines were used. This search was conducted on March 15, 2015 (see Appendix A). Since the use of any other metaphor was rarely found, this study adapted these most used metaphor categories (computer, book, industry) as previously used by Hellsten and Nerlich (2011).

BOX 3 | Corresponding words to most used synthetic biology metaphors

Computer
- Codes, booting up, software, hardware, programming, executing, engineer, tagging, programme, controls, digital, cutting, pasting, editing, designing/engineering.

Book
- Letters of life (DNA nucleotides), reading, writing, instruction books, language, phrases, letters, words, sentences, paragraphs, chapters, edit, spell, translate, transcribe, copy, print, publication, cut, paste, cook book, guidebook (map), telephone book, instruction manual (blueprint, handbook, library.

Industry
- Building blocks, BioBricks, Lego bricks, building, designing, engineer, (electrical/control) circuits, tinkering, standardisation, automation, customation, industrialisation, architecture, construction.

(adapted from Hellsten & Nerlich, 2011)

For the CSO analysis a similar method was used. Two CSO's were chosen (*Rathenau Instituut* and *Kennislink*), due to their frequent communication on synthetic biology in the Netherlands. On their websites, the five latest publications were analysed on synthetic biology metaphor use, leading to a total of ten included publications (see Appendix A). For *Kennislink* the publications were selected from the synthetic biology theme page based on explanation about synthetic biology; for the *Rathenau Instituut* the publications were selected on relevance of the search term 'synthetic biology'. This search was conducted on April 17, 2015 (see Appendix A). The outcomes are displayed in the results section.

Expert interviews

In order to gain more insight in experts' views on how to communicate synthetic biology in an effective way to secondary school students (sub question 2) semi-structured interviews with synthetic biology experts were conducted.

Criteria for expert selection

Experts had to match several criteria in order to be part of this study, they: (i) have expertise in the field of synthetic biology, (ii) are located in the Netherlands, (iii) are willing and able to cooperate. Expertise in one of the several fields of synthetic biology (criteria 'i') is essential. Therefore, Dutch experts at the *Rathenau Instituut*, Ministry of Health, KNAW and several professors specialised in molecular biology, biotechnology and/or synthetic biology were approached. A total of nine experts were asked to participate. Three declined due to lack of interest or time. As a result, a total of five experts were willing to participate in this study (see Table 1).

This group is as heterogeneous as possible, by including experts from different locations and work fields, such as research, communication, policy or university education (see Table 1). However, the Ministry of Health was not willing to cooperate. Expert heterogeneity was a deliberate choice, since all these fields have some interest or benefit on communicating synthetic biology. By including experts from different fields a more in-depth view of how to communicate and educate synthetic biology is represented. The results are thereby applicable for more widespread use, since multiple participating actors have had some influence on the outcome.

Table 1
Overview of participating experts, who are also represented by their capitols.

Expert	Function	Field	Location	Visit date
Dr. L. Hanssen (LH)	Director of DEINING Societal Communication & Governance	Scientific communication	Nijmegen	20-11-2014
Prof. dr. W.P.M. Hoekstra (WH)	Emeritus Professor Molecular Biology	Scientific research/university education	Zeist	24-11-2014
Dr. D. Stemerding (DS)	Senior Researcher at *Rathenau Instituut*	Scientific policy	Den Haag	01-12-2014
Prof. dr. R.A.L. Bovenberg (RB)	Professor Synthetic Biology and Cell Engineering	Scientific research/university education	Groningen	04-12-2014
Prof. dr. H.A.B. Wösten (HW)	Professor Molecular Biology	Scientific research/university education	Utrecht	10-12-2014

Interview protocol

To increase reliability of collection, an interview protocol for the expert interviews was developed, and discussed with other researchers based on the research question (see Appendix B), thereby creating a standard technique for data collection. Besides this, the experts were informed in advance via email about the aim and method of this study, and again at the beginning of the interview, to increase validity by making sure the interviewer and the expert were on the same page. The key questions in the expert interview protocol were question 3, 9 & 10 (see Box 4) (see Appendix B). To take triangulation into account questions 9 & 10 were asked in multiple ways, first open and thereafter more closed, by filling in a list of possible options (see Appendix B). To increase reliability question 9 was coded by a second researcher, securing inter-rater reliability. In order to secure a high descriptive validity all interviews were audio recorded and transcribed verbatim. Interviews generally took 50 to 80 minutes.

BOX 4 | Key questions of expert interviews

Q3: What is synthetic biology?

Q9: What information should upper secondary students minimally understand in order to make well-founded decisions about synthetic biology?

Q10: What is your opinion on current most used synthetic biology metaphors?

The main question in these interviews focussed on the way synthetic biology should be communicated to the public and more specific young citizens (Appendix B, question 9). Moreover, the experts were asked about their opinion on currently used synthetic biology metaphors (Appendix B, question 10) and about the exact meaning of synthetic biology (Appendix B, question 3) (see Box 4). The interview protocol included four questions (4 - 8) which were either used for support for key question 3 (question 4) or for the purpose of another study (question 5, 7 and 8). Question 1 and 2 were merely questions for introduction. These questions will not be reported on in this study. Question 6 was not interesting due to a lack of response by the experts and is therefore not used in this study.

Expert interview analysis

The interview transcripts were analysed with use of the “Grounded Theory” (Glaser and Strauss, 1998), which roughly means that categories arise from reading and rereading the raw data. Full transcripts were analysed on key question 3, 9 & 10. From these analysis categories arose, from which general answers for the key questions were determined. These answers were returned to the experts for feedback (member check), in order to increase reliability.

For question 9 (see Box 4) several categories were formed based on the interviews, coding of these categories was done by a second researcher in order to increase inter-rater reliability. Categories mentioned by the experts matched 100% between the two researchers, minor differences in amount of mentioning certain categories were due to different views of the point where a certain quote ended and the next one began. The weight of these different categories of synthetic biology for learning was not yet determined. Hence, the experts were asked to distribute hundred points each among the formed categories in the member check. The categories and the distributed points can be found in the results. First version of consensus of questions 3 and 10 were also returned to the experts for comments. After this feedback, experts’ answers were used to make adjustments to the first consensus if necessary. These answers, including comments, are included in the results. The member check ensures the researcher and experts are viewing the data consistently (Brink, 1993).

Phase 2

Metaphor associations

In order to gain more insight in which essential knowledge is evoked by the synthetic biology metaphors (sub question 3), both quantitative and qualitative research methods were used. The secondary school students were asked to fill in a questionnaire that consisted of part A and part B. This questionnaire consists of open and closed questions, providing qualitative and quantitative data. Thereafter, some students were interviewed to provide more qualitative reasoning on their answers.

Target group

The target group concerns 11th grade pre-university students with an average age of approximately 17 years old (equivalent to Dutch school system 5VWO), and have biology in their curriculum. This group is chosen due to their prior knowledge about genetics, which is taught in 10th grade (4VWO). Both males and female are represented in this study. During analysis gender was taken into account as a possible reason for difference between associations towards the metaphors. The ratio of males and females whom participated in this study was respectively 103 : 109 (N = 212).

School selection

A total of eight schools were contacted for participation in this study. The next three criteria guided the school selection, (i) they should have students that fit the selected target group (11th grade pre-university students who have biology in their curriculum), (ii) in order to assure a representative outcome, geographic and social variety was taken into account as much as possible, and (iii) schools should be willing and able to cooperate. For pragmatic reasons, this last criterion was considered more important than criteria (ii). From the eight contacted schools, six were willing to participate in this study: Erasmiaans Gymnasium (Rotterdam), Koninklijk Wilhelmina College (Culemborg), Christelijk Lyceum (Veenendaal), Stanislascollege Westplantsoen (Delft), Emmauscollege (Rotterdam), Onze Lieve VrouweLyceum (Breda) (see Table 2). Some schools were able to provide several classes that participated in the study. The questionnaire was administered to 212 students during their regular biology class (return rate 100%). Completion of the questionnaire generally required 20 to 25 minutes.

Student questionnaire

The questionnaire was formed based on discussion with other researchers and is partly based on previous studies (Condit et al., 2002; Heijkoop, 2013). A pilot test was conducted with two students that fit the target group. While filling in the questionnaire, they were asked to comment on any ambiguities. The questionnaire was slightly adjusted and improved based on the pilot test and the expert interviews, mostly considering adjustments in language. The final questionnaire can be found in Appendix C, section 3. The questionnaire was administered to nine classes in six schools, in order to gain more insight in the associations and preferences with several synthetic biology metaphors.

In the questionnaire the main goal was to gain insight in the reaction students have with different synthetic biology metaphors. The questionnaire consists of two parts: A & B (see Appendix C, section 3). In part A, three different versions were designed (each containing one metaphor – either computer (Appendix C, section 2, version A1), book (Appendix C, section 2, version A2), or industry (Appendix C, section 2, version A3) –) to explain the meaning of synthetic biology via a text structured around a metaphor, which was created based on scientific literature with feedback of other researchers (see Box 5). Three versions were designed in order to remove the bias of other metaphors. Thereby the associations of each of the three metaphors could be determined separately. The questionnaire consists of (i) open questions with space for students to write no more than a short paragraph, (ii) two 7-point Likert-scale questions, and (iii) a 5-point semantic scale for associations.

BOX 5 | Descriptions of the book metaphor which was used in the questionnaire (see Appendix C, section 2)

A1: Computer metaphor

Synthetic biology (SynBio) is a new field of science. In SynBio, the software (DNA) is designed and it is put inside the hardware (cell). Different software activates different programmes (processes in the cell). By cutting, pasting and combining pieces of software, all sorts of programmes, with different functions can be created. Even software that does not normally exist in a cell can be developed. This is how scientists created a bacteria that produces a malaria medicine, for instance.

A2: book metaphor

SynBio is a new field of science. In SynBio, scientists cannot only read the code of DNA (ACTG), they can also write it. Thereby forming a new language, in which is written what cells should do, some sort of new manual for the cell. Also completely new manual can be written. This is how scientists created a bacteria that produces a malaria medicine, for instance.

A3: Industry metaphor

SynBio is a new field of science. In SynBio, scientists work with the bricks of which DNA is build (ACTG). These building bricks are then molded into standardised packages with a certain function (BioBricks). With these BioBricks the architect (scientist) can build a factory (cell), that functions exactly as the architect intended. This is how scientists created a bacteria that produces a malaria medicine, for instance.

The questionnaire (Appendix C, section 3) starts with two open questions, in which students were asked to write down their first thoughts in both a sentence (question 1) and in three words (question 2). Thereafter, the students were asked to fill in two 7-point Likert-scale questions about whether the provided text (A1, A2, A3; see box 5) was clear (question 3) and whether their attitude towards synthetic biology is positive or negative (question 4).

The semantic scale with connotative pairs was used in order to see student associations towards synthetic biology. This scale originates from a previous study (Condit et al., 2002) and has been previously used by Heijkoop (2013), both studied associations of genomic metaphors in secondary school students. Heijkoop translated the semantic scale to Dutch and adjusted it slightly based on her pilot studies. A slightly changed version of the semantic scale by Heijkoop (2013) is used in this study. This semantic scale consists of several connotative pairs in which the student has to check the blank on the scale that represents how close the shade of meaning of the word is to either the word on the left or the word on the right, like small/large (groot/klein), variable/uniform (variabel/uniform) (see Appendix C, section 3, part A, question 5). Added to Heijkoop's (2013) list were growth/production (groei/productie), living/dead (levend/dood) and living/lifeless (levend/levenloos). Also 'bepaald' was changed to 'vastgesteld'. These changes were based on Condit et al. (2002), peer feedback, pilot studies, and expert interviews.

In part B of the questionnaire, the students were shown all three metaphors from the three different versions of part A. One of these texts was already familiar, the other two were new to the student. They could now comment on the different explanations and their preferences and aversions. The students were also given space to explain their opinions briefly.

The quantitative data – gathered from the 7-point Likert scale, the semantic scale and the student preference – from the questionnaires was analysed with the use of SPSS, version 22. A test for multivariate analysis of variances (MANOVA) was used to find differences between the semantic scales for the three metaphors.

Student interview

After the student questionnaire, a qualitative method was used to gain more insight in the answers given in the questionnaire. Several face-to-face interviews (1 or 2 per school) in which males and females were equally represented in a 7:7 ratio (N = 14) were conducted in order to clarify common given answers, and get more insight in the connotative pairs. A manual for these interviews can be found in Appendix D. The outcomes of these interviews and questionnaires were analysed to determine which reaction these metaphors create with the students. The open questions of the questionnaire and the interviews provide more qualitative data and were analysed using the Grounded Theory.

Table 2
Overview of the six participating schools. Location, area, religion and the amount of students per version of part A (A1; computer, A2; book, A3; industry) and the number of students that were interviewed from each class are represented in the table.

School	Location	Classes	Area	Religion	Students	Version (A1:A2:A3)	Student Interviews
1	Rotterdam	1	Urban	Public	26	9 : 10 : 7	2
		2			28	13 : 8 : 7	1
		3			20	8 : 5 : 7	1
2	Culemborg	4	Rural	Christian	27	7 : 11 : 9	2
		5			17	6 : 2 : 9	2
3	Veenendaal	6	Rural	Christian	35	9 : 13 : 13	2
4	Delft	7	Urban	Christian	25	9 : 8 : 8	2
5	Rotterdam	8	Urban	Christian	16	4 : 7 : 5	1
6	Breda	9	Urban	Christian	18	6 : 6 : 6	1
				Total	**212**	**71 : 70 : 71**	**14**

Results

Phase 1

Metaphor analysis

In their review study, till May 2010, Hellsten & Nerlich (2011) found three different synthetic biology metaphors that were used in English-speaking press coverage between 2008 and May 2010., namely ‘computer’, ‘book’ and ‘industry’. In this study we analysed scientific articles and CSO publications explaining synthetic biology post-Hellsten & Nerlich.

A total of 23 scientific articles and ten CSO publications were analysed on metaphor use for explanation of what synthetic biology is. The total list of articles can be found in Appendix A, the outcomes are presented in Figure 2. During analysis it became clear that there is some overlap between the three metaphors. Computer and industry have the designing component in common, while computer and book have the language component in common. Therefore, an article was often structurally founded within a range of two metaphors, unless more specifics were given in the explanation of the article. For example, an explanation about synthetic biology such as: ‘What is unique to synthetic biology is the application of an engineering-driven approach to accelerate the design-build-test loops required for reprogramming existing, and constructing new biological systems’ (Hodgman & Jewett, 2012) fits with both the computer and the industry metaphor. Another reason for multiple results from one article is that sometimes multiple metaphors were used. These are problems Hellsten and Nerlich (2011) encountered in their analysis and explains why there are more results than the number of articles.

The analysed scientific articles – in English language – did not use the book metaphor at all, either the computer metaphor and/or the industry metaphor was used. In Dutch CSO publications, all three metaphors were used, but the industry metaphor the most (see Figure 2). No other metaphor usage was found in both analysis and therefore no other metaphors were included in this study.

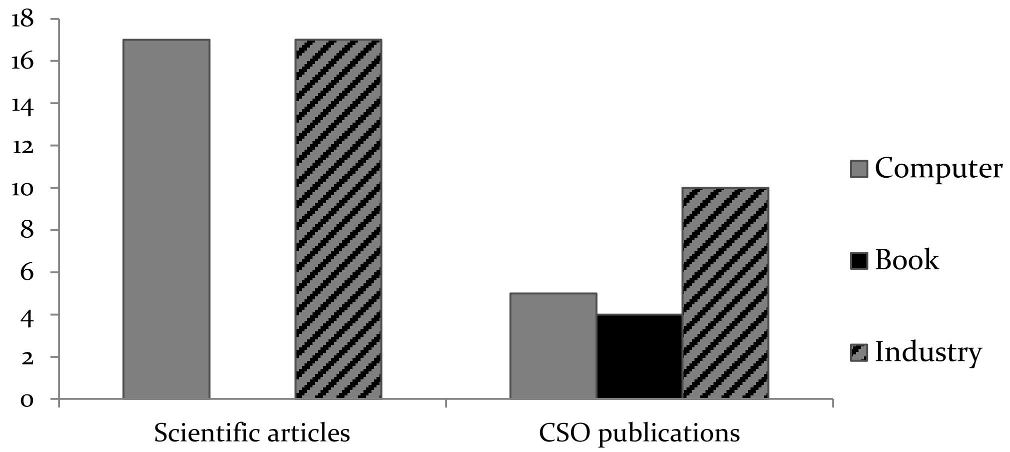

Figure 2. Analysis of synthetic biology metaphor use in articles between June 2010 and May 2015 (n = 23) and in CSO publications since 2007 (n = 10), that were most relevant.

Expert interview

The key questions of the expert interviews led to a result, which was returned to the experts for revision via a member check. The results of these key questions are displayed in this section. These key question are (i) Question 3: What is synthetic biology? (ii) Question 9: What should upper secondary school students know about synthetic biology? (iii) Question 10: What do you think of the currently most used synthetic biology metaphors?

Question 3: Synthetic biology

The expert interviews led to a consensus of what synthetic biology entails. Most experts seemed to agree on the consensus definition below, which was based on the several interviews and was presented to the experts in the member check:

Synthetic biology is the application of engineering principles on biological systems.

1) This differs from previous techniques by a larger amount of control on the process and therefore more opportunities. The terms 'extreme genetic engineering' and 'biotechnology 2.0' are therefore opaque.
2) This can either be done by redesigning existing biological systems (top-down), or by the complete building of biological systems (bottom-up).
3) Most applications will be for the benefit of medical and pharmaceutical practice and for higher efficiency of energy supplies.

The member check showed that most experts agreed on this consensus. Two experts provided additional comments.

"The bottom-up method requires more than DNA. It also requires the combining of other components of the cell and this makes it substantially different from biotechnology in which only DNA modification occurs" – Expert HW.

"*The difference with previous/current technology is due to more emphasis on the design for the desired functionality and (the revolution in) the realisation and characterisation of prototypes*" – Expert RB.

Due to lack of time these comments could not be returned to the experts for a more elaborate consensus and are provide therefore a basis for the search of a clear synthetic biology consensus.

Question 9: Essential knowledge

Prior to the member check question 9 required more in-depth analysis. Firstly, the transcripts were coded based on different categories the experts deemed important for the students to learn. This led to the formation of 12 different categories (see Table 3).

Secondly, for each expert it was defined how many times each category was mentioned. This coding was also done by a second independent coder, which gave an correspondence of 100% match in categories. Minor differences between coders were on the amount certain categories were mentioned by the experts. After intersubjective agreement a consensus was formed (see Table 3).

Table 3
Categories derived from and mentioned in the expert interviews. The several experts are represented with their capitols: [LH] Lucien Hanssen; [WH] Wiel Hoekstra; [DS] Dirk Stemerding; [RB] Roel Bovenberg; [HW] Han Wösten. The column 'Amount' represents the amount of scientists that mentioned a certain category, ranging from 1-5.

Categories	LH	WH	DS	RB	HW	Amount
Underlying biological principles	1	3	4	2	4	5
Difference with previous technologies	3	4	3			3
Different approaches of SynBio	1	1			1	3
Explanation regarding current possibilities		2				1
Explanation regarding future possibilities		1				1
SynBio applications	2	3	4			3
Name-calling: Craig Venter	1	1				2
Comparison with natural processes					2	1
Importance of SynBio	3	1	7		2	4
Alternative solutions			2			1
Balance between positive and negative	1	2			1	3
Ethical context		2			1	2

After that, the member check was conducted. The experts were asked whether they agreed with the answers that were formed on questions 3, 9 and 10. For question 9, the experts were also asked to distribute 100 points over the several categories in order to determine the weight of these categories (see Table 4).

Table 4
Determination of the weight of several synthetic biology categories. Each expert was given 100 points to divide among the formed categories.

	Categories	LH	WH	DS	RB	HW	Total
	Underlying biological principles	10	20	10	25	8,3	**73,3**
	Difference with previous technologies	10	5	10		8,3	**33,3**
	Different approaches of SynBio	10	5	10	25	8,3	**58,3**
	Explanation regarding current possibilities	20	20	10	5	8,3	**63,3**
	Explanation regarding future possibilities		10	10	5	8,3	**33,3**
	SynBio applications	20	10	10		8,3	**48,3**
	Name-calling: Craig Venter		5			8,3	**13,3**
	Comparison with natural processes					8,3	**8,3**
Social Context	Importance of SynBio		10	10	10	8,3	**38,3**
Social Context	Alternative solutions	10		10	10	8,3	**38,3**
Social Context	Balance between positive and negative	10	5	10	10	8,3	**43,3**
Social Context	Ethical context	10	10	10	10	8,3	**48,3**
	Total	100	100	100	100	100	**500**

The points attributed to each category by the experts were added up, forming a total amount of points per category (see Table 4). Thereafter, these total scores were transformed into percentages, which are presented in Figure 3. Most important categories were underlying biological principles (17,67%) and the sum of all social context issues (33,67%).

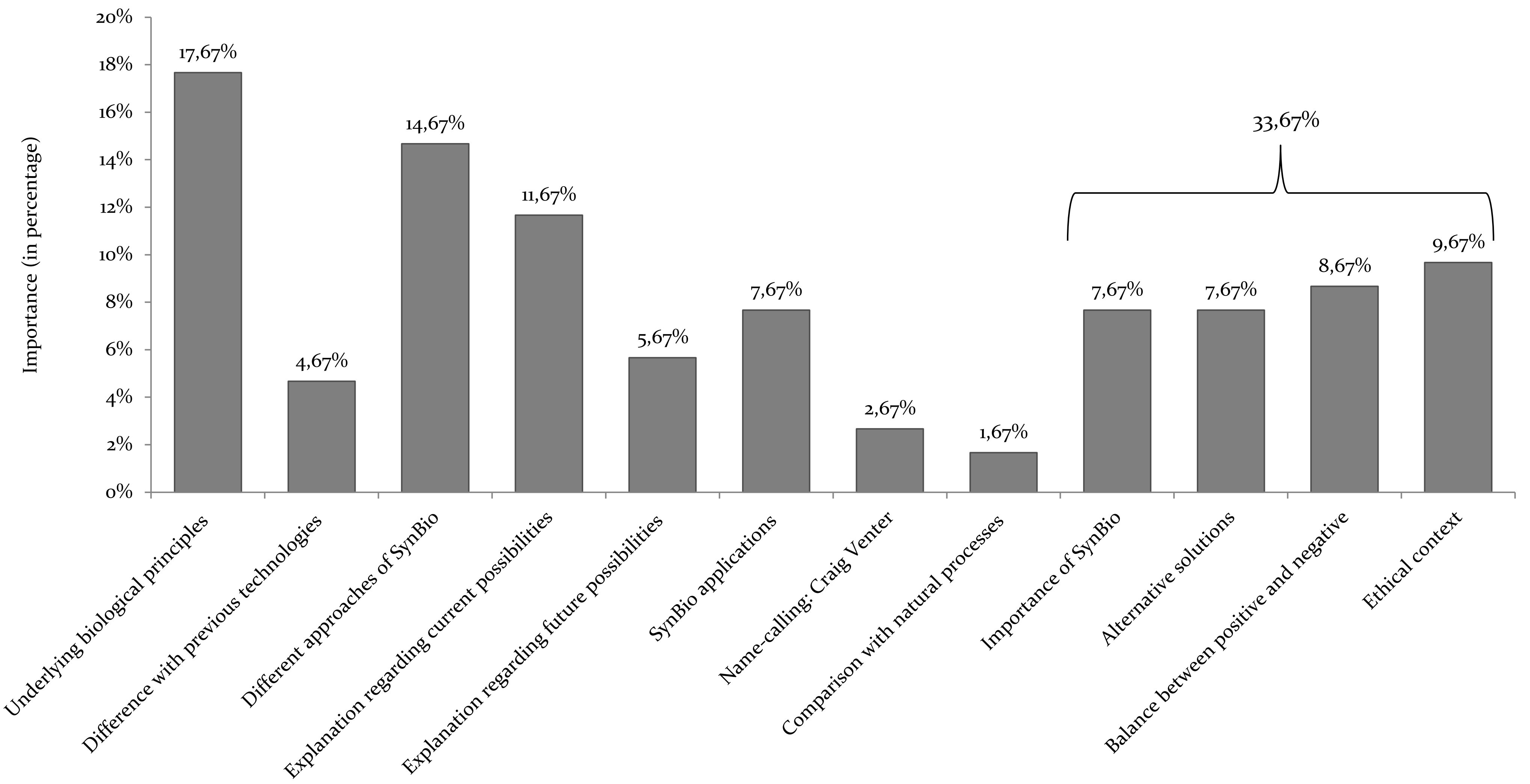

Figure 3. Weight of the several synthetic biology categories. Percentage of the points distributed by the five experts whom participated in this study. Categories belonging to social context are also represented together.

Question 10: Synthetic biology metaphors

During the interview the experts were asked about their opinion on the several most used synthetic biology metaphors. From these data several general statements were formed and via the member check submitted to the experts. The experts were asked to fill in the statements they agreed with and could comment on their answers, the outcome can be found in table 5. Only one expert decided to comment on a given answer. Expert WH commented to strongly prefer the use of the industry metaphor.

Table 5
Experts' view on synthetic biology metaphor use

	Expert				
Statement	**LH**	**DS**	**WH**	**RB**	**HW**
The computer and the book metaphor are practically the same. Both concern the writing of a new language.			X	X	X
The computer metaphor is more modern and might therefore be more suitable for students of this generation.	X		X		X
The computer and the industry metaphor are best usable.		X	X		X
The use of the book metaphor is too simplistic and therefore limited.			X		
A combination of metaphors seems like the best way of communication.				X	
Univocal use of metaphors seems like the best way of communication.	X				X

Out of the five experts four thought the computer metaphor is either less usable than the computer and industry metaphor or the computer metaphor is more modern and therefore more suitable for this generation. Only expert RB did not seem to have a strong opinion on the use of the book metaphor.

Experts were also asked if they had a preference with other synthetic biology metaphors (question 10d). Most experts did not, however expert DS mentioned a lot of other metaphors, including the music of life, plug & play and dressage. However, none of these metaphors were deemed more useful than the three metaphors that are used in this study.

Phase 2

Student questionnaires

The quantitative data of the student questionnaires (Appendix C, section 3) consists of a 7-point Likert scale, and a 5-point semantic scale in part A to test associations made with different metaphors and an indication of metaphor preference in part B. The outcomes of these parts will be discussed in this section.

Analysis of questionnaire part A

Part A of the questionnaire starts with four questions, which are two open questions and two 7-point Likert-scale questions. Thereafter, the semantic scale is discussed.

Question 1 to 4

Question 1 and 2 were included to see what students first association towards a certain metaphor were. However, no noteworthy results came out of these questions. However, these questions led to some bycatch. After reading the texts, the students were asked to write down (question 1) their first thoughts and (question 2) the first three words they thought of. The example used in all written metaphor texts was about the production of a malaria medicine (see Appendix C, section 2). A total of 80 of the 212 students (37,74%) named a word related to healthcare (medicine, cure, health, diseases, etc.).

No significant differences were found between the three different metaphors between question 3: clearness of the explaining texts (unclear-clear) and question 4: attitude towards synthetic biology (negative-positive). A 7-point Likert-scale was used for these questions. Averages for clarity of the text varied from 5.38 to 5.62 and averages for attitude varied from 5.38 to 5.56. Although, no significant values were found, the highest values (5.62 and 5.56) were related to the book metaphor.

Semantic scale

Difference between different versions in part A (A1; computer, A2; book, A3; industry) were analysed in order to see whether explanation of synthetic biology via different metaphors, raised different associations with the students. Using a MANOVA test, no significant difference was found between associations of the semantic scale with connotative pairs for different versions of questionnaire part A. After these tests, the data was transformed from a 5-point to a 3-point semantic scale. The two categories on the left and the two categories on the right were merged, a neutral category remained. Another MANOVA test was performed, and alpha was lowered to 0.01 in order to maintain reliability. The outcome was again not significant, F (34, 386) = 1.222, p = 0.189; Wilk's Λ = 0.815, partial η^2 = .097. A Bonferonni post-hoc was performed to determine differences between certain categories (see Table 6). The only significant difference found showed that students associate the computer metaphor (A1) as more personal than the industry metaphor (A3), which was more often associated with industrial (p = 0.003).

Besides differences between the three metaphors, differences between gender were analysed. This analysis was performed in order to see whether males and females associate differently towards certain categories, however no significant difference was found between semantic scale associations in gender, F (2, 209) = 0.670, p = 0.513; Wilk's Λ = 0.994, partial η^2 = .006. A Bonferonni post-hoc test also showed no significant difference.

Table 6
Associations with metaphors based on a 3-point semantic scale with connotative pairs. Bonferonni post-hoc test of a MANOVA between different versions of part A of the questionnaire (A1; computer, A2; book, A3; industry), alpha is 0.01.

	3-point semantic scale		
Category	**A1-A2**	**A1-A3**	**A2-A3**
Living/dead	1.000	1.000	1.000
Large/small	0.123	0.546	1.000
Possibilities/risks	1.000	0.140	0.015
Variable/uniform	0.106	1.000	0.383
Personal/industrial	0.037	0.003*	1.000
Malleable/fixed	1.000	1.000	1.000
Living/lifeless	1.000	1.000	1.000
Good/bad	1.000	1.000	1.000
Growth/production	0.422	1.000	0.422
Complex/simple	1.000	1.000	1.000
I use/others use	1.000	1.000	0.732
Free/determined	1.000	0.983	0.322
Friendly/threatening	1.000	0.049	0.229
Growth/halt	1.000	1.000	1.000
Active/passive	1.000	1.000	1.000
Familiar/unfamiliar	1.000	1.000	1.000
Unique/universal	1.000	1.000	1.000

Analysis of questionnaire part B

Part B of the questionnaire was mainly about preferences of students. Students were asked about which of the three explanation they preferred and which one they rejected. Multiple tests were conducted with the outcomes of these preferences and aversions.

Firstly, the differences between the preferences and aversions were observed. Not all students had an outspoken preference or rejection, leading to some missing values – in consideration to the total amount of participating students (N = 212) – for preference (n = 207) and aversion (n = 209). The book metaphor is most popular among the students (n = 112; 54,1%), followed by the computer (n = 48; 23,2%) and the industry metaphor (n = 47; 22,7%). The version towards the different metaphors is inversely proportional, thus the book metaphor is least rejected (n = 36; 17,2%), followed by the computer (n = 86; 41,1%) and the industry metaphor (n = 87; 41,6%) (see Figure 4).

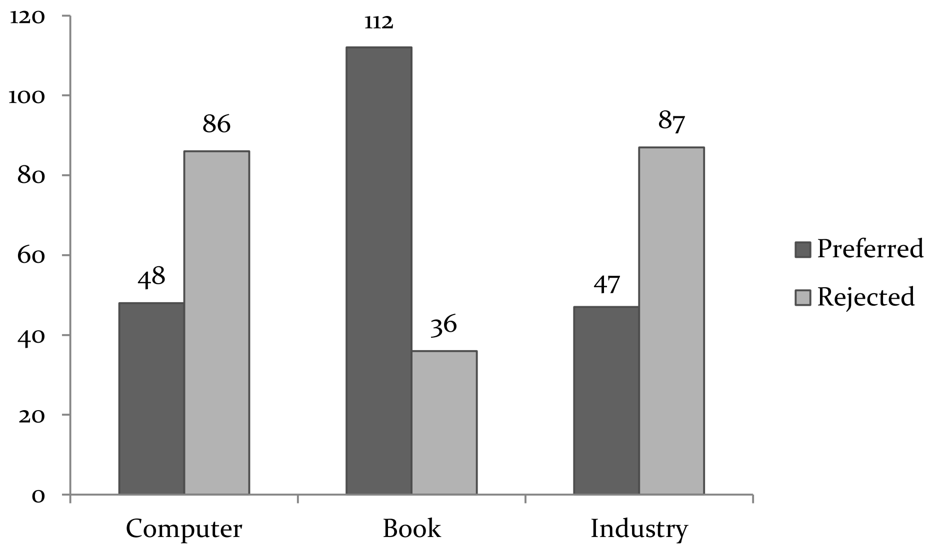

Figure 4. Most preferred (N = 207) and rejected (N = 209) metaphors by the students.

Secondly, it was determined whether there was a link between the different versions the students were provided with in questionnaire part A, and the preferences in part B. In other words, did the first contact with a synthetic biology metaphor influence the students in their preference. With the use of a MANOVA test a statistically significant difference was found between groups with different versions of questionnaire part A (A1, A2, A3) based on student's preference (version 1, 2, 3), F (4, 416) = 13.74, $p < 0.05$; Wilk's Λ = 0.941, partial η^2 = .03.

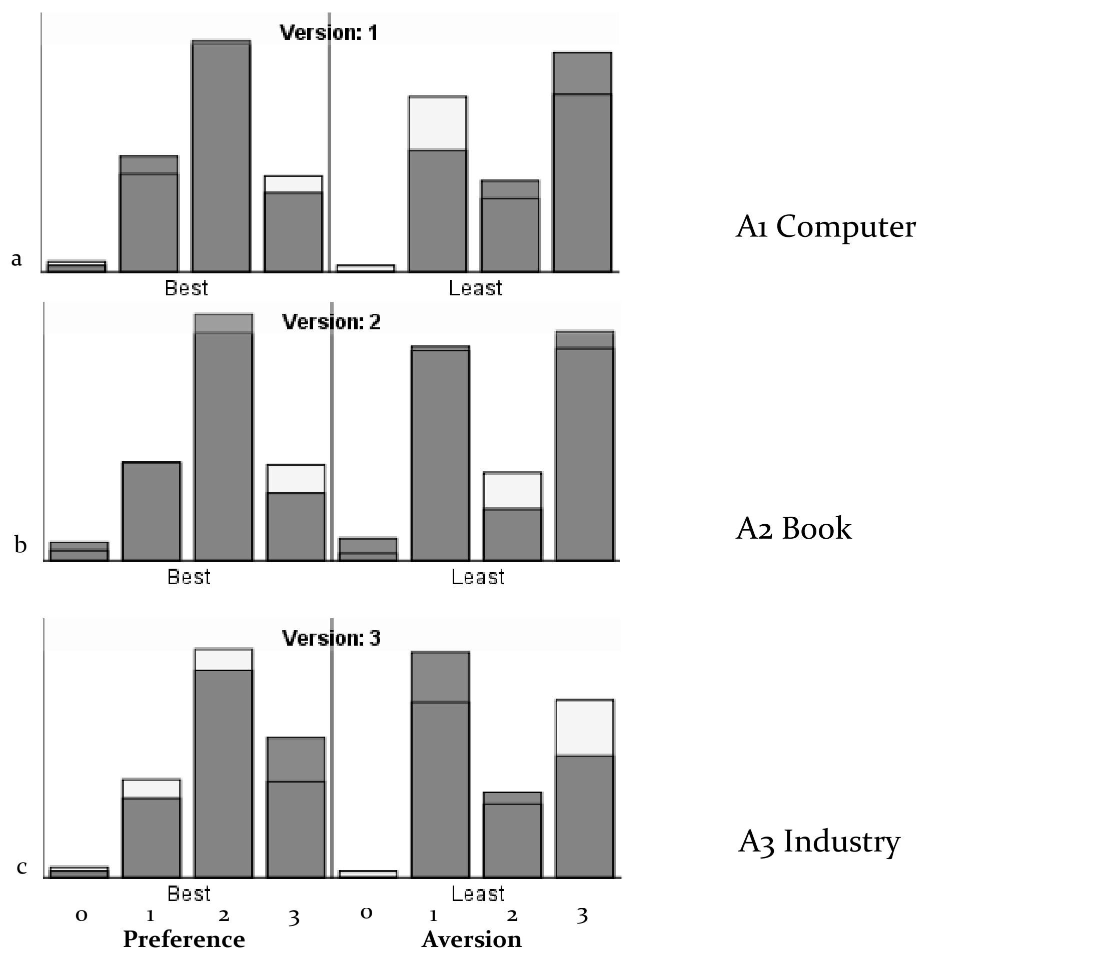

Figure 5. Representation of the preferences (left) and aversion (right) between the different groups. Figure 6a shows the preference and aversion of students who were given version A1 (computer) in questionnaire part A, Figure 6b shows this for version A2 (book) and Figure 6c for version A3 (industry). Student preference and aversion could either be version 1, 2, 3 or if indecisive 0 (missing values). The dark-lined column represents the mean.

Between the three different groups of students, depending on the version they were given in questionnaire part A – A1 (computer), A2 (book) or A3 (industry) – each group is relatively positive towards its own version as the best preferred version and towards rejection as the least preferred version, in comparison to the average of all three groups (see Figure 5). In other words, the version that was presented the computer metaphor (A1) in part A still preferred the book metaphor most, however they were most positive towards the use of the computer metaphor than the groups who were presented with either the book (A2) or the industry (A3) metaphor in part A of the questionnaire. This pattern was found in all three groups, the metaphor presented with first is valued more highly.

Beside the different versions, it was also important to see whether there is a difference in gender in relation to preference. With the use of a MANOVA test, no significant difference on the best or least preferred method of explanation was found based on gender, F (2, 209) = 0.67, p = 0.51, Wilk's Λ = 0.99, partial η^2 = .01.

Lastly, students whom possessed prior knowledge could have been influenced prior to this study on their preference, therefore student preference was also checked for amount of prior knowledge. Prior knowledge of synthetic biology is categorized as 'no prior knowledge (0)', 'heard of it (1)', 'know about it (2)', 'had a lesson about it (3)'. There was no statistically significant difference based on student's preference between these four groups with different levels of prior knowledge, F (6, 414), p = 0.63, p = 0.71; Wilk's Λ = 0.98, partial η^2 = .01.

Student interviews

The student interviews were performed to provide support for answers given in the questionnaires of both part A and part B. This was done in order to gain more insight in the reason why students gave their answers.

As mentioned before, students mostly preferred the book metaphor, the interviews provided more in-depth information about the reason why they do. The reason students give for their preference of the book metaphor has to do with familiarization. They have heard the book metaphor most and consider it as 'normal':

- Student Ea19: *"For me, this was the most clear. Since what we have always learned is written in this style. So that works really well."*
- Student Eb14: *"These words are more often used here in school, so it is more normal."*

Due to this familiarisation, some students did not even notice the book metaphor as a metaphor, although they did notice the computer and industry metaphors as metaphors.

- Student Ec14*: "I did not even think about a metaphor with this one, but obviously it is."*
- Student Kb7: *"The book metaphor did not have any strange comparisons" [Interviewer mentioned there are comparisons] "O, yes, I had not realised that, they are less obvious."*

Students' main preferences for the computer and the industry metaphor had to do with visualisation:

- Student Ka20: *"You can compare it to something. If you cannot compare it, then it is hard to visualise."*
- Student S2: *"It gave me a clear image of how it works in the cells."*

Main critics the students provided were the same for all three versions; be careful with the use of too many metaphors. Extreme use of metaphors can easily come across as patronizing and disparagingly.

During the interviews the students were also asked to give a definition of synthetic biology in their own words. These definitions differed, but all contained some sort of form of changing the DNA. Most students were able to state how this differed from previous technologies, when asked. Some students were more elaborate in their definition than others.

Short definition given by student S1:
"*DNA is being written by scientists and then they can adjust the functions of a cell.*"

Elaborate definition given by student KB7:
"*I thought it was that you use the code to exchange the building blocks of DNA, but you can also put them together and thereby create or manipulate functions of the cell. This is different from previous techniques, because it is not merely rewriting. It is not just adding a component, but changing it completely.*"

However, no reason for these differences could be found. This was variable throughout all different versions of part A of the questionnaire, between gender and between preferences.

Conclusion

This study showed that some metaphors might be more fruitful to clarify synthetic biology adequately in upper secondary education than others. In order to reach this conclusion, this study conducted research several groups, leading to several sub questions. In this section, these sub questions are answered firstly, in order to provide an answer to the main question of this study.

Metaphor inventory

The inventory was performed to see what synthetic biology metaphors are most frequently used. This minor inventory was conducted to determine whether the study of Hellsten & Nerlich (2011) was still representative in present day. The use of the book metaphor was not found in scientific articles, however it was found in CSO publications. The computer and the industry metaphor were found in both scientific articles and CSO publications. No other metaphors were found in the inventory. Therefore, the Hellsten & Nerlich (2011) metaphors are still deemed representative for current synthetic biology communication.

Expert interview

The expert interviews were conducted since there were several obscurities on the field of synthetic biology. These obscurities include the definition, the information students should learn, and the use of metaphors.

A unambiguous definition still remains unclear, however a consensus between the participating experts was formed: *"Synthetic biology is the application of engineering principles on biological systems"*. This definition, however still is not complete and therefore nuances had to be added in order to create a consensus. These nuances had to do with the relation to prior techniques, such and recombinant DNA techniques, and it remains indecisive whether it is something completely new or merely a continuum in the development of biological engineering.

Another obscurity had to do with the information students should learn about synthetic biology. According to the experts the foremost topic students should learn about in relation to synthetic biology has to do with the underlying biological principles (17,67%). Other important categories were different approaches of synthetic biology – top-down and bottom-up – (14,67%), using current possibilities as explanation (11,67%) and several issues that had to do with social context – ethical context (9,67%), balance between positive and negative (8,67%), importance of synthetic biology (7,67%) and alternative solutions (7,67%) – (combined 33,67%). Noteworthy is that the experts clearly prefer the use of explanation via current possibilities (11,67%) in comparison to the explanation with the use of future possibilities (5,67%) (See Figure 3, p. 26).

On the use of synthetic biology metaphors, experts advise caution. Many of the experts showed some form of rejection towards the use of the book metaphor and would rather use either the computer or the industry metaphor in order to explain synthetic biology. The use of the book metaphor is considered either limited or old fashioned. This is in line to with the scientific article analysis, in which the book metaphor was rarely found.

Student inquiry

The reaction of students towards the different synthetic biology metaphors was tested twofold; associations and preferences. No clear differences were found between associations students have with the metaphor, however the computer metaphor was seen as more personal, in comparison with the industry metaphor ($p = 0.03$), which was more often seen as industrial.

Despite the lack of clear differences in association, students did have a clear preference for metaphor usage. The students preferred the book metaphor in relation to both the computer and industry metaphor. The reason for this preference had to do with recognisability and familiarization. Since associations did not differ and a clear preference is present, it seems wise to use the version that is most preferred by the students. Besides this, every group of students also had a relative preference towards the metaphor it was first presented with.

General conclusion

There is a direct conflict between student preference and expert preference on metaphor use for synthetic biology education in upper secondary school. The reason for this is that the experts consider the book metaphor as too restricted and old-fashioned. However, in the student questionnaires no difference in association between the different metaphors was found. Students preferred the book metaphor most and beside that had a relative preference for the version they were first presented with. Taking the relative preference into account, it seems wise to use univocal language when teaching students about synthetic biology. Students would than most likely prefer the book metaphor for the use of this univocal synthetic biology language, since this is considered ‘normal’. The desire for effective univocal communication via another metaphor could require a more elaborate change throughout biological communication as a whole, in order to create such a ‘normal’ state.

At this point, it is therefore advised to use the synthetic biology metaphor in upper secondary education that connects most closely to the student preference, which is the book metaphor. This metaphor seems the most fruitful in clarifying synthetic biology to upper secondary school students. However, further research is essential, which is discussed in the next and final section of this study.

Discussion

Limitations

During the execution of this study several restrictions interfered with the study. In order to be completely transparent these restrictions are mentioned here. The main restrictions were related to limited time and resources. Ultimately, each of the aspects of these study would have been executed on a larger scale, which would have led to a more thorough literature analysis and more participating experts and students.

For the expert interviews this has to do with the heterogeneity and the amount of the experts. Several experts were contacted, from which only five were able and willing to participate. More resources and time could have led to a more elaborate expert interview section. Besides that, the Ministry of Health was contacted in several ways, but was not willing to cooperate, which decreased the heterogeneity of the expert group. On top of that, all interviewed experts were male. Unfortunately, in this field, female experts were scarce and unavailable due to lack of time.

For the student questionnaires restrictions meant compromises. Ultimately, the study would have been performed on a nationwide scale, with dozens of schools and thousands of students participating. However, since this study was executed within just one year with no available resources (such as money) only six schools participated, which led to a respectable number of 212 students.

Relation to other studies

There are no known studies, in the Netherlands or in any other country, that studied the usability of synthetic biology metaphors. Therefore, these results are new and do not directly link to any other study. However, other studies provide a foundation for this study due to their communication about synthetic biology metaphors.

Many studies report about the epochal changes that will most likely happen due to the rise of synthetic biology. Most of this research reports on applications (e.g. Ball, 2004; Campbell et al, 2014; Keasling, 2007; Yadav, 2012) and on impacts on society, such as biosafety and ethical issues (e.g. Andrianantoandro et al, 2006; Boldt, 2010; Bedau et al, 2009; Serrano, 2007, Yearley, 2009). However, not much research has been conducted on synthetic biology communication.

Hellsten & Nerlich (2011) did, however, study communication of synthetic biology. They showed which synthetic biology metaphors are used most often by conducting an analysis of English-speaking press coverage. They analysed dozens of articles between 2008 and may 2010. This led to the finding of three main metaphors; book, computer, industry. These metaphors provide the foundation of this study and are therefore of critical essence. As the article analysis of this study has shown these metaphors are still most used, although scientific articles do not seem to be keen on the use of the book metaphor anymore.

Previous studies used the semantic scale in order to determine differences in associations between metaphors (Condit et al., 2002; Heijkoop, 2013). Condit et al (2002) used the semantic scale to determine whether the associations between the recipe and the blueprint metaphor for explaining the genome differ within a group of 122 undergraduate college students. They found differences in 11 of their 16 connotative pairs. Heijkoop (2013) later used this semantic scale in order to determine these differences between recipe and blueprint metaphors for the genome in Dutch upper secondary education. Therefore, she translated the semantic scale to Dutch and presented it to 148 students and found some clear differences between the two metaphors. This translated semantic scale provided the foundation for the semantic scale used in this study. However, no clear differences were found between associations the three metaphors in this study.

This study shows a new perspective in an existing field. Synthetic biology is rising and metaphors are used every day to communicate synthetic biology, however, it was never studied what the impacts of these metaphors were and which metaphors were preferred by certain groups. The first group, Dutch upper secondary school students, has now been studied and a foundation has been built for the study of other groups, such as students, experts or the common public.

Further research

However, more research is needed to give a clear advise about teaching synthetic biology to students. This study raised several proposals for further research, which are suggested below.

Firstly, it is important to determine whether these results are representative and applicable for every member of the public. In that case, CSO's could also use these metaphors for communicating synthetic biology towards the public. Therefore, it should be determined whether there is a different association in relation to age. To do so, it should be studied if lower secondary school students differ from upper secondary school students and how they differ. On top of that, differences between several levels of secondary education (In the Netherlands: *VMBO*/*HAVO*/*VWO*) should be studied, since this study merely focussed on the highest level of secondary school education in the Netherlands (*VWO*) and might thereby not be representative for the general public.

Secondly, other groups should be studied for their preferences. This study, due to time limitations, only studied experts on synthetic biology and students. However, there are more groups that should be represented in order to be thorough, for instance didactical experts and teachers. Experts on didactics might have important opinions on the way to communicate synthetic biology to students. Teachers might have entirely other preferences than students, which may collide directly, since teachers are the ones to teach the students. It should therefore be studied which metaphors teachers prefer for explanation and what association teachers have towards synthetic biology. Besides this, it should be studied whether teachers have enough knowledge about this topic, in order to decide whether teacher training on the field of synthetic biology is a necessity.

Thirdly, it is important to study whether the use of these metaphors during a biology lesson in a normal class situation actually gives a clear image of synthetic biology. This study merely provided evidence based on interviews and questionnaires, but did not implement the real-life, everyday class situation.

Lastly, it should be studied what possible role the use of either mixed metaphors (Ceccarelli, 2014) or multiple metaphors (Cameron, 2002) could play. At this point the questions still remains whether combining metaphors influences each other. And if so, in which manner. If this question is answered, it can then be discussed whether we need univocal communication of synthetic biology, in which case; students preferred the use of the book metaphor.

Bycatch

While conducting the study for metaphor association, a noteworthy factor was found. The use of examples seemed to influence student associations greatly. The example used in all written metaphor texts was about the production of a malaria medicine (see Appendix C, section 2). When the students were asked to write down the first three words they associated with synthetic biology after reading the text in the questionnaire (either part A1, A2 or A3) 80 of the 212 students (37,74%) named a word related to healthcare (medicine, cure, health, diseases, etc.). Therefore, it is strongly advised to carefully select an example or multiple examples and in order to do so conduct further research in this direction.

Acknowledgements

Firstly, I would like to thank my supervisor, dr. M.C.P.J. (Marie-Christine) Knippels for all her feedback, support and ideas during this research project. Secondly, I would like to thank all synthetic biology experts for their cooperation in this study: dr. L. (Lucien) Hanssen, prof. dr. W.P.M. (Wiel) Hoekstra, dr. D. (Dirk) Stemerding, prof. dr. R.A.L. (Roel) Bovenberg and prof. dr. H.A.B. (Han) Wösten. Thirdly, I would like to thank all teachers and students that participated in this research project, by helping me gathering data via questionnaires and interviews: Erasmiaans Gymnasium (Rotterdam), Koninklijk Wilhelmina College (Culemborg), Christelijk Lyceum (Veenendaal), Stanislascollege Westplantsoen (Delft), Emmauscollege (Rotterdam) and Onze Lieve VrouweLyceum (Breda). Last but not least, I would like to thank all fellow master students who helped me with gaining new insights and motivation in times of need and desperation, especially Anouk Haverkamp.

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Appendices

Appendix A: Synthetic biology metaphor inventory

Scientific articles between June 2010 – February 2015

Search engine	Article	Metaphor use
Google Scholar	1. Ruder, W. C., Lu, T., Collins, J. J. (2011). Synthetic Biology Moving into the Clinic. *Science, 333*(6047), 1248-1252. doi:10.1126/science.1206843.	Computer/Industry
	2. Ellis, T., Adie, T., Baldwin, G. S. (2011). DNA assembly for synthetic biology: from parts to pathways and beyond. *Integrative Biology*, *3*(2), 109-118. doi:10.1039/c0ib00070a.	Industry
	3. Nandagopal, N., Elowitz, M. B. (2011). Synthetic Biology: Integrated Gene Circuits. *Science, 333*(6047), 1244-1248. doi:10.1126/science.1207084.	Computer
	4. Elowitz, M., Lim, W.A. (2010). Build life to understand it. *Nature, 468*(7326), 889-890. doi:10.1038/468889a.	Industry
	5. Hodgman, C.E., Jewett, M.C. (2012). Cell-free synthetic biology: Thinking outside the cell. *Metabolic Engineering, 14*, 261-269. doi:10.1016/j.ymben.2011.09.002.	Computer/ Industry
	6. Weber, W., Fussenegger, M. (2012). Emerging biomedical applications of synthetic biology. *Nature reviews,* 13, 21–35. doi:10.1038/nrg3094.	Industry
	7. Medema, M.H., Breitling, R., Bovenberg, R., Takano, E. (2011). Exploiting plug-and-play synthetic biology for drug discovery and production in microorganisms. *Nature Reviews Microbiology*, *9*(2), p. 131-137. doi:10.1038/nrmicro2478.	Industry
	8. Bashor, C.J., Horwitz, A.A., Peisajovich, S.G., Lim, W.A. (2010). Rewiring Cells: Synthetic biology as a tool to interrogate the organizational principles of living systems. *Annual Review of Biophysics, 39*, 515-537. doi:10.1146/annurev.biophys.050708.133652.	Computer/ Industry
	9. Callura, J.M., Cantor, C.R., Collins, J.J. (2012). Genetic switchboard for synthetic biology applications. *Proceedings of the National Academy of Sciences USA, 109*(15), 5850-5855. doi:10.1073/pnas.1203808109.	Computer
	10. Erickson, B., Singh, R., Winters, P. (2011). Synthetic Biology: Regulating Industry Uses of New Biotechnologies. *Science, 333*, 1254-1256. doi:10.1038/483029a.	Computer/ Industry
Web of Science	11. Buhk, H.J. (2014). Synthetic biology and its regulation in the European Union. *New Biotechnology, 31*(6), 528-531. doi:10.1016/j.nbt.2014.02.007.	Industry
	12. Huang, H., Camsund, D., Lindblad, P., Heidorn, T. (2010). Design and characterization of molecular tools for a Synthetic Biology approach towards developing cyanobacterial biotechnology. *Nucleic Acids Research, 38*(8), 2577-2593. doi:10.1093/nar/gkq164.	Computer/Industry
	13. Frow, E., Calvert, J. (2013). ‘Can simple biological systems be built from standardized interchangeable parts’ Negotiating biology and engineering in a synthetic biology competition. *Engineering Studies,* 5(1), 42-58. doi:10.1080/19378629.2013.764881.	Computer/Industry
	14. Heyer, L.J., Poet, J.L. (2014). Synthetic biology: A new frontier. *The American Mathematical Monthly, 121*(9), 857-867. Retrieved from http://www.jstor.org/discover/10.4169/amer.math.monthly.121.09.857?uid=3738736&uid=2134&uid=2&uid=70&uid=4&sid=21106101221781.	Industry
	15. Huang, H., Densmore, D. (2014). Fluigi: Microfluidic Device Synthesis for Synthetic Biology. *ACM Journal on Emerging Technologies in Computing Systems, 11*(3), 1-19. doi:10.1145/2660773.	Computer

	16. Kaebnick, G.E., Gusmano, M.K., Murray, T.H. (2014). How Can We Best Think about an Emering Technology? *Hastings Centre Report*, *44*(5), 2-3. doi:10.1002/hast.391.	Computer/Industry
	17. Knuuttila, T., Loettgers, A. (2014). Varieties of noise: Analogical reasoning in synthetic biology. *Studies in History and Philosophy of Science, 48*, 76-88. doi:10.1016/j.shpsa.2014.05.006.	Computer
	18. Oberotner, E., Bhatia, S., Lindgren, E., Densmore, D. (2014). A rule-based design specification language for synthetic biology. *ACM Journal on Emerging Technologies in Computing Systems, 11*(3), 1-19, doi:10.1145/2641571.	Computer
	19. Pei, L., Schmidt, M., Wei, W. (2011). Synthetic biology: An emerging field in China. *Biotechnology Advances, 29*(6), 804-814. doi:10.1016/j.biotechadv.2011.06.008.	Computer
	20. Wareham, C., Nardini, C. (2015). Policy on Synthetic Biology: Deliberation, Probability, and the Precautionary Paradox. *Bioethics, 29*(2), 118-125. Doi:10.1111/bioe.12068.	Computer/Industry
ERIC	21. Campbell, A.M., Eckdahl, T., Cronk, B., Andresen, C., Frederick, P., Huckuntod, S., … Yuan, J. (2014). pClone: Synthetic Biology Tool Makes Promoter Research Accessible to Beginning Biology Students. *Life Sciences Education, 13*(2), 285-296. doi:10.1187/cbe.13-09-0189.	Computer/Industry
	22. Mitchell, R., Dori, Y. J., Kuldell, N. H. (2011). Experiential Engineering Through iGEM – An Undergraduate Summer Competition in Synthetic Biology. *Journal of Science Education and Technology, 20*(2), 156-160. doi:10.1007/s10956-010-9242-7.	Computer/Industry
	23. Wolyniak, M. J., Alvarez, C. J., Chandrasekaran, V., Grana, T. M., Holgado, A., Jones, C. J., … Yang, Y. (2010). Building Better Scientists trough Cross-Disciplinary Collaboration in Synthetic Biology. A Report from the Genome Consortium for Active Teaching Workshop 2010. *CBE Life Sciences Education*, *9*(4), 399-404. doi:10.1187/cbe.10-07-0097.	Computer/Industry

CSO Publications

CSO	Publication	Metaphor use
Rathenau instituut	1. De Vriend, H., Van Est, R., Walhout, B. (2007). Leven maken: maatschappelijke reflectie op de opkomst van synthetische biologie. *Rathenau instituut, Working document 98, the Hague, the Netherlands.* Retrieved from http://www.rathenau.nl/uploads/tx_tferathenau/Leven_Maken.pdf.	Book/Industry
	2. De Vriend, H., Van Est, R., Walhout, B. (2007). Synthetische biologie: Nieuw leven in het biodebat. *Rathenau instituut, the Hague, the Netherlands.* Retrieved from http://www.rathenau.nl/uploads/tx_tferathenau/BAP_Synthetische_biologie_sept_2007.pdf.	Computer/Book/Industry
	3. Stemerding, D., Rerimassie, V., Messer, P. (2013). Het Bericht: Synthetische biologie vereist samenspraak. *Rathenau instituut, the Hague, the Netherlands.* Retrieved from http://www.rathenau.nl/uploads/tx_tferathenau/Het_Bericht_-_Synthetische_biologie_vereist_samenspraak.pdf.	Industry
	4. Stemerding, D., & Van Est, R. (2013). Geen debat zonder publiek: het opkomende debat over synthetische biologie ontleed. *Rathenau instituut, the Hague, the Netherlands.* Retrieved from http://www.rathenau.nl/uploads/tx_tferathenau/Rapport_Geen_Debat_Zonder_Publiek.pdf.	Computer/Industry
	5. Rerimassie, V. & Stermding, D. (2012). Politiek over leven. In debat over synthetische biologie. *Rathenau Institue, the Hague, the Netherlands.* Retrieved from http://www.rathenau.nl/uploads/tx_tferathenau/Rapport_Politiek_over_leven.pdf.	Computer/Industry
Kennislink	6. Jansma, M., Aalbers, F. S., Poolman, B. (2014). Van Lezen naar schrijven. *Kennislink, the Netherlands*. Retrieved from http://www.kennislink.nl/publicaties/van-lezen-naar-schrijven.	Book/Industry
	7. Veldhuizen, R. (2009). Wat is synthetische biologie? *Kennislink, the Netherlands.* Retrieved from http://www.kennislink.nl/publicaties/wat-is-synthetische-biologie.	Book/Industry
	8. Veldhuizen, R. (2008). “Burger kan profiteren van synthetische biologie”. *Kennislink, the Netherlands.* Retrieved from http://www.kennislink.nl/publicaties/burger-kan-profiteren-van synthetische-biologie.	Computer/Industry
	9. Jansma, M., Aalbers, F. S., Poolman, B. (2014). Nu écht synthetisch: hoe bouw je een nieuwe cel? *Kennislink, the Netherlands.* Retrieved from http://www.kennislink.nl/publicaties/nu-echt-synthetisch-hoe-bouw-je-een-nieuwe-cel.	Industry
	10. Veldhuizen, R. (2009). Klussen met beloftes. *Kennislink, the Netherlands.* Retrieved from http://www.kennislink.nl/publicaties/klussen-met-beloftes.	Computer/Industry

Appendix B: Expert interview manual

- Begroeten, bedanken voor medewerking. We hebben een uurtje gepland. Is er eventuele ruimte voor uitloop of heeft u daarna een afspraak?
- Het gesprek wordt opgenomen, gaat u daarmee akkoord?
- Dit interview wordt gebruikt voor mijn masterscriptie.
- Dit onderzoek kijkt naar hoe synthetische biologie dient te worden uitgelegd aan middelbare scholieren.
- Kan ik uw naam vermelden in mijn masterscriptie? Hoe wilt u vermeld worden?
- Ik stuur na de interviews met alle experts een resultaat ter goedkeuring (consensus/validering). Daar kunt u dan online eventueel nog extra opmerkingen aan toevoegen.
- Ook kan ik mijn eindscriptie opsturen indien u dat wilt (verwacht juni 2015).

1. Persoonlijke informatie
   a. Waar werkt u?
   b. Wat is uw functie?
   c. Welke rol heeft synthetische biologie in uw functie?

2. Wat zijn de eerste vijf woorden waar u aan denkt bij SynBio?

3. Hoe zou u SynBio definiëren?

4. Wat is volgens u het verschil tussen Synbio en genetic engineering?
   - Recombinant DNA technology
   - Genetic modification

5. *Vindt u de volgende casussen vallen onder SynBio of niet?*
   a. Casus 1: MIN protein cell division
      Petra Schwille onderzoekt hoe cellen delen in Duitsland. Ze kijkt als een natuurkundige en niet als een bioloog. Een bioloog wil elk onderdeel van een systeem weten, een natuurkundige alleen de principes (algemene regels). Ze wil de essentie van celdeling begrijpen. Daarvoor gebruiken ze fluorescentie technologie om een molecuul dat erbij betrokken is te kunnen bekijken. Door de patronen van het MIN eiwitten te observeren, komt ze meer te weten over celdeling. Om deze observatie makkelijker te maken, lieten ze het MIN eiwit werken in een protocel.
      - Waarom wel/niet?
   b. Casus 2: Lantibiotics
      Antibiotica zijn schaars en worden in de komende jaren alleen maar meer schaars. In Groningen is Oscar Kuipers bezig met het ontwikkelen van nieuwe antibiotica, met behulp van bekende peptide structuren, genaamd lanbiotics. Er is veel bekend over lantibiotics, we kennen er meer dan honderd, met verschillende ringstructuren. Door deze ringstructuren in allerlei combinatie te mengen worden miljoenen nieuwe peptiden gecreëerd, die getest worden op werking als antibiotica.
      - Waarom wel/niet?

6. Zou u Bijlage 1 willen invullen. Wat zijn uw associaties m.b.t. SynBio?
   - Mist u nog categorieën in deze lijst?

7. Welke toepassingen van SynBio denkt u dat over 10 jaar aanwezig zijn?

8. Gevolgen
   a. Wat zijn de grootste voordelen/kansen?
   b. Wat zijn de grootste risico's/nadelen?

Door deze toepassingen van SynBio moet de bevolking goed worden ingelicht om weloverwogen keuzes te maken over de gevolgen hiervan. Vergelijkbaar met uitleg van genetica ten behoeve van genetische testen hiervoor.

9. Welke informatie zou het algemene publiek/5VWO minimaal moeten weten/begrijpen over SynBio om hierover goede beslissingen te kunnen nemen?
   a. Eerst open vraag
      i. Waarom deze informatie?
      ii. Wat als ze deze informatie niet weten?

   b. Dan in de lijst (zie Bijlage 2) aanvinken wat wel/niet belangrijk is voor het algemene publiek.
      i. Lijst mag worden aangevuld naar eigen inzicht.

10. Wat is uw mening als expert over de momenteel meest gebruikte metaforen op het gebied van SynBio? (Bijlage 3)
    a. Bruikbaarheid van deze metaforen?
    b. Roepen deze metaforen denkt u, in bepaalde mate, de essentiële kennis op?
    c. Risico's van deze metaforen?
    d. Weet u nog andere metaforen, die u wellicht beter bruikbaar vindt?

* Question 5 to 8 are included in this interview for providing information for other researchers and are not discussed in this study.

Bijlage 1

Synthetische biologie

Levend	_	_	_	_	_	Dood
Groot	_	_	_	_	_	Klein
Mogelijkheden	_	_	_	_	_	Risico's
Variabel	_	_	_	_	_	Uniform (eenduidig)
Persoonlijk	_	_	_	_	_	Industrieel
Veranderbaar	_	_	_	_	_	Vast
Levend	_	_	_	_	_	Levenloos
Goed	_	_	_	_	_	Slecht
Groei	_	_	_	_	_	Productie
Complex	_	_	_	_	_	Simpel
Ik gebruik het	_	_	_	_	_	Anderen gebruiken het
Vrij	_	_	_	_	_	Vastgesteld
Vriendelijk	_	_	_	_	_	Bedreigend
Groei	_	_	_	_	_	Stilstand
Actief	_	_	_	_	_	Passief
Bekend	_	_	_	_	_	Onbekend
Uniek	_	_	_	_	_	Universeel

Bijlage 2

- Nieuwe vorm van genetische modificatie

- Verschil met huidige genetische modificatie, zoals recombinant DNA technologie en kunstmatige selectie:
    - Creëren i.p.v. veranderen

- Kennis van onderliggende principes:
    - Cellen
    - DNA
    - Translatie & transcriptie
    - Technieken

- Verschillende soorten synthetische biologie:
    - Top-down en bottom-up
    - DNA-based device construction, genome-driven cell engineering, protocell creation

- Belangrijke personen in SynBio:
    - Craig Venter
    - Jay Keasling
    - Tom Knight

- Belangrijke huidige applicaties:
    - Artimisinin
    - Genome mapping
    - Protocell creation

- Belangrijke toekomstige applicaties:
    - Bacterie die CO_2 omzet in fossiele brandstof
    - Toekomstscenario's (Rathenau moral-vignettes)

- Gevolgen van SynBio:
    - Positief (technologische mogelijkheden)
    - Negatief
        a. Hard impacts: biosecurity, biosafety
        b. Soft impacts: Trade patterns, monopoly

Overige factoren

-
-

Bijlage 3

SynBio is een boek

Bij synthetische biologie kunnen wetenschappers de code van het DNA (ACTG) niet alleen lezen, ze kunnen deze code nu ook schrijven. Daardoor wordt een nieuwe taal gecreëerd, waarin geschreven staat wat cellen moeten doen. Dit is als het ware een vernieuwde handleiding voor de cel. Ook kunnen compleet nieuwe handleidingen worden geschreven.

[lezen, schrijven, code, taal, handleiding]

SynBio is een computer

In synthetische biologie wordt de software (DNA) ontworpen en in de hardware (de cel) gestopt. Verschillende software zorgen voor andere programma's (processen in de cel). Door stukjes uit de software te knippen, plakken en combineren kunnen allerlei programma's, met verschillende functies worden ontworpen. Ook software die normaal niet in de cel voorkomt kan worden ontwikkeld.

[software, hardware, programma, knippen, plakken, kopiëren, code, design]

SynBio is een industrie

In synthetische biologie wordt met de bouwstenen van het DNA gewerkt (ACTG). Deze bouwstenen worden dan opgebouwd tot standaardpakketjes met een bepaalde functie (BioBricks). Met deze BioBricks kan de architect (wetenschapper) een fabriek (de cel) bouwen die exact het gene doet dat de architect voor ogen heeft.

[BioBricks, bouwstenen, bouwen, onderdelen, constructie, architect]

Appendix C: Student questionnaire

Section 1: Overview of participating schools.

Table 1: Elaborate information of school visits, including visit date.

School	Location	Code	Visit date	Students (n)	Version (A1:A2:A3)	Interviewed (n)
1	Rotterdam	Ea	07-01-2015	26	9 : 10 : 7	2
		Eb	11-02-2015	28	13 : 8 : 7	1
		Ec	11-02-2015	20	8 : 5 : 7	1
2	Culemborg	Ka	14-01-2015	27	7 : 11 : 9	2
		Kb	04-02-2015	17	6 : 2 : 9	2
3	Veenendaal	C	27-01-2015	35	9 : 13 : 13	2
4	Delft	S	30-01-2015	25	9 : 8 : 8	2
5	Rotterdam	EM	13-02-2015	16	4 : 7 : 5	1
6	Breda	O	12-03-2015	18	6 : 6 : 6	1
			Total	**212**	**71 : 70 : 71**	**14**

Section 2: Texts of different versions provided to students

A1 computer metaphor
Synthetische biologie is een nieuwe tak van wetenschap. In synthetische biologie wordt de software (DNA) ontworpen en in de hardware (de cel) gestopt. Verschillende software zorgen voor andere programma's (processen in de cel). Door stukjes uit de software te knippen, plakken en combineren kunnen allerlei programma's, met verschillende functies worden ontworpen. Ook software die normaal niet in de cel voorkomt kan worden ontwikkeld. Zo hebben wetenschappers bijvoorbeeld een bacterie kunnen maken die een malariamedicijn produceert.

A2 book metaphor
Synthetische biologie is een nieuwe tak van wetenschap. Bij synthetische biologie kunnen wetenschappers de code van het DNA (ACTG) niet alleen lezen, ze kunnen deze code nu ook schrijven. Daardoor wordt een nieuwe taal gecreëerd, waarin geschreven staat wat cellen moeten doen. Dit is als het ware een vernieuwde handleiding voor de cel. Ook kunnen compleet nieuwe handleidingen worden geschreven Zo hebben wetenschappers bijvoorbeeld een bacterie kunnen maken die een malariamedicijn produceert.

A3 industry metaphor
Synthetische biologie is een nieuwe tak van wetenschap. In synthetische biologie wordt met de bouwstenen van het DNA gewerkt (ACTG). Deze bouwstenen worden dan opgebouwd tot standaardpakketjes met een bepaalde functie (BioBricks). Met deze BioBricks kan de architect (wetenschapper) een fabriek (de cel) bouwen die exact het gene doet dat de architect voor ogen heeft. Zo hebben wetenschappers bijvoorbeeld een bacterie kunnen maken die een malariamedicijn produceert.

Section 3: Student questionnaire

Universiteit Utrecht

Vragenlijst deel A **Versie 1/2/3**

Beste leerling, bedankt voor je medewerking aan dit onderzoek. Deze vragenlijst is onderdeel van een onderzoeksproject voor de Universiteit Utrecht.

Aan het begin van de vragenlijst willen we graag wat persoonlijke informatie weten. Alle informatie in deze vragenlijst is strikt vertrouwelijk en wordt niet verstrekt aan derden. De uitkomsten van dit onderzoek worden anoniem gebruikt.

De vragenlijst bestaat uit twee delen (A & B). Als iedereen klaar is met deel A (+/- 10 min) wordt deel B uitgedeeld (+/- 5 min). Beantwoord alle vragen a.u.b. zo zorgvuldig en duidelijk mogelijk. Als je een antwoord wilt veranderen, kruis dit duidelijk door en vul een ander antwoord in.

De vragen in deze vragenlijst gaan over synthetische biologie. Dit is een nieuw gebied in de wetenschap en is nauw verbonden met genetica. Afgelopen jaar hebben jullie al wat geleerd over genetica (DNA, erfelijkheid etc.), dus jullie beschikken al over enige voorkennis.

Alvast bedankt en succes!
Frank Sekeris

Persoonlijke informatie

Naam:..

Leeftijd:.............................

Geslacht: Man/Vrouw

Voorkennis

a. Heb je ooit iets gehoord over synthetische biologie?
   - o Ja
   - o Nee

b. Zo ja, wat?

....

....

....

c. Via welke bron heb je dit vernomen?
   - o Krant
   - o Sociale Media
   - o Populair wetenschappelijk magazine
   - o Anders, namelijk...

Hierna wordt een korte uitleg gegeven over synthetische biologie. Daarna volgen enkele vragen.

Tekst versie A1/A2/A3 (see Appendix C, section 2)

1. Wat is het eerste wat bij jou opkomt als je dit leest?

   ....

   ....

2. Wat zijn de eerste drie woorden waar je hierbij aan denkt?

   ....

   ....

   ....

Omcirkel het antwoord dat jij denkt.

3. Voor mij is bovenstaande uitleg over synthetische biologie:

   Erg onduidelijk – 1 – 2 – 3 – 4 – 5 – 6 – 7 – Erg duidelijk

4. Door deze uitleg is mijn houding ten opzichte van synthetische biologie:

   Erg negatief – 1 – 2 – 3 – 4 – 5 – 6 – 7 – Erg positief

5. Zet een kruisje op de plaats waar jij denkt dat het synthetische biologie staat ten opzichte van de begrippen. Bijvoorbeeld: als jij denkt dat het woord "snoep" dichter bij "zoet" staat dan bij "zuur", dan vul je dit als volgt in:

			Snoep			
Zuur	_	_	_	**X**	_	Zoet

Synthetische biologie

Levend	_	_	_	_	_	Dood
Groot	_	_	_	_	_	Klein
Mogelijkheden	_	_	_	_	_	Risico's
Variabel	_	_	_	_	_	Uniform
Persoonlijk	_	_	_	_	_	Industrieel
Veranderbaar	_	_	_	_	_	Vast
Levend	_	_	_	_	_	Levenloos
Goed	_	_	_	_	_	Slecht
Groei	_	_	_	_	_	Productie
Complex	_	_	_	_	_	Simpel
Ik gebruik het	_	_	_	_	_	Anderen gebruiken het
Vrij	_	_	_	_	_	Vastgesteld
Vriendelijk	_	_	_	_	_	Bedreigend
Groei	_	_	_	_	_	Stilstand
Actief	_	_	_	_	_	Passief
Bekend	_	_	_	_	_	Onbekend
Uniek	_	_	_	_	_	Universeel

Vragenlijst Deel B

Universiteit Utrecht

Vul eerst je **naam** in.

Naam:..

In het **deel A** van deze vragenlijst werd gevraagd hoe jij over één stuk uitleg dacht. In **deel B** wordt gekeken naar jouw voorkeur van verschillende soorten uitleg.

Op de volgende pagina staan drie stukjes tekst. Eén daarvan heb je net gelezen, de andere twee zijn nieuw. Lees ze allemaal goed door en beantwoord dan de vragen.

I.

In synthetische biologie wordt de software (DNA) ontworpen en in de hardware (de cel) gestopt. Verschillende software zorgen voor andere programma's (processen in de cel). Door stukjes uit de software te knippen, plakken en combineren kunnen allerlei programma's, met verschillende functies worden ontworpen. Ook software die normaal niet in de cel voorkomt kan worden ontwikkeld.

II.

Bij synthetische biologie kunnen wetenschappers de code van het DNA (ACTG) niet alleen lezen, ze kunnen deze code nu ook schrijven. Daardoor wordt een nieuwe taal gecreëerd, waarin geschreven staat wat cellen moeten doen. Dit is als het ware een vernieuwde handleiding voor de cel. Ook kunnen compleet nieuwe handleidingen worden geschreven

III.

In synthetische biologie wordt met de bouwstenen van het DNA gewerkt (ACTG). Deze bouwstenen worden dan opgebouwd tot standaardpakketjes met een bepaalde functie (BioBricks). Met deze BioBricks kan de architect (wetenschapper) een fabriek (de cel) bouwen die exact het gene doet dat de architect voor ogen heeft

Voorkeur

1. Welke uitleg vond jij het beste? Uitleg I/II/III? Verklaar waarom.
   ....
   ....

2. Welke uitleg vond jij het minst goed? Uitleg I/II/III? Verklaar waarom.
   ....
   ....

3. Heb je nog andere opmerkingen over de stukjes uitleg?

   I. ....
   ....

   II. ....
   ....

   III. ....
   ....

4. Leg in je eigen woorden uit wat synthetische biologie volgens jou is.
   ....
   ....
   ....

5. Kun jij zelf nog een andere manier van uitleg bedenken voor synthetische biologie?
   ....
   ....

Als je klaar bent met de vragenlijst, graag inleveren zoals aangegeven door de docent. Heel erg bedankt voor het invullen van deze vragenlijst, Frank Sekeris.

Appendix D: Student interview protocol

Ik houd met enkele studenten een interview om een beter beeld te krijgen van wat je precies bedoelt met de antwoorden die je gegeven hebt. Uitleg in woorden is soms makkelijker dan op schrift.

1. Kan jij aan mij uitleggen, in je eigen woorden, wat jij denkt dat synthetische biologie inhoudt?
   - Indien niet duidelijk; hoe verschilt dit met al bekende genetische modificatie (kunstmatige selectie? Recombinant DNA technologie?)

2. Kan jij nader toelichten wat jij bedoelt met jouw antwoord op vraag X?

3. Waarom heb jij de X van vraag 5 op die plek neergezet?

4. Waarom vond jij metafoor X het prettigst?
   - Wat vond jij daar het prettigst aan?
   - Welke vond je het minst?
   - Waarom?

5. Tips? Do's en Don'ts voor gebruik van metaforen in uitleg?