

Synthetic biology

A theological-ethical evaluation from a Reformed perspective

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Dissertation submitted in fulfilment of the requirements for the
degree *Magister Artium* in *Ethics* at the Potchefstroom
Campus of the North-West University

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November 2014

Preface

I would like to express my gratitude to

- Prof Riaan Rheeder. Thank you for becoming my supervisor on such short notice and then walking a road of discovery with me. Thank you for your continual patience and guidance.
- my mom and dad, Louismari and Chris Kruger. Thank you for all your support and motivation during the easy times, but especially during the tough times. I love you very much.
- my family and friends, specifically Laura, Jomé, Shané, Lindie, Tiaan, Nettie and Oom Hannie. Thanks for your support and all the help with ideas, writing and getting people to understand synbio.
- my critical readers, and in particular Johan Kluyts. Thank you for the time and effort you invested in the improvement of this study and suggesting finishing amendments.
- Antoinett Moerdyk. Thank you for your initial input and belief that I can do this.
- Hester Lombard from the Theological (Jan Lion-Cachet) Library. Thank you for your superb assistance.
- Leentje de Lange who, even after she has passed away, still inspire me to pursue ethics.
- The NWU financial support services for a postgraduate bursary.

I ultimately give thanks to God for blessing me with the abilities and will to complete this study.

Soli Deo Gloria!

Abstract

Synthetic biology is a relatively new discipline within the field of biotechnologies. In essence it is the artificial creation of microorganisms. Though similar in principle, it differs from genetic engineering because it creates an organism from scratch, rather than cutting and pasting DNA (deoxyribonucleic acid) between existing organisms. This study investigates the ethical aspects (both rational and theological) concerned with synthetic biology through the use of a literature analysis. The study starts by investigating and describing the origins, pioneers, science and uses of synthetic biology. Secondly, it describes and ethically assesses the rational arguments for and against synthetic biology by comparing its benefits and risks. Lastly, the study describes and ethically assesses synthetic biology within the Reformed tradition, mainly by using the creational perspective of Christian ethical evaluations (including concepts such as *creatio ex nihilo*; *creatio continua* and *imago Dei*) and secondary the re-creational and eschatological perspectives.

The final conclusion reached shows that synthetic biology is acceptable from a Reformed theological-ethical perspective, because humans as the image of God can create, just as God constantly creates new things and created a new universe from nothing. The rational arguments state that the potential benefits of synthetic biology surpass the risks it poses. Hence, it supports the idea that synthetic biology can be used to fulfil God's commandment to love one's neighbour, by improving his circumstances and activating hope. Nevertheless, Christians should always stay vigilant about motives and possible uses when dealing with new technologies. How and for what synthetic biology is used should in the future be constantly reviewed. In this way Christian scientists can still inquire about their work: Does it glorify God?

Key terms

Bioethics; Christian ethics; *creatio ex nihilo*; *creatio continua*; evaluation, *imago Dei*; Reformed perspective; synthetic biology

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Chapter 1 – An introduction to synthetic biology

What I cannot create I do not understand.

– Richard Feynman

1.1 Background and problem statement

1.1.1 Background

As a relatively new field of study in biotechnology, synthetic biology (synbio) finds its origins within genetic manipulation but relies mainly on engineering principles. Sparrow and Brady (2007:50) explain that the union between mechanical engineering and biology leads to the interdisciplinary field of synthetic biology. Furthermore, they give a workable definition to a field that is actually very difficult to define: "This area of research investigates how to build artificial, biological machines using engineering principles and procedures by taking parts (molecular and subcellular) and principles of naturally occurring biological systems, characterising and simplifying them" (Sparrow & Brady, 2007:51). In essence, synthetic biology is the design and construction of biological components and functional systems (organisms) that either do not exist naturally or that are adapted from an existing natural template (Rodemeyer, 2009:16; SynBerc, 2013; Syntheticbiology.org, 2013). These organisms are usually a type of bacteria or virus (Bedau & Larson, 2013:69; Federal Ethics Committee on Non-Human Biotechnology, 2010:8). Various writers, for example Aus der Au (2013:50), Dabrock (2009) and Rheeder (2014b), query this apparent creation of life from a Christian ethical perspective and one may thus wonder if synthetic biology tries to "play God" by creating artificial life.

Synthetic biology is fundamentally the artificial or synthetic creation of DNA (deoxyribonucleic acid). Hutson (2011) explains that the desired DNA sequence is read into a machine that then produces the DNA from its base component, namely sugar. Consequently, one can order any combination of DNA sequences for study or experimentation. These basic DNA sequences are called BioBricks and can be mail-ordered worldwide from a manufacturing company (Jha, 2005).

Synthetic biology is divided into two fields of study (Syntheticbiology.org, 2013). The first field (called the *bottom-up* or Lego model) uses BioBricks to build a completely new genetic organism (Federal Ethics Committee on Non-Human Biotechnology, 2010:8). The scientist designs a molecular structure that does not exist naturally, but one that can fulfil the role of a natural organism. The final aim is to create a new, fully functional, artificial organism (Bolt, 2013:37).

The second field (*top-down* or chassis model) starts by stripping the molecular structure of a naturally occurring organism until the bare minimum of components remain and then using BioBricks to build up the organism until it is functional again (Federal Ethics Committee on Non-Human Biotechnology, 2010:8). Although this model seems very similar in principle to genetic engineering, the main distinction is the complete use of synthetic materials when creating the final product (Lustig, 2013:16). Existing DNA can be cut and pasted. As such, the final product's molecular structure might be similar to that of the originals, but the function and purpose of the new organisms are completely different. The new organisms are placed within a closed system for observation but their behaviour is sometimes unnatural and unpredictable (PCSBI, 2010:50).

A mere ten years ago, in 2004, MIT (Massachusetts Institute of Technology) launched a holiday programme for students to promote synthetic biology. Students were challenged to build the best biological machine (Jordaan, 2011). This competition was such a success that since 2012 the International Genetically Engineered Machine (iGEM) competition has been run independently from MIT and teams from all over the world compete (iGEM, 2012). In 2011 a South African team comprising of students from the University of Witwatersrand (Wits) and personnel from The Council for Scientific and Industrial Research (CSIR) competed and was placed third in the European branch of the competition with their Bio-tweet project (Jordaan, 2011). The Wits-CSIR team created a synthetic bacterial cell that can act as a marker or flag. The synthetic cell changes colour when exposed to a predetermined substance. The significance of these marker cells is that they can be used to find and eliminate harmful cell structures, for example cancer cells (Jordaan, 2011).

There are various other ways in which synthetic biology is researched and developed, for example:

Biofuels – Synthetic biology works toward the creation of a biofuel that is cheaper and more environmentally friendly to produce (Rodemeyer, 2009:19).

Biomaterials – Synthetic biology aspires to create new materials by improving on the DNA code of existing material that has a promising attribute, for example a synthetic fabric with the properties of a spider web (Federal Ethics Committee on Non-Human Biotechnology, 2010:9).

Biopharmaceuticals – Synthetic biology aims to reduce the costs of the production of the base components in the production of pharmaceuticals, such as the anti-malarial drug artemisinin (Rodemeyer, 2009:20).

Biomilitary – Synthetic biology may be used or misused in the development and use of bioweapons (Federal Ethics Committee on Non-Human Biotechnology, 2010:9).

According to Rheeder (2014a), there are now more advantages than disadvantages to the further study and development of synthetic biology. Furthermore, Hutson (2011) mentions that synthetic biology is only developing and growing as each project is initiated and completed. To the author it is clear that the potential of synthetic biology is lying beneath the surface and is only waiting for the right circumstances to break free.

1.1.2 Problem statement

The previous section uses constructs closely associated with synthetic biology, such as “biological machines”, “artificial life” and “artificial organism”, that can create alarm in the minds of Christians who practise natural science. These friction constructs make us question if humans are trying to break the apparent boundaries of science. The crux of the theological-ethical problem seems to be the creation of life, an action that before the 21st century was only associated with God. It can be argued that genetic manipulation and cloning still use existing DNA materials and structures and as such cannot be seen as pure creation – for more on this distinction, see Bolt (2013:37). Synthetic biology offers humans the freedom of pure creation with the unlimited combinations available for the formation of new cells and organisms. It is definitely new in the sense that no naturally occurring organism has a molecular structure precisely the same as that of the artificially created organism (PCSBI, 2010:45). Regardless of the similarities between the molecular structures, characteristics or functions, the synthetically created organism was uniquely designed and then produced by a human (ETC Group, 2010:7). The following problem presents itself: Can humans really claim ownership of the title *creator of new life* with the creation of a fully functional living organism through glued-together BioBricks?

The defining of life is central to debates about synthetic biology and bioethics in general. Think for instance of the debates about what life is in discussions regarding abortion, genetic manipulation or artificial fertility programmes. Synthetic biology has infused this debate with new vigour and depth. The author does not in this section wish to pursue the question of the right to life for sentient entities – see Vorster (2004) in this regard – but rather questions how humans perceive life in nonsentient entities. Even so, we can concur with Du Toit (1988:3) when he observes that “in the course of ordinary daily life we have no difficulty in distinguishing between the living and the nonliving”. However, the complexity of such an obvious observation is intensified since synthetic biology creates a nonsentient entity from artificial materials. A purely objective scientific paradigm sees life as “nothing more than especially complex physics and chemistry” (Du Toit, 1988:4). Bolt (2013:39), however, links this scientific view to synthetic biology with the term “living machine”, since engineering generally produces “machinelike

artefacts". He also argues that "synthetic organisms are undoubtedly living organisms". It can thus be concluded that an organism created by synthetic biology is entitled to the same rights as a natural organism.

Aus der Au (2013:54) provides a unique perspective that moves the focus from *what is life?* to *how do humans respond to life?* She further stresses that humans must be "*homo respondendus*", because we respond to God's mandatory order to respect and safeguard other creations (Aus der Au, 2013:57). The view of Vorster (2011:101) is that "[a]nimals and plants are inherently valuable because God created them", evidently to show that the rights and dignity of nonsentient entities should be taken into consideration.

The main question that arises from this discussion regarding the place of synthetic biology in Christian theology is:

Is synthetic biology acceptable from a Reformed theological-ethical perspective?

The following subquestions are used to answer the main research question:

- What are the origins and science of synthetic biology?
- What are the rational ethical arguments for and against synthetic biology?
- What is an ethical assessment of synthetic biology within the Reformed tradition?

1.2 Research aim and objectives

1.2.1 Research aim

The aim of this study is therefore to evaluate synthetic biology theologically and ethically according to a Reformed paradigm.

This study makes use of the Creation perspective (Vorster, 2004:80–82) as theme for its theoretical framework. The re-creation and eschatological perspectives (see Vorster, 2004:82–84), are only discussed and used briefly as supportive framework due to the time and length constraints pertaining to this study. The creation perspective is Trinitarian based on God the Father who creates through the Son and with the Holy Spirit (John 1:9 and Genesis 1:2). Thus the one triune God (Father, Son and Holy Spirit) created the whole world from nothing and still maintains it today (see The Belgic Confession: Articles 8, 9, 12 & 13). God's creation from nothing (*creatio ex nihilo*) exhibits his divineness, power and flawlessness (Atkinson & Field, 1995:268), because only God can create by will alone.

Creation without any predecessor (something entirely new) is not the same as human secondary creation, which always contains some primordial influence (Spykman,

1992:159,160). The doctrine of *creatio ex nihilo* is important for this study because as argued by Moltmann (1985:87–89), God creates the universe outside his own presence, but during this interaction, his presence again fills creation. Thus, God is divinely active with every part of his creation. We can link God's continued creation (*creatio continua*) to *creatio ex nihilo*, because as Pannenberg (2006:364) explains: "The notion of *creatio ex nihilo*, therefore, does not only apply to the first beginning of the world; it applies to *each* act of creation of something genuinely new in the history of the world." Polkinghorne (2006:60) rightly points out regarding *creatio continua* that God is as much the Creator today as he was when the world began many years ago. Thus, we can concur when Moltmann (1985:209) explains *creatio continua* as God's preservation of the world. However, we must, take into account the place of people within creation, as well as his divine mandate regarding God's creation. Humans are "co-creators" with God, which according to a biotechnology perspective as argued by Cole-Turner (2006:942), means that God can act through humans and technology to still create today.

Human beings are the crown of God's creation, created in his image and ordered to inhabit, rule and preserve the earth and its inhabitants (Genesis 1:26-28). A human as the image of God (*imago Dei*) represents all other humans (Erickson, 2001:175–176) regardless of gender or race, as the image is visible within human nature. *Imago Dei* literally means "to mirror God and to represent God" (Hoekema, 1986:67). *Imago Dei* has a particular signification within bioethics because it includes all humans under the characteristic that prescribes our earthly existence: the inheritance, rule and preservation of the earth. Vorster (2004:81) emphasises that humans have a responsibility towards God's creation, nature and other humans, namely to preserve **all** forms of life. This responsibility does not only call for preservation but also for acting towards the promotion of a right to life and the improvement of all circumstances of life (rule **and** preservation). According to Vorster (2004:256), this order is not only a privilege given to humans by God, but it is also a responsibility. We are called to be responsible stewards of the earth as God's representatives.

However, the influence of the fall – as described in Genesis 3 – cannot be disregarded in the interaction between humans and nature. Sin distorted the balance of the hierarchy established at creation (see Vorster, 2011:100) and consequently humans have disregarded their responsibility to safeguard nature. The "threefold relationship: between man and God, between man and his fellowmen, and between man and nature" (Hoekema, 1986:75) has become corrupted and we worship idols instead of God, we selfishly manipulate others instead of loving them and we exploit natural resources rather than safeguard them (Hoekema, 1986:84–85). Sin can therefore cloud every good intention of humans, if it is not motivated and guided by the Holy Spirit. We must therefore tread cautiously concerning the purpose and aim of synthetic

creations, because humans can and will use this exceptional technology for their own selfish gain or to hurt others.

After the fall, God saves humanity (Belgic Confession, 2013: Articles 21–22 and 2 Corinthians 5:17) through re-creating humans in Christ and restoring the relationship between humans and God. This restoration also includes humans' moral and ethical natures (Heyns, 1982:95). Consequently, the focus of believers' lives changed from selfishness to love for God and other humans. Humans should follow Christ's example, for instance by being holy because God is holy, loving one's neighbour because God is love, or creating new things because God creates new things. As such everything done by Christians should be to the glory of God (*solī Deo gloria*) because as stated by Fergusson (2007:73), the "world was not made for human benefit, but for glory of God".

Vorster (2011:19) explains that the re-creational work of Christ takes place in the present, but will only conclude in the future. At present, the world is in despair, but God is still present and active in preserving it (Fergusson, 2007:78). It is humans' longing for the fulfilment of God's creation that creates an eschatological perspective of hope. This hope is in bettering the current world humans live in without falling into despair. Synthetic biology aspires to create new organisms to provide hope and improvement in believers' lives.

God creates from nothing (*creatio ex nihilo*), but God also creates continuously (*creatio continua*) and preserves that which he creates. This study holds that humans as "co-creators" can be measured according to God's creation conduct and as *imago Dei* must be a true representative of God. Berkhof (1996:136) puts the emphasis on the fact that the ultimate purpose of creation is to glorify God. While humans await the re-creation and coming of Christ they can obtain hope through helping others. Synthetic biology is such an initiative to improve people's lives. Accordingly, all human creations should be measured to this standard: Does it glorify the almighty God?

1.2.2 Research objectives

Each of the research objectives is used as theme for the study's individual chapters:

- To investigate and describe the origins and science of synthetic biology.
- To describe and ethically assess the rational arguments for and against synthetic biology.
- To describe and ethically assess synthetic biology within the Reformed tradition.

1.3 Central theoretical argument

The central theoretical argument of this study is that synthetic biology is acceptable in a Reformed perspective, since it can be seen as a product of God's *creatio continua* through humans as image-bearers. However, we must show discernment regarding the motives with which synthetic biology is practised, because there are few regulations and safeguards in place. When people live out their *imago Dei* to the fullest, they glorify God in all they do. This can also be expected for Christians involved with synthetic biology.

1.4 Research design

This study has been done within the Reformed tradition and used the methodology of Nullens and Volgers (2010:79) to direct the different aspects. In Table 1-1 the headings of the research objectives are presented in **bold** print and the methodological steps are given in *italics*, while the author's application follows in normal print.

Table 1-1-1: Research design

The research problem	
<i>Formulate the research question</i>	Is synthetic biology acceptable from a theological-ethical standpoint?
The investigation and description regarding the origins and science of synthetic biology	
In order to study and describe the origins and science of synthetic biology, a literature analysis was conducted.	
<i>Examine historical sources</i>	Although synthetic biology is a new field of study, the ethical topic of genetic engineering has proven useful.
<i>Examine interdisciplinary sources</i>	Current research regarding the scientific aspects of synthetic biology was studied, with a specific focus on various reports of commissions of enquiry regarding synthetic biology, such as the ETC Group or the Presidential Commission for the Study of Bioethical Issues (PCSB).
The description and ethical assessment regarding the arguments for and against synthetic biology	
In order to study and describe the ethical arguments for and against synthetic biology, a literature analysis was conducted.	
<i>Examine current sources</i>	Current research regarding the ethics arguments for and against synthetic biology was studied. This provides a rational evaluation, rather than a theological perspective. Main sources used are Bolt, Dabrock and Rheeder.
The description and ethical assessment of synthetic biology within the Reformed tradition	
A thematic (systematic theology) approach was used with the creation perspective as main theme and the re-creational and eschatological perspectives as subthemes.	
<i>Investigate within the broad Biblical context and revelations</i>	Synthetic biology was investigated from the theme of creation perspective with particular examination of the works of Berkhof, N. Vorster and K. Vorster.

<i>Contemporary context</i>	Both the rational and reformed evaluations give a holistic perspective for the Christian scientist or researcher, as well as the everyday believer.
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1.5 Concept clarification

The following concepts are explained in more depth. They are listed alphabetically:

Bible version – The New International Version (1996) was used.

Bioethics – The scientific study of ethical issues that are associated with any biological discipline, used as a synonym for medical ethics (Levinson & Reiss, 2003:4).

Christian ethics – Ethics approached from a Christian perspective. The term is used as synonym for theological ethics and deontological ethics – ethics that are grounded in Biblical principles and obligation (Vorster, 2004:2). According to De Bruyn (2008:7), theological ethics is the scientific study of the revealed will of God concerning human thought, words and acts. God’s will is revealed in nature and throughout history, and in the Bible and Reformed doctrines. The main objective of Christian ethics is to identify principles within God’s revelation, deriving norms that are formulated in such a way that human actions can be evaluated as right or wrong. The focus is thus on the principles and norms derived from Biblical themes and scriptures.

Male form of address – Although the male form of address is used throughout this document, the author refers to both genders.

Reformed tradition – Calvin’s theology left a heritage from the time of the Reformation that is still accepted by Reformed and Protestant churches today (Vorster, 2004:2). This study builds on the ethical principles and norms developed by theologians within this tradition.

1.6 Ethical considerations

The study was purely theoretical and consequently no empirical research was conducted. Nonetheless, good ethical conduct requires us to use the Bible in a sincere and humble manner as the written Word of God and not as an academic textbook or source (De Bruyn, 2008:2). The primary aim of the Bible is after all to provide believers with everything they need for salvation; its secondary aim is to act as a guide for a religious and devoted life. It must therefore be used within its intended context (De Bruyn, 2008:2; De Klerk & van Rensburg, 2005:7). Together with the writer of Psalm 119:34, we call out to the Holy Spirit to guide us in the understanding and use of the Holy Word: “Give me understanding, and I will keep your law and obey it with all my heart.”

Chapter 2 – The origins and science of synthetic biology

A scientist discovers that which exists; an engineer creates that which never was.

– Theodore von Karmen

2.1 Introduction

Synthetic biology is seen as a merger of various disciplines; practitioners can therefore be scientists that discover but also engineers that create. Synthetic biologists are thus only constrained by the limits of their own creativity and innovation. One may, however, wonder where and how the field of synthetic biology originated or how it actually works. This chapter aims to answer such questions by explaining the *when*, *who*, *how* and *why* of synthetic biology in a way that most people can understand. It starts by exploring the possible origins of synthetic biology and identifying the pioneers of this field. The middle section focuses on how synthetic biology works by describing its components, methods and how it is applied. Lastly, some possible benefits and harmful effects of synthetic biology are set out.

2.2 An overview of the origins of synthetic biology

2.2.1 How synthetic biology started

Synthetic biology has its origins in the field of microbiology and thus shares a common ancestry with other fields of biotechnology such as genetic engineering and nanotechnology (Parens *et al.*, 2009:11). It might even be said that synthetic biology is the result of the continuous development and integration of molecular biology and genetic engineering (PCSBI, 2010). Admittedly, it is impossible to pinpoint the precise origin of synthetic biology, as all writers differ on the exact date or scientist responsible. However, the first definite mention of synthetic biology (*la biologie synthétique*) was in 1912 by Stéphane Leduc, a French professor of medicine (Campos, 2009:7).

What is today called synthetic biology can be traced back to the early 1970s and the work of Herb Boyer and Stanley Cohen regarding gene splicing or recombinant DNA (rDNA) technology (Rodemeyer, 2009:11). The rDNA technique enables the manipulation of genes by cutting, moving and then reattaching the DNA, now known as traditional genetic engineering (PCSBI, 2010:38). The first commercial product of rDNA technology was the manufacturing of insulin for the treatment of diabetes (PCSBI, 2010:38-39). The 1980s saw the development of the polymerase chain reaction (PCR) technique that makes it easier to copy DNA sections (PCSBI, 2010:39). Automated DNA sequencing consequently became available in the early 1990s and

during the same period the race to complete the Human Genome Project accelerated the process of gene sequence identification (PCSBI, 2010:39).

As scientists became more proficient with identifying naturally occurring gene sequences, they could further develop DNA synthesis machines for synthesising longer and more complex DNA segments (PCSBI, 2010:42). Since the 2000s synthetic biology has mainly been constrained by production costs and by the machines necessary for DNA synthesising. According to the ETC Group (2007:10), to produce a DNA base pair cost in the region of \$10-12 in 2000 and about \$1-2 in 2006. In 2014 the cost per base pair was under \$0,5 and it can be shipped to the customer within a week, depending on the length of DNA segment ordered (GenScript, 2014). The race is thus on to build a better machine in order to build longer and more intricate DNA segments faster and at a lower fee (ETC Group, 2007:7, 10).

2.2.2 The links between synthetic biology and genetic engineering

Although synthetic biology has been closely associated with genetic engineering (or genetic manipulation) since the 1930s (Campos, 2009:13), there is a distinct difference between the two fields. Genetic engineering can be seen as the cutting and pasting of DNA between existing organisms (ETC Group, 2007:6). Rather than using rDNA technology to slice and dice existing DNA, synthetic biology is a natural advancement of rDNA techniques to design and build new genetic structures (Rodemeyer, 2009:11).

An analogy used by Bolt (2013:38) states that genetic engineering edits written text while synthetic biology starts writing on a blank page. “The transition from descriptive biology to genetic engineering to synthetic biology can thus be paraphrased as the development from reading to editing to writing DNA” (Bolt, 2013:38).

2.2.3 Pioneers of synthetic biology

According to Parens *et al.* (2009:6), there are four pioneers to watch regarding the further development of synthetic biology, namely Drew Endy, Craig Venter, George Church and Jay Keasling. Each of these individuals spearheads and advocates a unique approach to and goal for synthetic biology.

2.2.3.1 Drew Endy

Drew Endy aspires to make biology easier to engineer. He pioneers what O'Malley *et al.* (2008:57) call DNA-based device construction. This entails the reduction of the biological complexity of a cell and the standardisation of its parts (Shetty *et al.*, 2008). In other words, a bottom-up approach is used to construct a synthetic cell by using standardised parts, but these

parts (BioBricks) first have to be designed and then compiled for use (see 3.2 for more detail). Endy is the co-founder of the BioBricks Foundation established in 2005 (The BioBricks Foundation, 2014) as well as the co-founder of the Registry of Standard Biological Parts, which provides a registry of BioBricks for public use (Parens *et al.*, 2009:6). He also contributed to the founding of the International Genetically Engineered Machines competition (iGEM) that challenges students to build the best possible biological machine (Parens *et al.*, 2009:6). At present (2014), Endy is an assistant professor of bioengineering at Stanford University California (Stanford University, 2014).

2.2.3.2 Craig Venter

Dr Craig Venter is the founder, chairman and CEO of the J. Craig Venter Institute (JCVI) situated in Rockville, Maryland and San Diego, California (J. Craig Venter Institute, 2014). The JCVI is a genome-driven research organisation that *inter alia* devised a revolutionary splicing method, which contributed to the completion of the Human Genome Project (Rodemeyer, 2009:17). Venter is best known for the first complete synthesis of a whole bacterial genome (*Mycoplasma mycoides*) and the subsequent acceptance of the synthetic genome into a closely related *Mycoplasma capricolum* cell (Kaebnick, 2014:812; Schmidt & Pei, 2011:205).

He is mainly focused on what O'Malley *et al.* (2008:58) term genome-driven cell engineering or what Schmidt and Pei (2011:205) dub DNA synthesis or synthetic genomics. The essence of this research is to produce a minimal genome that has all its genes removed except those that are essential for supporting life. "The goal is to create a cellular platform or 'chassis,' in other words a simple cell with a so-called minimal genome that has the least possible number of genes able to survive under (specific) laboratory conditions" (Schmidt & Pei, 2011:207). Both the bottom-up and top-down methods are used to analyse and then modify an organism until it can only sustain life (O'Malley *et al.*, 2008:59).

During an interview with *National Geographic* in March 2014 (Vergano, 2014), Venter announced the launch of a new project to sequence the gene maps of 40 000 volunteers with the goal of understanding human aging. The focus is on "aging-related human biological decline ... [because] aging is a central component of every disease that we want to address therapeutically. We believe that many of the processes at the cellular and the genomic level that we call aging are related and connected". This project might further expand our knowledge regarding DNA growth and behaviour.

2.2.3.3 George Church

George Church is a professor of genetics at Harvard Medical School, Boston, and the founder of the Personal Genome Project (PGP), a nonprofit organisation “working to generate, aggregate and interpret human biological and trait data on an unprecedented scale using open-source, open-access and open-consent frameworks” (Personal Genome Project, 2014). He also helped to initiate the Human Genome Project during the 1980s (Bethge & Grolle, 2013).

Church pursues what O'Malley *et al.* (2008:59) term protocell creation. A protocell or synthetic cell is an assembled organism with only minimal life functions, produced with chemical components using the bottom-up method. (Schmidt & Pei, 2011:207). The protocell is thus a fully synthetic cell to which we can add any genes to determine its new function. This can be seen as a combination of what both Endy (using BioBricks) and Venter (developing a minimal genome) aspire to achieve.

2.2.3.4 Jay Keasling

Jay Keasling is a chemical engineering professor at the University of California at Berkeley (head of Keasling Laboratories) and the CEO of the Joint BioEnergy Institute (Parens *et al.*, 2009:8). Although his work has strong ties with traditional genetic engineering (Parens *et al.*, 2009:8), it includes one of the foremost breakthroughs of synthetic biology, namely the successful production of a synthetically created anti-malarial drug: artemisinin. “The most celebrated achievement is the design of a metabolic pathway to produce a precursor of the antimalaria compound artemisinin, a substance naturally found in the wormwood plant that could not be produced by micro-organisms” (Schmidt & Pei, 2011:5). The development and production of artemisinin is discussed in more detail in section 3.1.2. Keasling still contributes to the development of biofuels to replace gasoline, diesel and jet fuel (Sample, 2011).

2.3 How synthetic biology is practised

2.3.1 Base components

Synthetic biology takes place at subcellular level within the genome of a cell. The genome of each cell contains the complete genetic code of that organism and is made up of a distinct number of chromosomes peculiar to the species (PCSBI, 2010). Chromosomes are comprised of DNA (deoxyribonucleic acid) structured like a spiralling stepladder. A gene is a segment of DNA that contains the information to produce a specific product, most often a protein (Wassenaar, 2012:75).

When a cell replicates genes, DNA serves as an information template to build new DNA strands from amino acids. Gene segments are split up by stretches of DNA, similar to the stoppers used when beading a necklace. Of these DNA stretches, some only serve as separators while others are instructions regarding the time and quantity for production of the gene (Wassenaar, 2012:76). Each gene is composed of nucleotide base pairs: adenine (A), cytosine (C), guanine (G) and thymine (T) that are connected to a sugar-phosphate backbone (ETC Group, 2007). An overview regarding this cell structure is provided in Figure 2.3.1–1 (adapted from PCSBI, 2010:37).

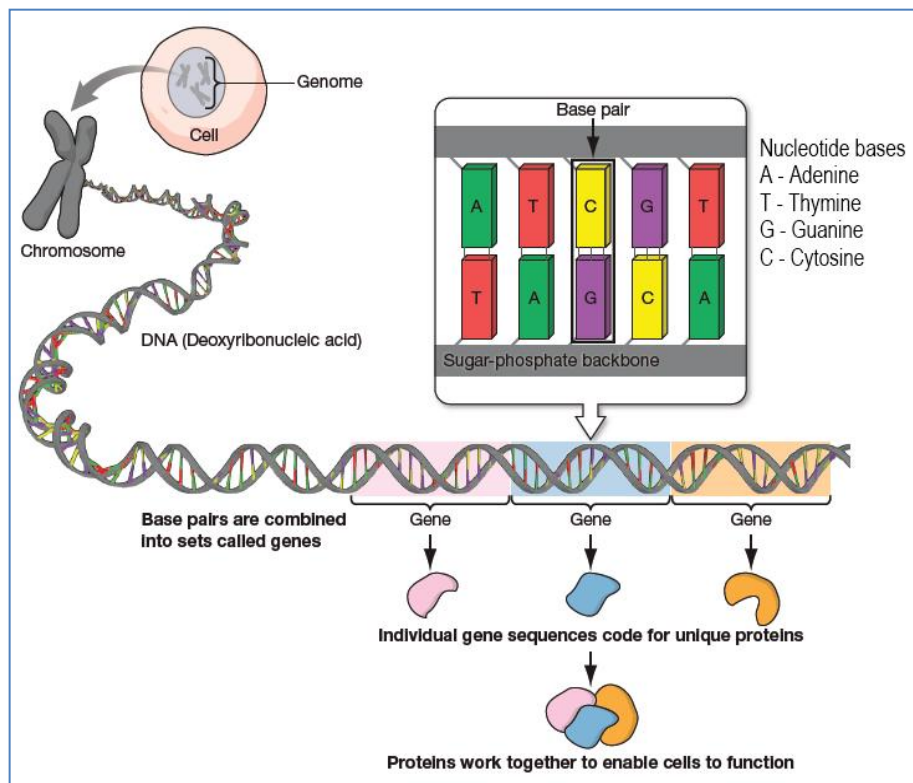


Figure 2.3.1–1 The cell structure

Synthetic biology can artificially replicate any gene by combining the nucleotide base pairs in the desired order. The synthetic DNA is produced from sugar isolated from sugar cane (ETC Group, 2007:9). However, it is not limited by the four naturally occurring base units, as two extra pairs (the A-T and C-G base pairs) were artificially produced so that more complex DNA combinations could be created (Wassenaar, 2012:173). This is where BioBricks come into play as an attempt to standardise genes and DNA sequences.

2.3.2 BioBricks

BioBricks are biological parts mainly developed by the bottom-up approach. “A biological part [is] a natural nucleic acid sequence that encodes a definable biological function” (Shetty *et al.*, 2008). A biological part or BioBrick can therefore be called an artificially created gene. However, the part has to meet a specified standard to be considered a BioBrick. For example, two biological parts must be compatible for easy assembly without compromising the structural element of the new DNA sequence (iGEM, 2014d).

This is done “through the use of a prefix and suffix (found on plasmid backbones), which flank the beginning and end of a part sample, respectively”

(iGEM, 2014d). The prefix and suffix are the connectors between individual BioBricks like the couplings between train cars. Figure 2.3.2–1 (taken from iGEM, 2014f) is an example of a BioBrick, where part *BBa_B0034* is bordered by a standard prefix (P) and suffix (S) and it also provides an example of how a BioBrick system can be assembled. Shetty *et al.* (2008) observed that in 2008 the Registry of Standard Biological Parts had an assortment of over 2 000 standardised BioBricks, each with a unique identification number, but in the 2014 online catalogue this number has grown to over 20 000 BioBrick parts (iGEM, 2014e).

According to Shetty *et al.* (2008), there are two major advantages of the use of BioBricks. Firstly, it standardises the parts as well as the process of synthetic biology; for example, two engineers from different parts of the world can work with the same BioBricks resulting in a compatible process and parts. The second advantage is that standardised parts reduce the failure rate of the trial and error method, and subsequently the results can be replicated both constantly and reliably.

BioBrick systems can be compared to the initial blank circuit board used by electronic engineers to design a new product. The engineers know how and where to use each available component to get the optimal result. These are the aspirations of synthetic biologists. When synthetic biology has a similar repertoire of tools at its disposal, it moves beyond the basics to more complex ideas such as multi-cellular systems and nonbiological functions (Bio F.A.B. Group *et al.*, 2006). BioBricks are essential to the bottom-up method, but are not as important to the top-down method. The next section will discuss how these approaches differ.

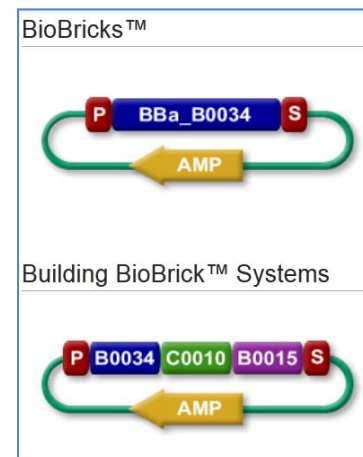


Figure 2.3.2–1 BioBrick and BioBrick systems

2.3.3 Synthesising methods

Synthesising utilises the bottom-up method (called the *in vitro* or Lego model) or top-down method (called the *in vivo* or chassis model). The terms *in vitro* (in glass) and *in vivo* (in life) (ETC Group, 2007:36) actually depict a key distinction between the two methods, since the top-down method always starts with an existing organism, while the bottom-up method starts with nothing but an idea.

The bottom-up method sees synthetic biology as a blank slate on which to build an organism from scratch, using nonliving molecules (Bolt, 2010:21). It aims to remake rather than reshape (Anon, 2006:383). As explained in the BioBrick section (2.3.2), the bottom-up method uses interchangeable parts to build artificial biological systems similar to simplified circuit boards (Rodemeyer, 2009:16). This is also called a “construction of life” approach by De Lorenzo *et al.* (2006:127), where “the goal is to build systems that [are] inspired by general biological principles, use biological or chemical components to reproduce the behaviour of live systems”.

The top-down method breaks down the genome of an existing organism so that only the most crucial genes needed to sustain life are left and then synthetic genes are added to give the organism a new function (Bolt, 2010:21). Minimal genome research aims to find “the minimal set of genes required by an organism to support cellular life in an ideal environment. It can be also considered as the minimal species-specific ‘operating system’ or ‘software’ for cellular life” (Acevedo-Rocha *et al.*, 2012:273).

A goal of the top-down method is to better understand life (and biological systems) by disassembling an organism to comprehend the function of individual parts (Rodemeyer, 2009:16). Similarly, De Lorenzo *et al.* (2006:127) refer to a “deconstructing life” approach to synthetic biology that includes minimal genome research and the definition of biological systems. The top-down method was initially limited to the use of existing organisms like algae, bacteria and viruses (Federal Ethics Committee on Non-Human Biotechnology, 2010:8) but is not limited to what can be done when synthetically altering the organism (Rodemeyer, 2009:18).

2.3.4 iGEM

The International Genetically Engineered Machines competition (iGEM) will most likely be the platform where the next major breakthrough regarding synthetic biology will occur. Guan *et al.* (2013:25-26) praise the educational success of the iGEM initiative, where theory, practice and fun are combined into one: “They are all designed to elicit enthusiasm among young scholars in science and engineering in a stimulating but stringent process and in a group of like-minded

peers.” The students who compete come from a wide range of interdisciplinary fields, including engineering science, computer science and life science.

According to the iGEM website (iGEM, 2014b), each team is composed of undergraduate students from an accredited tertiary institution, with two compulsory instructors and voluntary graduate students or post-doctorates serving as team advisors. The teams must present their project at the conference through a poster and a twenty-minute presentation. In addition they must also design and create a collaborative website (known as a wiki) describing their project, team etc. Each team furthermore contributes to the expansion of the Registry of Standard Biological Parts by submitting the standardised BioBricks and accompanying documentation used in their project.

In 2014 there were 246 teams registered to compete worldwide, with 82 teams from Asia, 68 teams from Europe, 14 teams from Latin America and 86 teams based in North America (iGEM, 2014g). Table 2-1 gives an indication of how the iGEM competition grew from five teams in 2004 to 215 teams in 2013 as well as an indication of the BioBrick parts that were contributed yearly to the Registry of Standard Biological Parts (iGEM, 2014c).

Table 2-1-1: iGEM Growth

Year	Number of teams	Number of parts submitted to registry
2004	5	±50
2005	13	±125
2006	32	±724
2007	54	±800
2008	84	1 387
2009	112	1 348
2010	130	1 863
2011	165	1 355
2012	190	1 708
2013	215	1 708

Noteworthy projects from previous years promoted by the iGEM website (2014a) are:

2006 Arsenic Biodetector – University of Edinburgh team

The team designed a biosensor to detect different concentrations of arsenic in drinking water and then produce a change in pH in response to the perceived concentration. This detector was

designed to be cheaper and more user-friendly than other detectors to use in under-developed countries such as Bangladesh.

2007 BactoBlood – The UC Berkeley team

The BactoBlood project is intended to be a cost-effective substitute for red blood cells that can safely transport oxygen in the bloodstream. BactoBlood can also be stored in a freeze-dried state for extended periods, thereby extending the “shelf life” of blood stores.

2009 E. Chromi – The Cambridge team

This team revolutionised biosensor design and construction by developing an identifying technique. They developed an *E. coli* that changes colour in response to different concentrations of an inducer. It can be compared to the test kit used to determine the amount of chlorine in a swimming pool.

As it expands, iGEM poses a unique contamination risk because of the multitude of projects concentrated in one area. A study done from 2003 to 2011 by Guan *et al.* (2013:27, 30–31, 33) raises the question of biosafety precautions at the iGEM competitions. Results indicated that as the competitors grew in numbers there was more awareness from the teams regarding the possible risks connected with their projects and what they could do to minimise the risks. Some teams even went as far as developing a built-in safety mechanism or “kill switch”. The iGEM organisers also encourage biosafety by making it a qualifying criterion to be considered as a prize-winner.

The iGEM competition is a prime example of the possible benefits (any innovative project presented there) and of the possible harms (such as biosafety and contamination risk) of synthetic biology. The next section looks at the current benefits and harms within the profession.

2.4 The benefits and harms of synthetic biology¹

2.4.1 Possible benefits of synthetic biology

Broadly speaking there are two major benefits to synthetic biology, according to Rodemeyer (2009:14). Firstly, the promotion of our knowledge and understanding of nature, which links closely to the *in vivo* method because it encompasses the deconstruction of life. Secondly, there are useful applications for synthetic biology. The subsequent section describes the main areas of research: biofuels (ethanol and butanol) and biopharmaceuticals (artemisinin).

¹ In agreement with the Universal Declaration on Bioethics and Human Rights article 4 (UNESCO, 2005:76) the terminology of benefits and harms is used rather than advantages and disadvantages.

2.4.1.1 Biofuels

Synthetic biology biofuels are fuels designed to be more environmentally friendly and with the added benefit of being cheaper to produce. The aim is to influence the production process of current biofuels at critical points, in order to reduce cost such as an extraction process of sugar from cellulose biomass (Rodemeyer, 2009:19). Zarilli (2006:5) describes biomass as follows:

Biomass includes organic matter available on a renewable basis, such as forest and mill residues, agricultural crops and residues, wood and wood residues, animal wastes, livestock operation residues, aquatic plants, fast-growing trees and plants, and the organic portion of municipal and relevant industrial wastes.

Ideally, the only biomass that should be used are those components that do not compromise the production of food.

Jang *et al.* (2012:992-993) describe the current biofuel condition regarding the metabolically engineering of ethanol

(the only effectively produced renewable biofuel) and butanol (an alternative fuel). Ethanol is naturally produced in large quantities by the bacteria

Saccharomyces Cerevisiae (yeast) (Willey *et al.*, 2011:1026) and *Zymomonas mobilis* (Willey *et al.*, 2011:1042), but only from some carbon sources. However, *Escherichia coli* [*E. coli* see Figure 2.4.1–1 taken from Willey *et al.* (2011:36)] also produces ethanol in small quantities and can make use of most carbohydrate components as source. Synthetic biologists have exploited this property of *E. coli* by metabolically engineering it for increased ethanol secretion. This is done “through the introduction of foreign genes, elimination of competitive pathways, and disruption of by-products formation” (Jang *et al.*, 2012:992–993). Thus, through synthesising *E. coli* with incorporated *Zymomonas mobilis* genes the resultant bacteria can decompose all five different sugars (glucose, xylose, mannose, galactose and arabinose), which is not possible for any natural organism (Willey *et al.*, 2011:1042). The production of butanol is attractive because it has a higher combustion point than ethanol, so that it can be used as a direct fuel alternative. *Clostridium acetobutylicum* (Willey *et al.*, 2011:556) was metabolically engineered to improve Butanol production, but due to the difficulty of influencing *C. acetobutylicum* bacteria, *E. coli* and yeast are considered better alternatives. The further development of this research should lead to “micro-organisms capable of producing various biofuels cost effectively on industrial scale” Jang *et al.* (2012:992-993).

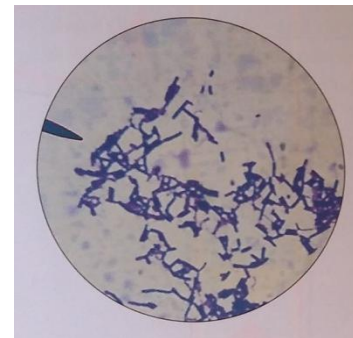


Figure 2.4.1–1 *E. coli* crystal stained violet

2.4.1.2 Biopharmaceutics

The success story of the anti-malarial drug artemisinin, used in combination therapy, serves as a prime example of the potential benefits of synthetic biology. Synthetic biology was able to reduce the cost of production for the drug's base components (Rodemeyer, 2009:20). The Artemisinin Project (as described by Hale *et al.*, 2007:198–202) was motivated by the high cost of artemisinin-based combination therapies (ACTs), which are a hundred percent effective against malaria infections. The project's aim is to help poor countries, mainly in Africa and Asia, to combat the devastation of malaria infections. The Artemisinin Project uses the top-down method to engineer the metabolic pathway found naturally in the artemisinic acid secreting wormwood plant.

2.4.2 Possible harms of synthetic biology

2.4.2.1 Biosecurity

Biosecurity encompasses all issues regarding the possible harmful misuse (Schmidt *et al.*, 2011:327) of synthetic biology such as bioweapons and bioterrorism (ETC Group, 2007:48). The easy production of bioweapons may be possible in the future with synthetic biology (ETC Group, 2007:24). According to Garfinkel *et al.* (2007:13), it is presently easier for a terrorist to obtain a virus using other means than synthetic biology. The potential security risk admittedly cannot be ignored due to possible future developments.

A key example of a potential weapon would be the synthesis of the 1918 Spanish influenza pandemic virus (Tumpey *et al.*, 2005:77). The motivation of the project to better understand influenza pandemic viruses and the development of potential anti-measures is admirable (Tumpey *et al.*, 2005:88). However, one has to question the wisdom of re-creating such a deadly disease, even though it is securely controlled (Garfinkel *et al.*, 2007:13).

2.4.2.2 Bioregulation

The regulation of synthetic biology has always played a crucial role in any synthetic biology discussion. Nevertheless, in discussions regarding biosafety, which is concerned with the avoidance of accidental consequences (Schmidt *et al.*, 2011:327), the focus is on self-regulation and preventing potential contributions from being exploited by bioterrorists, so that excessive governmental regulations can be avoided (Schmidt, 2006:1048). The risk of accidental or intentional environmental contamination still looms on the horizon. According to the ETC Group (2010:38), the use of *E. coli* bacteria increases the ecological risk, because the bacteria is very common in nature. As such, there is no certain prediction of how a synthetic organism might mutate with or cross-contaminate naturally occurring *E. coli* bacteria.

Then again, according to Guan *et al.* (2013:31), “the situation has become even more critical with the emergence of the so-called *amateur biology* (or *biohacker*) community—a group that has begun to conduct biological projects in their own garages and in home-made molecular biology laboratories”. The following case demonstrates the particular danger of biohackers. Kickstarter is an independent company that facilitates crowdfunding for creative projects where backers can pledge money to a specific project (Kickstarter, 2014). “Glowing Plant: Natural Lighting without Electricity” (see Figure 2.4.2–1) is such a project run by a team of biohackers in California, USA (The ETC Group, 2013). The project obtained backing of \$484 013 from 8 433 people who in September 2014 would each receive bioengineered seeds for plants that can glow in the dark (Anon, 2014). The ETC Group (2013) strongly opposed the notion of “the world’s first uncontrolled, unmonitored and unregulated release of synthetic organisms”, but was unsuccessful. The creators maintain that they took enough precautions to avoid biocontamination as the plant they are modifying, arabisopsis, is not native to the US (Geere, 2013). All that is left is to take a wait and see approach until the seeds are shipped.

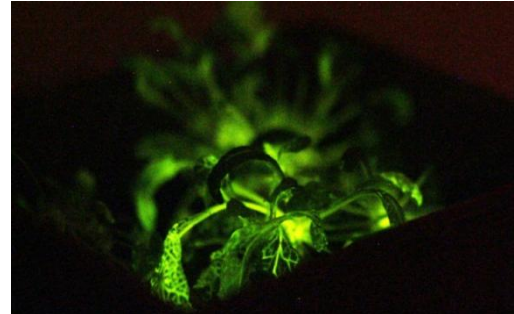


Figure 2.4.2–1 Glowing plant

2.5 Summary

This chapter endeavoured to expand the reader’s basic understanding of synthetic biology. From its origins in rDNA techniques and genetic engineering to the groundbreaking pioneers Drew Endy, Craig Venter, George Church and Jay Keasling synthetic biology remains an innovative field. The scientific basis of the cell structure and BioBricks supports understanding of the two methods (bottom-up or top-down) used to practise synthetic biology. The iGEM competition discussion shows how the methods are executed to create revolutionary projects. This leads to the discussion regarding benefits such as biofuels and biopharmaceuticals. Nonetheless, benefits cannot be separated from the possible harms and the dangers posed by synthetic biology, such as biosecurity (weapons that can be used by terrorists) and bioregulation (possible contamination). Once a subject is understood, one can evaluate it; that is the purpose of Chapter 3, in which the possible harms and benefits are stacked up and tallied to make a rational ethical evaluation with reference to the arguments for and against synthetic biology.

Chapter 3 – The ethical arguments for and against synthetic biology

We're making it easier for people to make anything. They can make good things, they can make bad things, and if we're going there, we're going there very fast, at alarming exponential rates.

– Professor George Church

3.1 Introduction

As with most issues in life, synthetic biology has both support and opposition. This chapter is concerned with the arguments for and against how synthetic biology is practised and its possible further developments. Most of the support for synthetic biology comes from the potential benefits proclaimed by its pioneers as well as evidence of its growth within commercial and research sectors. In contrast, its critics emphasise the potential risks and concerns posed. The aim of this chapter is to examine the motivation and the arguments behind synthetic biology's supporters and critics within a rational debate. There is agreement with Link (2013:436) that “[u]p to now the discourse has been much more about *anticipating* possible objections” rather than criticising actual situations.

The point of departure of Chapter 3 is from a natural law perspective, since theological ethics can and should use rational arguments within any debate (VanDrunen, 2009:30). John Courtney Murray (in Pope, 2001:88) further promotes the use of natural law, “[b]ecause natural law is grasped by reason, it stands independent of religious faith and thus provides a broad basis for the moral consensus needed to unite the diverse citizens of a pluralistic society”, which is especially true regarding multi-disciplinary diversity of synthetic biology.

Different headings and categories are used to discuss the ethical and moral considerations of synthetic biology. The “benefits and risks” groupings are popular, where risks mainly focus on biosafety and biosecurity (Garfinkel *et al.*, 2007:12–15; Rodemeyer, 2009:23,24; Schmidt *et al.*, 2011:327). Categorising the risks as “physical and nonphysical harms” as proposed by Parens *et al.* (2009:4) has also gained traction. In recent times concerns that are intrinsic in nature, such as the value of life or distinguishing between natural and unnatural organisms (Murray, 2010; Parens *et al.*, 2009:25) have also become common. In this study, the benefits of synthetic biology are compared to the risks to determine the weight of the arguments against each other. Valid concerns regarding the governance and regulation of synthetic biology remain. Two frameworks are offered to examine how synthetic biology is practised, regulated and governed namely a proactionary framework and a precautionary framework.

3.2 Natural law

Natural law is an ethical system for moral judgments established by Thomas Aquinas (Pope, 2001:79). He based his theory on prior works of the Stoics regarding the idea that a moral system can develop when societies conform to the natural order found in human nature (Pope, 2001:77). Aquinas (in Elders, 2005:200–201,209) theorised that there exists two laws that govern all moral conduct. The first law is the *eternal law*, which is essentially God's divine plan expressed within the Bible (also called specific revelation). It entails the principles for moral conduct directly expressed in the Bible. The second law is a sublaw that exists within the eternal law, called the *natural law* (or general revelation). The natural law is comprised of norms derived from principles observed in human nature. A Christian can observe God's will in the inherent human qualities of his fellow human, but also has the Bible as resource for specific instruction on how to serve God.

According to Ryrie (1972), the natural law (or general revelation) primarily reveals God within nature (Romans 1:18–21) and within human's morality as image of God (Gen 1:26; Ac 17:29), but the eternal law in contrast is visible in Christ (John 1:18) and throughout the Bible (1 John 5:9–12). When God writes his law upon the hearts of all people (as described in Romans 2:13–16) he gives them a way to serve him in accordance with the eternal law. Subsequently the natural law is the inborn morality regarding right and wrong found within all humans within any culture or religion.

John Locke (in Pope, 2001:80, 85–86) further developed natural law to show it does not originate from social order and is not dependent on religious beliefs as supposed by the Stoics, but is inherent to human nature. For example, people know that violence without any reason is wrong and that one may not take another person's property (compare with God's given law in Exodus 20:13, 15 and Matthew 22:35–40). Natural law is seen within the governance of any decent community and recognised by cultures worldwide. Natural law consequently explains the good deeds performed by nonbelievers, for example. The use of natural law is especially evident in Paul's conversion of the Athenians in Acts 17:22–34 when he preaches to them about an unknown God, using reason and cultural arguments.

Natural law should be used in Christian ethical evaluations, because it is founded on reason, which Elders (2005:208–209) shows is evident when people can reflect on and then evaluate their own actions. VanDrunen (2009:29) consequently confirms that the moral value added by rational arguments within a Christian ethical debate should not be ignored, because the debate can then be applied to all people and not only to Christians. The rest of this chapter therefore uses a rational perspective to ethically discuss synthetic biology. Chapter 4 then builds on the general revelations discovered here to ethically evaluate synthetic biology from a theological

perspective. The theological evaluation can thus be seen as an interpretation of Aquinas' eternal law or the doctrine of specific revelation, while this rational evaluation is an interpretation of his natural law or doctrine of general revelation.

3.3 Rational discussion: Support for vs criticism of synthetic biology

Synthetic biology promises to influence and change many aspects of life and contribute to the improvement of society by embracing human creativity and ingenuity. Although this is a lofty promise to make, some benefits have already started to deliver. In this section, the benefits of synthetic biology (separated into knowledge-based and product-based and then subdivided into bioinformatics, renewable energy and biomedical benefits) are discussed in contrast to the potential risks (such as biosafety, biosecurity and intrinsic concerns).

3.3.1 Knowledge-based benefits

Synthetic biology provides new knowledge as a benefit, because it has much to offer on how life is viewed and understood. Knowledge gained through the research and development of synthetic biology has already contributed to new understandings of nature and organisms and more specifically in the understanding of DNA processes and the purposes of individual genes as well as the discovery of millions of new genes. Basic methods used for rearranging gene or genome sequences as used by various biological disciplines, have been improved to be less time-consuming (Garfinkel *et al.*, 2007:16–18; Kaebnick, 2014:816; Parens *et al.*, 2009:14).

It is easy to argue that the benefit of learning new things surpasses any objections, but some critics have intrinsic concerns that any organism has “worth in itself” (Link, 2013:436) and as such the specialness and sacredness of life comes into question. Synthetic biology is opposed because it might degrade nature (Kaebnick, 2014:821), where life as something unique and not fully understandable or creatable is replaced with a human replica. Link (2013:436–437) supports the idea that life holds intrinsic value and then questions if synthetic biology crosses a line by creating artificial life, by replacing natural life with un-natural life. Though not an ungrounded concern, there is no guarantee that artificial life would not hold intrinsic value.

A fundamental purpose and goal of synthetic biology is “to deconstruct life” and as Craig Venter has proven, synthetic biology also aspires “to build life” (Kaebnick, 2014:812; Rodemeyer, 2009:16). The multidisciplinary aspect of synthetic biology promotes this deconstruction-construction approach to science, because it is after all a characteristic of engineers and programmers to take something apart to understand how it works and then put it back together with a few improvements (De Lorenzo *et al.*, 2006:127). Hence, “biological machines” is a key term within the field of synthetic biology (see e.g. Rodemeyer, 2009:17; Sparrow & Brady,

2007:50) and is a clear indication that the microorganism designed and manufactured is not only alive with intrinsic value, but also has instrumental value. It is a living organism created to fulfil a function and task.

Reasonably, the question of the rights and moral standing of artificial organisms arises. However, according to Attfield (2013:26-28), biocentrism maintains that all living things have their own moral standing and rights, but that some rights may be more important than others. For example, the moral rights of plants must be suspended to accommodate animal and human consumption, because they need to eat to survive. Thus it can be said in agreement with Attfield (2013:28) that not all living creatures have equal moral standing. However, artificial organisms are alive, and thus receive rights within this framework.

There is a radical difference between the traditional biology and synthetic biology approach to studying life, but new ideas will always encouraged scientific development (O'Malley *et al.*, 2008:63). For example creating a synthetically heart or liver that is genetically fully compatible with the patient would reduce the risks of a normal transplant due to organ rejection (Hutson, 2011). This in turn leads to the improvement of human lives and thus growth within society as a whole (Hutson, 2011). Synthetic biology can produce original research so groundbreaking that it can change how we see and interact with nature and conduct biology (Brehm *et al.*, 2005; Church, 2005:423). Some nevertheless question exactly where synthetic biology will lead. Would it eventually, in the not too distant future, encompass the synthetic creation of animals or even the synthetic modification of humans? (Parens *et al.*, 2009:25) These fears originate from the aspiration to create synthetic body parts or bio-organs, such as the abovementioned heart or liver for a specific individual. Some critics fear that a fully synthetic human will be produced. However, this fear is at present ungrounded because (as confirmed by Murray, 2010) synthetic biology is still only concerned with micro-organisms and a long way from more complex life forms.

Bioinformatics is an emerging subfield that aspires to reduce the complexity of microorganisms. "[T]he development of computational models to analyze, simulate and predict the behavior of artificial and synthetic systems" (De Lorenzo *et al.*, 2006:128) combines information technology with biology. Synthetic biologists use computerised models to plan and simulate what they want to synthesise and consequently bioinformatics is vital to the further development of synthetic biology as a discipline. Bioinformatics link the knowledge-based aspects of synthetic biology research with the actual production of new organisms. By developing creative ways to program biology, new techniques and methods are developed that can be applied to other fields.

3.3.2 Renewable energy benefits

The research and development of biofuels is a valuable product-based benefit of synthetic biology, because the bulk of funding is received for research into renewable energy that is more eco-friendly than current fossil energy sources. As such, research focuses on the improvement of current scientific and industrial processes for producing biofuels to supplement and eventually replace fossil fuels (Gerotto, 2009:19) and establishing reusable energy as the main generator of power. According to the PCSBI (2010:57-62), there are two branches of research regarding the production of biofuels, namely the creation of photosynthetic organisms that use the sun as energy and the creation of organisms that use biomass as energy source.

A photosynthetic organism would most likely be a type of algae that can survive on land or in water and would absorb the sun's light as well as carbon dioxide to secrete useful bio-oils and as a by-product can reduce carbon emissions (Parens *et al.*, 2009:14; PCSBI, 2010:60). Another branch of research is to use synthetic biology to create organisms that secrete bio-alcohols like ethanol, butanol or even biohydrogen from sugar cane or cellulose biomass (PCSBI, 2010:57–62). Here, the problem of biosafety becomes evident, which can be described as "concerns regarding the prevention of unintended consequences" (Schmidt *et al.*, 2011:327) or the possibility of unplanned contamination.

Accidental contamination poses potential health risks such as the possible long-term effects of synthetic organisms in close proximity to humans and the likelihood of causing sickness or an unexplained genetic mutation (ETC Group, 2010:38; Kaebnick, 2014:817). Critics are concerned about the cost to whole ecosystems if a synthetic organism mutates from its safe and controlled form (ETC Group, 2007:43-44). Plausibly, this could be seen in the consequences of releasing transgenic crops in the 1990s, that has led to a low-level contamination of the engineered genes worldwide (ETC Group, 2010:38–39). Such fears, while not ungrounded, are highly improbable because genetic engineering and genetically modified microorganisms (GEMs) have already proven that natural life forms are more resilient than artificially created organisms. Research has shown that if GEMs are extensively modified, they are less likely to survive in nature when taken from a controlled environment (De Lorenzo, 2010:929).

If this does not alleviate the critics' concerns, Schmidt *et al.* (2011:328-329) moreover recommend using the NASA guidelines for unnatural synthetic biological agents to promote biosafety for synthetic biology. NASA requires space samples (e.g. from Mars) to be considered hazardous until proven otherwise through "physical, chemical and biological analysis" and this principle should be applied to work with novel synthetic biological organisms and systems. Such a framework of thought is in line with the precautionary principle discussed later in the chapter.

3.3.3 Biomedical benefits

Biomedical research promotes the advancement of human health care (Pei *et al.*, 2012:160). Synthetic biology can make medical care more cost-efficient and anyone, regardless of income, would then be able to afford healthcare (Church, 2005:423). Research and funding are mainly concerned with the development and production of biopharmaceuticals in the form of drugs and vaccines. Research is being done into making medicines more effective against specific diseases such as cancer by tailoring them to an individual patient (PCSBI, 2010:64–65). Similarly, research on vaccines focuses on building up a database that will reduce the time it takes to identify a virus and then on developing methods to create a DNA-based vaccines “on the spot” for the specific strand of virus (PCSBI, 2010:66).

It must be noted that such tailor-made use of synthetic biology has sparked concerns regarding biosecurity, which is defined as “dealing with potentially harmful misuse of unnatural biological systems” (Schmidt *et al.*, 2011:327) and include aspects such as bioweapons and bioterrorism. The creation of plagues or the weaponisation of existing viruses by terrorists, e.g. Spanish flu, smallpox, the H1N1 virus or the ebola virus (ETC Group, 2007:24–25; Parens *et al.*, 2009:15–17; WHO, 2014) cause significant concern regarding the governance of synthetic biology. Despite these fears, the current reality is that synthetic biology is still too hazardous and unstable to be truly effective as a weapon. Moreover, there are cheaper and more trustworthy methods to create bioweapons (Rugnetta, 2014; Murray, 2010).

The anti-malarial drug artemisinin is a prime example of how synthetic biology can reduce the cost of drug manufacturing (Rodemeyer, 2009:20). There does seem to be concerns about the livelihood of the people whose produce are replaced by synthetic products (ETC Group, 2010:40), such as the farmers of wormwood. Such farmers will not have any demand for their product if the production of artemisinin becomes fully commercial. Linked closely to this concern is the use of corn, sugar cane or cellulose biomass as food source for microorganisms, which could lead to the land used for food production (such as grain) being used to provide competitively priced materials to supply synthetic biologically produced items (ETC Group, 2010:28, 44). At the moment synthetic biology is not close to commercial implementation that would result in such drastic consequences.

3.3.4 Continual expectations and growth

There has been considerable growth in the research and development of synthetic biology across the globe, but the foremost ventures are in the United States and Europe. The following three studies provide evidence of the continual thrust and expectation for synthetic biology research.

Pei *et al.* (2012:159–160) investigated the funding of synthetic biology in Europe and found that the UK, Switzerland and the Netherlands have funding available for synthetic biology research. Both the UK and Switzerland have established research communities and the Netherlands has an emerging synthetic biology community. Austria and Germany show that potential funds would be available, but in France there is a lack of funds for synthetic biology research and development. However, France already has an existing synthetic biology research community. Germany has an emerging community, while there is basically no research community in Austria. The significance of this study is that synthetic biology research and development differ considerably based on where it is located. It is prudent to assume that the next breakthrough from Europe will happen in either the UK or Switzerland, as those are the only countries with both abundant resources and participants.

A study by the Woodrow Wilson International Center for Scholars (2010:2) looked into the difference in synthetic biology funding in the US and European Union (EU) and found that between 2005 and 2010 the US spent \$430 million and the EU \$160 million on synthetic biology research. Figure 3.3.4–1 (Woodrow Wilson International Center for

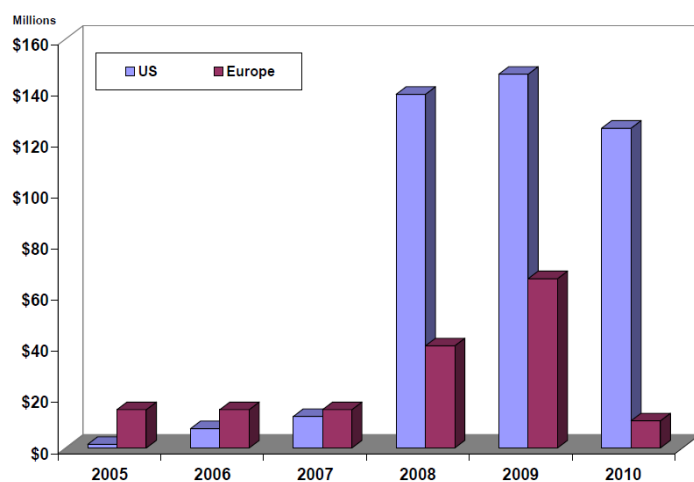
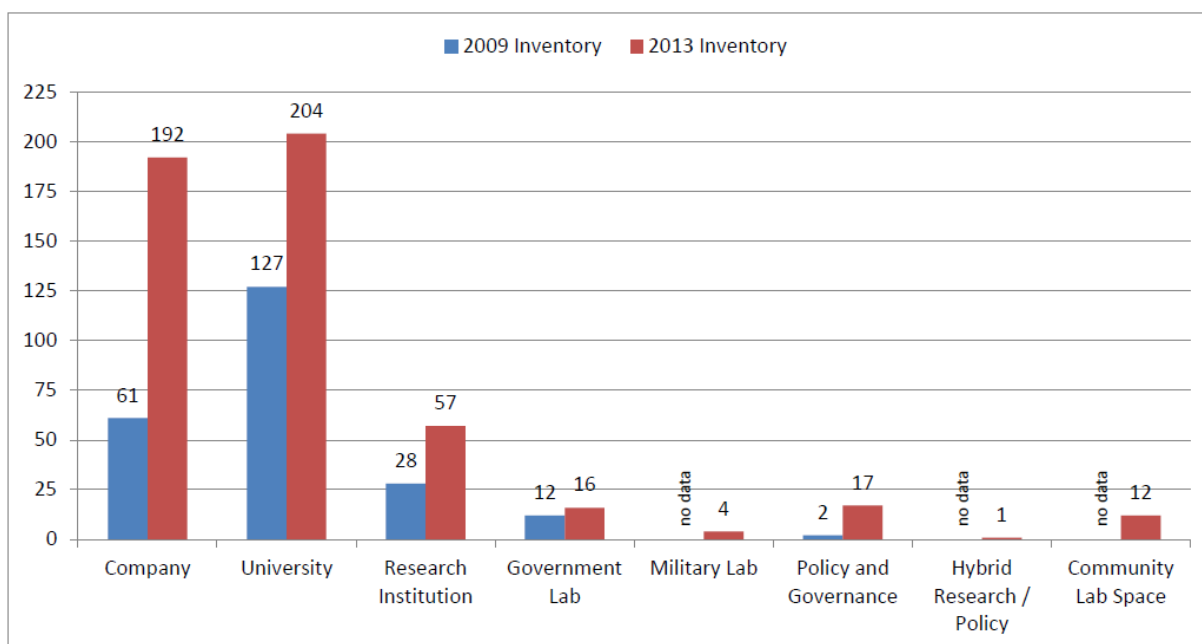


Figure 3.3.4–1 Funding in US and Europe 2005-2010

Scholars, 2010:2) indicates his findings per annum between 2005 and 2010. It is noteworthy that at the beginning of 2008 major funding moved from the EU to the US and showed significant increases in funds spend (averaging below \$20 million in 2007 to an average of about \$100 million in 2008). Further investigation has revealed that synthetic biology is primarily based within the US, rather than the EU. The contribution of the US to research and development is confirmed by the fact that all four the pioneers of synthetic biology (Drew Endy, Craig Venter, George Church and Jay Keasling as discussed in Chapter 2) are based in the US.

Lastly, a worldwide survey done by The Wilson Center (2013:2) indicates that entities involved with synthetic biology research and development are for the most part private companies, universities, research institutions, government laboratories and military laboratories. Figure 3.3.4–2 (taken from The Wilson Center, 2013:4) shows how the number of various entities involved with synthetic biology has changed between 2009 and 2013. Since 2009 the entities have increased from 278 to a new total of 508 in 2013.



Note: The categories "Military Lab," "Hybrid Research Institution/Policy Center" and "Community Lab Space" were not tracked in 2009.

Figure 3.3.4–2 Worldwide growth 2009-2013

As apparent in Figure 3.3.4–2, in 2013 universities conducted most of the research, demonstrating the willingness of the scientific and academic community to support synthetic biology, because they have invested time, effort and money into the potential benefits promised by synthetic biology. People want to believe in the potential of synthetic biology to solve economic, environmental and medical problems (Mackenzie, 2013:11). The problem of an overall moral objection to synthetic biology remains.

Some people feel synthetic biology is out of bounds and that humans should not even attempt it. In a 2010 research survey done in the US (as explained by Murray, 2010), a quarter of the participants felt it was morally wrong to create artificial life. Unfortunately, the study did not give participants the option of indicating why they felt it was wrong. The other major oppositions to synthetic biology were possible bioweapons, scoring just over 25%, and negative health effects, scoring just under 25%. These results concur with the findings of a small qualitative study regarding public perceptions of synthetic biology done by Hart Research Associates (2014). In addition, they found that as long as synthetic biology only encompasses microorganisms, no one is actually very alarmed by such moral objections, for example *creation of life* concerns. The Hart Research Associates (2014) study's findings confirmed previous research from 2011,

indicating that the public is optimistic about benefits (such as medical developments and environmental improvements), but concerned about risks (such as unintentional contamination).

The outcomes of these studies indicate that governments and scientific communities mostly support the further research and development of synthetic biology, but that the public and civil society organisations (such as the ETC Group) exhibit misgivings and uncertainty regarding synthetic biology as a whole. Granted, the concerns of The ETC Group are thoroughly researched and based upon fact, but one cannot say the same for public opinion. Regardless, in the end the support given by scientific communities and governments for synthetic biology grant it credibility as a suitable discipline to practise.

The benefits (both knowledge-based and product-based) are the reason for the major growth spurt in the research and development of synthetic biology and the continued growth in interest into the field. Even after over a decade of research, synthetic biology remains a buzzword. Preliminarily, this author supports further research and development of synthetic biology, but must acknowledge that there are still noteworthy issues regarding *how* synthetic biology is practised. At present there is little to no governance or regulation of synthetic biology, a state that cannot be left as is. The next section illustrates two frameworks that might be used to deal with the issue of how to safely and carefully practise synthetic biology.

3.4 Governance and regulation: Two possible frameworks

Most concerns are motivated and expanded by fear, more specifically the fear of the unknown. According to Murray (2010), people react in distinctly different ways when they cannot predict with reasonable certainty what will happen. Regarding the concerns for synthetic biology regulation and governance, these reactions are according to either a proactionary or precautionary framework or principle (Parens *et al.*, 2009:18).

A proactionary framework considers new technology to be “safe, economically desirable and intrinsically good unless and until it is shown to be otherwise” (Parens *et al.*, 2009:18) and can be explained by the phrase *when in doubt, go ahead!* (Murray, 2010). The supporters of synthetic biology mostly display this paradigm (Parens *et al.*, 2009:26) and use the potential benefits of synthetic biology to support their beliefs.

The critics of synthetic biology largely adopt a precautionary framework “which suggests that new substances should be considered dangerous until shown to be safe and that new technologies should be considered potentially threatening to ways of life and systems of meaning” (Parens *et al.*, 2009:20-21, 26) and can be explained by the phrase: *when in doubt,*

pause (Murray, 2010). They in turn use the potential harms and risks to motivate their arguments.

Both groups, however, agree that measures must be taken to prevent any potential physical harms and that it should be done through governance and public engagement (Parens *et al.*, 2009:18). According to Parens *et al.* (2009:18-19), proactionary supporters encourage public engagement by educating the public about synthetic biology and specifically how it can benefit each individual. They also support minimal governance options for synthetic biology, such as self-regulation to ensure continual growth. In contrast, supporters of the precautionary principle promote safety by slowing down new research to encourage extensive safety precautions, such as strict external and governmental regulation (Parens *et al.*, 2009:21, 26). Accordingly, supporters of the precautionary principle see public engagement not as an educational tool, but rather as a platform for the public to criticise new technologies such as synthetic biology, to try to gain public consensus regarding its further development (Parens *et al.*, 2009:22).

At this stage, the proactionary principle is being implemented worldwide, because no governing body will support and enforce standardised regulations for synthetic biology research, regardless of attempts to change. According to the ETC Group (2007:46-51), discussions regarding the regulation of synthetic biology began as early as October 2004, leading to an open letter from 38 civil society organisations urging the scientists attending the SynBio 2.0 conference in May 2006 to advocate for stricter regulation of synthetic biology. There was a response that included self-governance, but not the clampdown the writers of the letter hoped for. In their report, the ETC Group called for more regulations concerning social acceptability of synthetic biology, synthetic biology's wider socio-economic and ethical implications and the establishment of an international body to monitor and assess societal impacts of emerging technologies. They have not been implemented.

The ETC Group is a leading example of a precautionary attitude and approach. They have published two reports on synthetic biology (in 2007 and 2010) that advocate stricter regulation of synthetic biology and caution in further development (ETC Group, 2007:49–51; ETC Group, 2010:55-56). For example, in their recommendations regarding deliberate misuse or unintended consequences, the ETC Group (2007:50) stated:

[I]n keeping with the Precautionary Principle, synthetic microbes should be treated as dangerous until proven harmless. At a minimum, environmental release of *de novo* synthetic organisms should be prohibited until wide societal debate and strong governance are in place, and until health, environmental and socio-economic implications are thoroughly considered.

The Presidential Commission for the Study of Bioethical Issues regarding synthetic biology took a stance more in line with the proactionary principle that should “maximise public benefits, minimise risks, and observe appropriate ethical boundaries... [such as] responsible stewardship... [and] intellectual freedom and responsibility” (PCSBI, 2010:112, 123, 141).

The regulation of synthetic biology has always proven difficult, because initially (and even now) it does not drastically differ from traditional genetic engineering (Murray, 2010). One could conversely argue that genetic engineering has actually paved the way for synthetic biology and existing regulations should offer enough governance to prevent any major problems. Each reader and synthetic biologist has the choice to support either a proactionary or precautionary approach to the debates regarding governance and regulation. This author supports a proactionary framework because it encourages innovation and discovery from any scientist, be it a professor of engineering such as Jay Keasling, or an undergraduate student competing in an iGem competition. The clampdown proposed by advocates of the precautionary principle would restrict further development of the field. The author acknowledges that some form of global regulation should be established, and concurs with Church (2005:423) that “[s]ynthetic biology also needs to distinguish itself as a safe community effort that nurtures responsible practices and attitudes”. This means that more efforts are needed to accommodate the concerns posed by the public and civil society organisations, but not to such a degree that research comes to a standstill. A balance must be found between the freedom provided by self-regulation and the safety assured through external regulation.

3.5 Preliminary conclusion

The aim of Chapter 3 was to rationally discuss the benefits and risks of synthetic biology and it came to the conclusion that further development of the field is reasonable and should be encouraged. There are nevertheless concerns about practising synthetic biology, because of the absence of definite regulations or governance. Without any form of formal regulation or governance it is almost impossible to know what is going on in the field. At present, the proactionary framework offers a compromising solution to freedom of information and safety precautions, but does little to prevent nonessential contamination. A new framework of thought that provides balance between safety and innovation must be developed and implemented.

Chapter 4 - A Reformed ethical assessment of synthetic biology

what is mankind that you are mindful of them,

human beings that you care for them?

You have made them a little lower than the angels

and crowned them with glory and honour

– Psalm 8:4–5

4.1 Introduction

In Chapter 3, synthetic biology was evaluated from a rational perspective, using rational arguments to weigh synthetic biology's benefits against its potential harms. In contrast, this chapter is focused on how synthetic biology holds up against Biblical themes. Christians can and should participate in bioethical debates, but they must always remember that their "Christian faith has radically transformed their perspective on many important issues of life and death" (VanDrunen, 2009:29). As such, this chapter aims to illustrate how Reformed theology may evaluate synthetic biology and thus influence such perspectives.

The ethical framework for this study is built on the foundations of creational, re-creational and eschatological perspectives. While there are three perspectives, each with a specific focus, they must rather be treated as different angles on one principal foundation: the creation of God (Heyns, 1982:89). The work of the Father in the creation perspective cannot be excluded from the redeeming work of Christ in the re-creational perspective or removed from the hope awakened by the Holy Spirit in the context of the eschatological perspective. The main theoretical theme used for examining synthetic biology is the creational perspective (Vorster, 2004:80-82), which has a direct influence on synthetic biology. Due to time and space constraints, the main argumentation and focus is allocated to the creational perspective. The re-creational and eschatological perspectives are used to illustrate how synthetic biology fits into overall Christian ethics.

In this chapter, the focus of the creational perspective is on God who creates new things, but also the place of humans within creation, as well as the influence of sin. The re-creational perspective discusses how believers should mimic Christ. The eschatological perspective looks at the contrast between the present and the eventual fullness of time. These theoretical frameworks are continuously applied to synthetic biology. In the final section, a preliminary conclusion is drawn in the form of a theological evaluation. In short, this chapter will attempt to explain that synthetic biology is acceptable from a Reformed theological perspective.

4.2 The creation perspective

4.2.1 The God who creates

The Bible commences with the tale of creation in Genesis 1 to 3. It describes how God *triune* created the universe from nothing and established an order that regulates life. God the Father created the universe through the Son and together with the Holy Spirit (Erickson, 2013:344; The Belgic Confession: Article 8, 9, 12 & 13). Reformed theology holds that God created everything with a plan and instantaneously by willing and speaking (Erickson, 2013:342). This is confirmed in Psalm 33:9: “For he spoke, and it came to be; he commanded, and it stood firm.” God uniquely creates the universe with the purpose of exhibiting his glory (Psalm 9).

The significance of the creation perspective for Christians is that humans are dependent on God (Hoekema, 1986:5). This dependency is not limited to humanity’s initial creation, but they continually depend on him to live. Psalm 104 emphasises how God cares for all creatures and verses 29–30 specifically explains how God controls life and death: “... when you take away their breath, they die and return to the dust. When you send your Spirit, they are created...” However, God limits himself by giving creation the freedom to live, grow and evolve (Berkhof, 1990:158; Polkinghorne, 2006:61). What is tremendous is that God created the universe from nothing. This type of creation (from nothing) is called *creatio ex nihilo*.

God’s creation from nothing has sparked various debates about what the “nothing” of *creatio ex nihilo* entails (Fergusson, 2007:79–84). Some scholars hold that the nothing is an unknown substance that existed without form or shape. It is a so-called base matter from which God created, described by Fergusson (2007:80) as a “shadowy substance suspended between being and not-being”. This notion is directly contradicted in the account of God’s creation in Genesis 1-2. The tale of creation describes the universe as “formless”, “empty” and “dark”. This is rather a better description of a void than “matter” which supports the original claim of nothing, actually being nothing.

Accordingly, the nothing of *creatio ex nihilo* would rather mean the absence of anything and thus implies nonexistence or as described by Erickson (2013:342): “[n]othing, rather, is the absence of reality”. Fergusson (2007:80) also supports this notion: “in this respect ‘nothing’ simply denotes ‘not something’ ... what does not exist”. Regardless of what the nothing entails, the Bible supports the concept of *creatio ex nihilo*. In the Old Testament, Job 38 describes how God “laid the earth’s foundation”. The New Testament verifies this in Hebrews 11:3 “By faith we understand that the universe was formed at God’s command, so that what is seen was not made out of what was visible” and also in Romans 4:17 “... the God who gives life to the dead and calls things that are not as though they were”.

In his exploration of why God's *creatio ex nihilo* cannot be replicated by humans, Dabney (1972:251) stresses that to create anything out of nothing would require an "exertion of infinite power" and "infinite powers of understanding" and a "perfect acquaintance" with the laws of nature (see also Romans 1:20). It is thus no wonder that synthetic biology is only concerned with simplistic microorganisms, because humans cannot create something out of nothing. They can only create new things from existing matter.

From an ethical standpoint, the essential aspect of God's *creatio ex nihilo* is that he creates something new for the *first time*. The creation of the universe is truly a primary creation and exhibits God's greatness and creativity. Spykman (1992:159,160) argues that the "nothing" of God's *creatio ex nihilo* illustrates creation without any predecessor and therefore something entirely new. As such, *creatio ex nihilo* cannot only be seen as creation out of nothing, but also as the first creation of something new. Pannenberg (2006:364) rightly adds that "the notion of *creatio ex nihilo*, therefore, does not only apply to the first beginning of the world; it applies to *each* act of creation of something genuinely new in the history of the world". God does not stop creating after the initial *creatio ex nihilo*, but is at present still the same Creator as he was at the beginning of the universe.

God creates continually by maintaining and preserving his first creation. This method of creation is termed God's *creatio continua*, meaning that God does not stop creating. He continues to sustain everything in the universe moment by moment (Copan & Craig, 2004:161). *Creatio continua* could be seen as God's acts throughout creation and how he influences every adaption and mutation (Pannenberg, 2006:364). According to Moltmann (1985:209), the *creatio continua* can be regarded as God's preservation and providence of the world. This notion is supported by Vorster (2011:92): "The Spirit of God is present everywhere and sustains, nourishes and gives life to all things in heaven and on earth."

Creatio continua can be seen in the enduring creation within nature, such as when God creates new mountains, rivers and underwater rifts and ecosystems. Psalm 104:30 explains that God "renew [the] face of the earth". God also continuously creates new entities when an organism evolves and becomes different from its ancestor. Basic evolutionary theory is supported by *creatio continua* since "every new plant, animal or man means the origin of something new" (Berkhof, 1990:216). A last example of God's *creatio continua* is in his creation of human circumstances and situations. God created new opportunities for Israel, for example by saving them from Egypt and giving them Canaan. How God is involved in history, not just of events but also developments, is revealed in how he creates "new things" (Isaiah 43:19, Isaiah 48:7). Another opportunity is when he newly creates and then re-creates the covenant with his people, which reaches its peak in the salvation in Jesus Christ. God thus not only creates opportunities,

but he creates a new covenant and new humans when they become his children. As such the *creatio continua* is actually very similar and in some ways identical to God's *creatio ex nihilo*, although God acts through mediums such as humans or technology.

The ethical implications of the doctrine of creation are that God created the NEW universe with *creatio ex nihilo* and also creates NEW things with *creatio continua* throughout history. As such, according to Polkinghorne (2006:60), God is as much the Creator today as he was when the world began. However, God does not stop in the present but promises a new world for believers to live on when the fullness of time has come (Isaiah 65:17). "God created new things in the past (*creatio ex nihilo*), he presently creates new things (*creatio continua*), and he promises that he will create new things in the future" (Rheeder, 2014b). Consequently, an eschatological anticipation is created by believers who hope on a new heaven and earth.

Although synthetic biology is a process that humans use to create, God is still present and influences how each organism lives, grows and mutates (Moltmann, 1985:211). When Jesus teaches people not to worry in Matthew 6:25–34, he specifically mentions how God cares for creation. "Look at the birds of the air; they do not sow or reap or store away in barns, and yet your heavenly Father feeds them. Are you not much more valuable than they?" (verse 26). God is not only involved in the growth, development and evolution of naturally occurring organisms (König, 2001:87), but also in genetically engineered or synthetic organisms. This is because even though synthetically created by humans, they are after all alive and God is involved in the lives of all living things.

4.2.2 Humans as image-bearers

It has been established how God creates and that he creates new things, but some thought must be given to his creations. God creates all living organisms from bacteria to animals and humans. Humans are created in God's image (*imago Dei*). *Imago Dei* means that God creates humans as his representatives on earth. This implies that humans are similar to God, as *imago Dei* literally means "to mirror God and to represent God" (Hoekema, 1986:67); and in this, humanity is given the command to be a steward rather than oppressor of creation. *Imago Dei* is not some physical manifestation of God, as it is established that God is spirit (John 4:24). The essence of *imago Dei* is part of human nature and thus universal in all humans, regardless of gender or race; all are represented within *imago Dei* (Erickson, 2001:175–176). *Imago Dei* indicates that humans are similar to God (König, 2010:170). *Imago Dei* is not confined to Christians, although it is the most visible within them because their actions should amplify how God is (König, 2010:165).

It might also be prudent to look at the rest of creation in relationship to humans as God's representatives. Although humans are part of creation, they are also *imago Dei*; therefore God charges them with an additional mandate apart from "be fruitful and increase in number" given to all organisms in Genesis 1. Humans are the responsible stewards of God's creation. In Genesis 1:26–28 God created humans (men and women) in his image and gave them a divine mandate to rule over creation in his stead. *Imago Dei* links closely with the divine mandate to "... fill the earth and subdue it. Rule over the fish of the sea and the birds of the air and over every living creature that moves on the ground" (Genesis 1:28). Humans are charged with creation's safekeeping, but also its development. The tasks of stewardship thus not only call for preservation but also acting towards the promotion of a right to life and the improvement of all circumstances of life (thus rule **and** preservation). This order is not only a God-given privilege, but also a responsibility; humanity is called to be responsible stewards of the earth as God's representatives (Vorster, 2004:256). Believers should therefore promote the protection of all creation and be vigilant regarding the development of technologies that influence creation.

Life is not static but rather diverse and continuously changing. As such, humans as stewards must also adapt to the changes to care and protect nature. This is also true concerning all other life forms, because they do have value. *Creatio ex nihilo* shows God's initial creation of the world, including where he created all life forms with their own unique worth. They are valuable as is and not only as a means to an end. God finds all animals inherently valuable because he created them as independent creatures and not simply because they are beneficial to humans (Fergusson, 2007:84; Vorster, 2011:101). *Imago Dei* places humans in a direct relationship with God, but also with other humans (Vorster, 2011:92-93) and God's other creations. As explained by Vorster (2011:91), humans and animals are tied together through a shared earth. Accordingly animals and humans together form a "community of creation" because God saw and judged each individual and all together as a whole to be good (Genesis 1:31). This is evident in the fact that God still cares for creation; he preserves and supports it every day (*creatio continua*). As expressed by Vorster (2011:91), "each living creature has dignity because God dwells in it through his Spirit and sustains it". This relationship motivates the desire to be responsible stewards for God, but the mandate is actually a synecdoche in nature. Being responsible for nature is the bare minimum, but humans must be more than that – they must genuinely care for nature. Vorster (2004:81) emphasises that humanity has a responsibility towards God's creation, other humans and nature, to promote and preserve all forms of life. Humans should therefore follow God's example of respecting all forms of life, even those that are artificially modified or created.

The ethical implications of the *imago Dei* are that humans are called to mirror God in actions and essence. In Micah 6:8 it is then apparent that humans must follow his example: "And what

does the Lord require of you? To act justly and to love mercy and to walk humbly with your God.” Humans must thus attempt imitate their Creator. We are like God and consequently God must be visible in us (Hoekema, 1986:13; König, 2010:170). Humans must as a result look to Jesus Christ as the perfect image of God and strive to mirror his actions (Vorster, 2011:17). The new person in Christ is called to new actions and behaviour (Ephesians 4:22–24) and to follow Christ’s example. This also holds true in the lives of present-day believers. For example, believers are called to love because God is love (1 John 4:16). Or as indicated in Leviticus 11:44–45, Israel is called to be holy, because their God is holy. The same principle can be applied to creation. God creates, and to mirror and follow his example, humans have to create. Humanity should care for creation, but also care for life through the act of creation.

It is because we are like God that he calls us to follow his actions. However, one must keep in mind how God creates, because God does not create as humans do. As mentioned by Fergusson (2007:83): “the concept of creating [is] sharply distinguished from making or changing”. God creates *ex nihilo* and *continua*, but always something new. Humans cannot precisely replicate his *creatio ex nihilo* in the same way God does, because they are limited. Humans are restricted by the physical world, but God creates without any restrictions (Erickson, 2001:133). He created *ex nihilo*, new things without any bounds. God can give new life when he creates (Nehemiah 9:6), something that humans do not even fully understand. Their intellectual creation, imagination and creativity are the only way in which a semblance of God’s creation can be seen. Human creativity results in the development of the intrinsic potential within God’s creation (Atkinson & Field, 1995:271). However, human creations always remain secondary because there is always some primary influence present (Spykman, 1992:159, 160). Nor can humans create continuously in the exact same way as God does, but they do constantly look for new things to create. Humans not only create through physical actions such as art or construction, but also through intellectual creations and by choosing and adapting to new situations. It is especially in such creation that it is evident that God creates through humans.

Humans can be seen as co-creators with God. The idea of co-creators is explained by Cole-Turner (2006:942) as part of a biotechnology perspective resulting in God’s acting through humans and technology to still create today: “The vision of ‘co-creation’ is that through biotechnology we can accompany God’s own continuing creative work, which because of technology can operate now at a wholly new level.” Admittedly, the designation of co-creator does not presume that humans are on the same level as God, and they are not equal partners. Humans can rather be seen as junior trainees (Cole-Turner, 2006:943). God works through humans to accomplish his goals. Consequently, God uses humans to create new things and as explained by Atkinson and Field (1995:835), “technology should be done for the purpose of

creation-care and human benefit within the limits of the demand for justice and love”. It can thus be concluded that synthetic biology fulfils part of this mandate concerning ruling or developing natural resources. It aspires to create better life circumstances for humans by improving and healing nature. Atkinson and Field (1995:833) therefore motivate that “technology may be thought of as a human response to the divine mandate responsibly to open up the potential of creation”.

From the above it is evident that God is the Creator since the beginning of the universe (*creation ex nihilo*) and of new things since then (*creatio continua*) and humans as his representatives (*imago Dei*) should follow his example and create new things as well. God can therefore use both humans and technology through which to create new things. There appears to be two opposing arguments to synthetic biology as part of the creational perspective. Firstly, humans apparently attempt to “play God” by creating that which should be forbidden (Dabrock, 2009). This dispute does not hold ground when considering that humans are called to mimic God. The second argument holds that synthetic biology appears to devalue life by creating mechanical organisms (Rheeder, 2014b). This intrinsic concern was discussed in Chapter 3. However, as mentioned, God creates all beings with both inherent and functionality value, but animals and plants are less valuable than humans. Therefore, synthetic biology can and must be used to improve human lives.

4.2.3 The implications of sin

The preceding discussion shows how synthetic biology is in principle a suitable technology and ethically acceptable as central part of God’s *creatio continua*. Admittedly, the influence of sin and the fall (as described in Genesis 3) must be addressed, because they have a major influence on all human life. As a consequence of the fall, all humans are born into a sinful world and their very nature is evil (The Belgic Confession, 2013: Articles 14 & 15). Hoekema (1986:75) established that there has been a “threefold relationship: between man and God, between man and his fellowmen, and between man and nature” since God’s *creatio ex nihilo*. However, all these relationships are tainted by sin: idol worship in place of God, the uncaring manipulation of others instead of loving them and the misuse rather than preserving of natural resources (Hoekema, 1986:84–85). However, Vorster (2011:13, 16) maintains the “consensus that sin does not destroy humans’ image but rather deforms and distorts it” and resultantly God preserves *imago Dei* in humans “in spite of sin”. As such not all humans can or want to fulfil God’s mandate to be stewards; they end up as oppressors. This is because they have ignored their responsibility to protect nature, leading to the current ecological crisis (König, 2001:89). Humans therefore attempt to use nature to harm one another. This is obvious when taking into consideration the existence and demand for bioweapons, for which synthetic biology has the

potential. Sin can and will corrupt the good intentions of synthetic biology if Christians do not remain vigilant. They must remain observant about the motivations of synthetic biology projects as well as the prevention of possible accidents.

4.3 The re-creational and eschatological perspectives

From the creational perspective, it is clear that humanity as *imago Dei* can use synthetic biology to create, because it is an extension of their creative potential. Granted, the re-creational perspective acknowledges that sin has corrupted all human intentions to follow God's guidelines. Despite such a blatant rejection, God does not leave humanity to suffer the penalty of sin. He engineered their salvation through the death of Christ. The re-creational perspective is founded on the salvation and re-creational work of Jesus Christ (The Belgic Confession, 2013: Articles 21–22 and 2 Corinthians 5:17). He firstly re-creates the broken relationship between God and humans by removing the barrier of sin (1 John 2:2). Humans can thus find their identity by living in a relationship with him (Vorster, 2011:19). God also restores the ethical nature and moral character of humans to what they were before the fall, but as Heyns (1982:95) points out, it is the same God who created and restored humans and thus their ethical nature is also restored to its original state, not created anew. What is newly created is humans' relationship with God through Christ which calls believers to a new life. Christ is the beginning of the new humanity (1 John 2:2 and 2 Corinthians 4). It is through the salvation in Jesus Christ that humanity can overcome its sinful nature and live a godly life.

Christ has re-created humans in his image, not as totally new beings, but by restoring them to the original state in which they were created (Colossians 3:10). However, this restoration is not for all humanity, but only for children of God who accepted his gracious salvation. It is only by accepting and proclaiming Jesus Christ as his personal messiah that an individual can be reborn, while individuals who reject Christ stay trapped within the sinful nature (Heyns, 1982:96). Christians that accept the gift of salvation receive the Bible as moral guideline in their new lives. This guideline is condensed into the commandment of love as explained in Mark 12:29–31. The new human in Christ consequently has a new, distinctive feature, namely love. Christians are thus called to always act in love (1 John 3:11, 14). They must firstly love God, which has the implication of obeying his commands and awakening the desire to glorify God, entailing all actions to be to the glory of God (*solī Deo gloria*) (Vorster, 2004:82). Believers change their purpose and motivation from self-centredness to God-centredness. This is because, as stated by Fergusson (2007:73) the “world was not made for human benefit, but for glory of God”.

Secondary is to love other humans and this results in looking out for and caring for others. This can also be applied to synthetic biology, because by loving our neighbours we try to improve

their lives. The consequence of such love is the development of medicines that can reach more people, because they can afford them. Synthetic biology also shows love when developing biofuels, because it will help protect and sustain nature. Christians will resultantly seek to use and practise synthetic biology to help others in love, as thanks to God and with the motivation of glorifying God.

The eschatological perspective holds that believers are outsiders in the current world and actually citizens of God's kingdom (Hebrews 11:13). They hold out in hope for the second coming of Christ to enter the eternal kingdom of God. According to Peters (1996:155) a Christian ethic should anticipate the tangible fulfilment of the future reality within the present reality (Mathew 6:10). Humanity should therefore live with the expectation that the promises of heaven will be partially fulfilled in the present. God gives believers the hope of a better home when in 2 Corinthians 3:18 he shows that humans are "being transformed into his image with ever-increasing glory", thus giving them hope for a better future. At present, we still live in this physical world, broken and filled with corruption and despair, but God continues to sustain it: "even while it is the arena of decay, suffering, conflict and in this world remains God's good creation" (Fergusson, 2007:78). Humans are thus still called to be responsible stewards, because God created this world and continues to maintain it through *creatio continua*. Vorster (2011:19) explains that the "restoration of the image is an eschatological gift that starts in the present, but that is only fulfilled in the future". As such, despite current despair, humanity can hope for a better future and a new home, because: "The cosmos is really our home. It will always create cosmic optimism since earthly existence is meaningful, not pointless" (Vorster, 2011:98). Humans therefore do not live pointless lives, because as illustrated in 2 Peter 3:10–14, believers should not neglect their current life on earth but rather are called to "live holy and godly lives" (v. 11). Christians "were redeemed from the empty way of life" (1 Peter 1:18) and given a new meaning in life by the salvation through Jesus Christ. This new meaning is hope. As explained in Isaiah 65:17, God "... will create new heavens and a new earth. The former things will not be remembered, nor will they come to mind". This gives believers hope to focus on rather than the current reality of pain and misery. Christians are encouraged to also give and inspire hope, because it alleviates earthly suffering.

The re-creational work of Christ has not been concluded, but moves everything towards the fullness of time (Vorster, 2004:83), where not only humanity but also creation itself will be healed and fully restored to its original glory. Romans 8:20-21 confirms this, "For the creation was subjected to frustration, not by its own choice, but by the will of the one who subjected it, in hope that the creation itself will be liberated from its bondage to decay and brought into the freedom and glory of the children of God". Vorster (2004:83) explains that the hope cultivated by humanity for such a future should clearly be seen in an "ethics of hope" that can restore hope in

a hopeless world (see 1 Peter 1:3–9). Furthermore, he explains that while current efforts of ethical evaluations and decisions are not perfect and everlasting, it should still be seen as a constant struggle to live according to God’s will. As such synthetic biology can be seen as a real attempt to better our current situation, and within the earth strives towards God’s re-creation. This function^s as a symbol of the new earth and heaven. It aspires to create new organisms, while still trapped within the “now.” Its benefits aim to improve the lives of believers by encouraging and consoling them. Synthetic biology gives hope by improving the circumstances in which people live through better and cheaper medicine or sustainable biofuels. The result is that hope is kept alive.

4.4 Preliminary conclusion

Reformed theology and ethics do not oppose synthetic biology in principle, because humans are called to mimic God in creating new things. Humans are co-creators, which can be seen as a fulfilment of God’s mandate to be responsible stewards of the Earth. Admittedly, the influence of sin in such a broken world cannot be ignored and humans act immorally because of it. It is only in Christ that they can be restored to goodness. The solution is to live as a steward, to be not only a ruler, but rather a watchman that will vigilantly protect God’s creation. Thus Christians have to be watchful of and oppose blatantly wrong attempts to corrupt nature. Believers must always measure to the standard: does it glorify God? In every situation, Christians look not only towards the final goal, but also at the motivation behind a synthetic biology project. “The blessing pronounced by religion upon technology is conditional, depending not so much on the quality of the biotechnology as on the moral maturity and spiritual wisdom of its makers and users” (Cole-Turner, 2006:930). The methods and uses of synthetic biology must be studied and evaluated on a case-by-case basis. In most bioethical issues, there will be more to the situation than meets the eye. While ethical decisions are merely temporal, they still motivate further searches for new answers and the examination of proposed answers. It is a call to all Christians to stay “ethically active” as living hope within a world filled with despair. (Vorster, 2004:84). In conclusion, Berkhof (1996:136) emphasises that the essential purpose of the creation is to glorify God. Accordingly, all synthetic biology’s creations should also be measured to this standard: Does it glorify the almighty God?

Chapter 5 – Conclusion: A final evaluation

Praise the Lord, all his works everywhere in his dominion.

Praise the Lord, O my soul.

– Psalm 103:22

5.1 The essence of synthetic biology

Synthetic biology is the latest phase in the development of genetically focused biotechnology. At first, natural organisms could only be observed and described through biology. This grew into manipulation through genetic engineering by using recombinant DNA (rDNA) technology to change specific characteristics. Synthetic biology goes one step further and offers humans the opportunity to design and create new organisms. Researchers such as Craig Venter aim to strip down a cell to serve as a chassis. Specific genes are then added to the basic chassis to change the cell's function as needed. Drew Endy's focus is to compile a directory of BioBricks that act as possible interchangeable parts during the construction of a cell. George Church subsequently wants to create a fully synthetic chassis. However, it is Jay Keasling that achieved the greatest success, holding on to his engineering roots to create the synthetic anti-malarial drug artemisinin. At this stage one can only speculate where synthetic biology will lead, but it is obvious that humans have the means to unlock its potential. This is especially evident in the explosion of synthetic biology in the US within the last 10 years, added to the advances in Europe. For the most part, research is still being done primarily by private companies and universities. Synthetic biology has not yet become commercialised, although it has already delivered on some of its promises.

Rational ethical arguments concerning synthetic biology rest upon the potential benefits and harms the field poses. The success of the International Genetically Engineered Machines competition (iGEM) has shown that minor victories can promote synthetic biology in major ways. It is no surprise that with the core aspects of education, research and excitement, the iGEM competition continues to grow and draw young scientists to the promise of synthetic biology. The iGEM competition consequently exhibits and endorses the two major benefits of synthetic biology, namely (1) increasing knowledge and understanding and (2) the useful application of such knowledge, for example in biopharmaceuticals and biofuels. The creation of the anti-malarial drug artemisinin is synthetic biology's poster child for success, but other research is being done to improve the efficacy of current medicines and vaccines. Renewable energy research using synthetic biology receives a great deal of funding. The development of biofuels such as ethanol or butanol that utilise sun energy or biomass from crop residues seems to be a new alternative

to fossil fuels. Research has shown that in general people are optimistic about the benefits of synthetic biology with regards to its medical and environmental aspects, but they are primarily concerned about unintentional contamination. Understandably, synthetic biology does pose certain dangers, and concerns include the possible exploitation of agricultural land or the development of bioweapons. The synthetic biology community does encourage the implementation of biosafety (avoidance of unplanned consequences) and biosecurity (possible dangerous misuse) to safeguard against potential issues.

The benefit of gaining knowledge and understanding of nature and life is very alluring. Some seem to question if nature would still retain both its intrinsic and instrumental value if it is comprised of artificial organisms. Such concerns lead one to question if current genetically engineered organisms then lose their intrinsic value. However, God makes all organisms with value, be they natural, engineered or synthetically created. They thus have moral standing and rights as part of God's creation. The God who creates new things from nothing (*creatio ex nihilio*) and continuously (*creatio continua*) also created humans as his representatives. As image bearers (*imago Dei*) the ethical implications are that humans can and must also create new things. It is humanly impossible to mimic God exactly, but through the act of creation of new things or replication of existing things, God's image is shown in a "human way."

God that re-creates humans and restores their relationship with him also expects them to form new relationships with other humans. Christians that are motivated by God's love should promote consideration of other humans. This is rooted in the act of mirroring God. For example, God is love, so humans should love; and God is holy, so humans should be holy. It calls believers not only to love and not harm their fellow humans, but encourages them to look out for the best interests of all living things. As such, synthetic biology is practised as an act of love; because one loves others, one wants to make cheaper medicine or fuel available to them. This positive, caring attitude and lifestyle leads Christians to hope for the new creation when Christ returns; the new creation where suffering and worries will be things of the past. Christians therefore try to realise aspects of this promised future in the present time by improving the lives of their neighbours. Humans must be responsible for other humans but also nature and consequently all life forms. They are the watchmen that guard over all of God's creation.

The doctrine of natural law provides a platform for Christian ethics to use rational arguments within a theological ethical evaluation. God reveals himself through creation and history where unbelievers have the opportunity to witness his grandeur. However, it is through his special revelation in Christ, which is preserved in the Bible, that believers receive a more comprehensive knowledge of God. Christian ethicists must therefore always be aware of the possible contribution of rational arguments to an ethical investigation. The rational arguments of

this study show that at present the benefits of synthetic biology trump the potential harms. That is not to say that there are no risks, but it rather acknowledges that the risks are insignificant when compared to what can be gained by the further development of the field. The sinful nature of humans triggers such risks. It causes humans to want to harm other humans and creation. Christian scientists and ethicists should be encouraged to remain watchful.

Christians can and should support the further the development of synthetic biology, because it is right and good to utilise the technology God has made available to humans. The implications for such support include the call for better governance and regulation. While the current proactionary approach holds that synthetic biology is essentially good until proven otherwise, there is pressure from the supporters of the precautionary approach (which sees synthetic biology as dangerous until proven good) to implement severely constraining rules for governance and regulation. Although such claims seem justifiable, genetic engineering has shown that rigid governance is unnecessary. This is because extensively modified organisms have proven in the past to be less resilient than their natural counterparts. The use of self-governance and standardised regulations as proposed by the proactionary group aims to promote the development of synthetic biology as a discipline. Educating the public and potential practitioners allows safety concerns to be addressed and present opportunities for new innovative growth.

5.2 Limitations and further research

This study was done for a Master's degree and it obviously posed time constraints on the scope of what could be done. The scope of the study mainly focuses on ethical evaluation using the creation perspective, with fleeting attention given to the re-creational and eschatological perspectives. A more comprehensive theological ethical study would benefit from a wider scope that not only gives more attention to the re-creational and eschatological perspectives, but might also include other perspectives, for example, a deontological perspective, or using life as a central theme as opposed to the creation theme used in this study. A further study could possibly focus on in-depth investigations and exegesis of specific biblical texts.

This study provides only one perspective from a third world context (e.g. South Africa) that does not have the same intensive focus on new biotechnologies as in first world countries. Interviews with synthetic biologists to determine their perceptions of the links between synthetic biology and religion could provide a basis for the construction of a theological moral code of conduct. Such a qualitative study could investigate if there are grounds for doubt about the development of synthetic biology. The term "playing God" is often connected to genetic biotechnologies. Surprisingly in current literature, the term does not seem to actually hold any ground, but empirical research could confirm or dispute these claims. Lastly, there must also be research

done into the practices of biohackers and overall safety precautions taken by synthetic biologists to be aware of further risks.

5.3 An evaluation

In closing, the research question (*Is synthetic biology acceptable from a Reformed theological-ethical perspective?*) is answered in the affirmative. Synthetic biology as a scientific technology is acceptable from a Reformed ethical perspective, because humans live out their *imago Dei* by creating new things just as God creates new things through *creatio ex nihilio* and *creatio continua*. This evaluation is supported by the rational argument that at present the potential benefits of synthetic biology surpass the risks it poses. This is, however, a provisional approval because Christians should always be careful of motives when dealing with ethical issues. How and for what synthetic biology is used in the future might see its support eroded. Since our current ethical understandings and evaluations are incomplete attempts, this motivates ethicists to look deeper for answers and stay vigilant in dealing with new technologies.

This study consequently encourages scientists to use and develop synthetic biology in a responsible way, maximising the benefits and minimising potential risks. Ethicists are called upon to vigilantly and continually monitor and guide the further development of synthetic biology. Consumers stand before a choice to support or oppose products produced by synthetic biology. This author appeals to Christians to not shy away from new technologies such as synthetic biology. God gives humans the ability to create new things and use technologies such as synthetic biology to the benefit of other humans. Through responsible development and use, humans can show love for others and provide hope for a better future. In the end, Christians should ask if their actions (through synthetic biology) glorify God.

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