Soft Exchanges for Interaction Design

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Abstract

The boundaries and fabric of human experience are continuously redefined by microorganisms interacting at imperceptible scales. Though hidden, these systems condition our body and the environment we inhabit. Instruments such as microscopes and satellites have allowed us to observe scales of human experience, situating circumstances between those we effect and those effected by us. Advances in synthetic biology are enabling us to interact with this microscopic world in new and unforeseen ways. This thesis proposes using the new access we now have into this world, and with which we do not regularly interact, to experience our own world differently.

Soft Exchanges are created through the design and development of a camera like instrument implementing the *Bactograph* protocol developed in 2005 by Jeffrey Tabor, Assistant Professor of Bioengineering at Rice University. Of the many advances in Synthetic Biology, a notable one has been that of Jeffrey Tabor and his laboratory in creating a new capability for Escherichia coli to detect light and produce high resolution chemical images as bacterial photographs. This work is furthered, to realize new interactions with the design and implementation of a biological instrument towards the development of Human Biological Interactions.

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To those moments across the Institute, that can be experienced no place else, and with no other.

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1. Introduction

"In the year 1657 I discovered very small living creatures in rain water."

-Antoine van Leeuwenhoek

We are now at a moment to move beyond observation of the microbial world and towards interacting with it, though the framework and tools with which to do so remain undeveloped in the popular imagination. Parallel transitions such as those in the domain of Human Computer Interaction, as a function of technical advancement in the design, engineering, and implementation of computers developed from 1945-1967 serve as reference.

Moving beyond the harnessing of electricity for computation produced a set of interactions to allow us use of this technology and create experiences and artifacts of cultural value. Much as the field of Human Computer Interaction has articulated our exchanges with electronic signals, Soft Exchanges question how to design for invisible signals in biological materials, and the potential for a novel form of symbiosis with human experiences.

In this chapter the premise of the thesis is introduced in three parts. In *Motivation*, the discovery and experience of microorganisms in the human experience is a starting point for the development of Soft Exchanges. In *Overview of the Thesis*, the following chapters are put in context with the development of the concept, prototyping and evaluation. In *Summary of Contributions*, the structure of how Soft Exchange may lead to the development of Human Biological Interaction is outlined.

1.1 Motivation

As we have built a world that allows us to become aware of the invisible world around us, we have not yet built the corresponding framework and instruments to imagine our interactions with it. Increasingly the view that humans are the center of their experiences is being challenged.

The opportunities today for the general public to interact with this world are limited beyond global epidemics such as the [1]West African Ebola outbreak in 2014 or the common application of hand sanitizers. But consider instances which have allowed us to

FIGURE 1:
HAND SANITIZER

[1] How Many Ebola Patients Have Been Treated Outside of Africa? (2014, July 30). Retrieved May 2, 2015, from http://www.nytimes.com/interactive/2014/07/31/world/africa/ebola-virus-outbreak-qa.html

initially observe it then subsequently manipulate it.

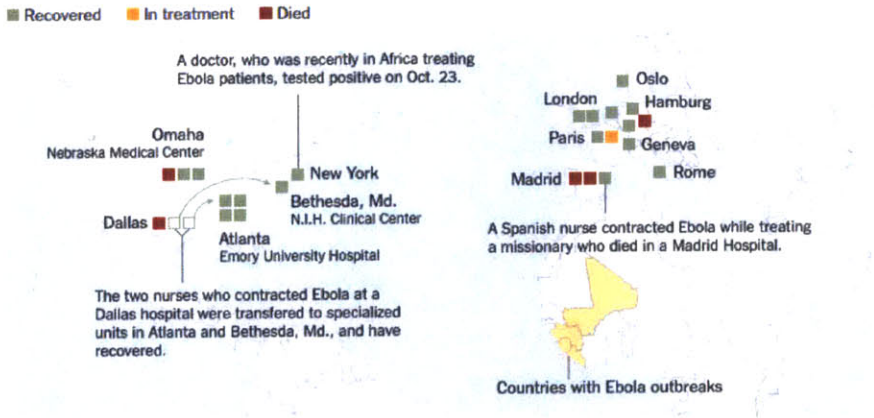

FIGURE 2: MAP OF THE EBOLA VIRUS OUTBREAK AS OF JANUARY 5, 2015

Antoine van Leeuwenhoek, by crafting optical lenses, advanced the making of microscope instruments leading to the identification of a previously imperceptible though essential layer of our environment. With this he saw what no one else had seen in a droplet of water, a microscopic world alive with "animalcules". From this moment on in 1657, we were granted access and have been exploring ver since what was there all along.

The significance of van Leeuwenhoek's instruments is that they were designed to produce a new set of experiences for the user. His microscopes and those that followed, enabled the viewer to enter momentarily the world of cells, offering the opportunity to engage with the material in relation to ourselves, by collapsing scales and expanding perceptions. The study of microbiology followed and has since continued to develop in fields as varied as medicine and energy production.

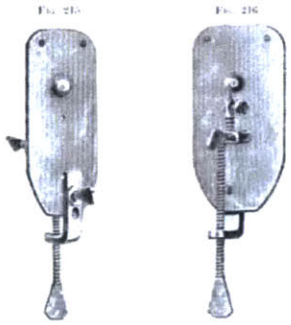

FIGURE 3: JOHN MAYALL DRAWING OF LEEUWENHOEK MICROSCOPE FROM THE JOURNAL OF THE ROYAL MICROSCOPICAL SOCIETY 1886

The transition from observing to manipulating biology is recent, and made most promising with the development of [2]CRISPR/Cas9 DNA gene editing protocol in 2013. The impact of increased control over cellular organization, regulation, and behavior is beginning to emerge most notably for gene therapeutics.

These discoveries are significant in that they represent relationships with materials other than ourselves. Repositioning the human experience in relation to the smallest of living organisms, while reinforcing our connection to them. While generations of scientists, engineers, and designers, have made

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[2] Mali, P., Esvelt, K., & Church, G., Cas9 as a versatile tool for engineering biology. Retrieved May 2, 2015, from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4051438/

this world visible, this thesis investigates what a biological instrument may enable our world to reveal for us.

1.2 Overview of the Thesis

The remainder of this thesis is organized into four chapters.

Chapter 2, *Background*, presents an overview of interaction design and synthetic biology, the principal domains in which this work is situated. The transition from purely computational objects and procedures to those focused on the human experience is reviewed. The basis for a new type of experience is explored as an ecological development, connecting the user to their environment. Design opportunities arising from the intersection of computational and biology are explored in terms of the experiences they provide.

Chapter 3, *Soft Exchange*, introduces a set of objectives for what constitutes interaction design with biological materials. The deliberate use of biology as a material and the framework for a Human Biological Interaction are developed. Scales of experience are explored betweens the microorganisms and the user. The camera is identified as an instrument uniquely suited for this exploration given its function in revealing the environment of the user to the user, and its recent history transitioning from an analog to digital object.

Chapter 4, *Design Experiments*, presents new work which supports this thesis. The development of a camera instrument that employs biology to create images. The design, materials and methods used for each of the instruments are described. The subsequent development of each prototype is based on the modification of an existing camera typology for the inclusion of increased biological procedures. Protocols performed in laboratory settings are accommodated within the design of the instrument, informing its use, and user interaction.

Chapter 5, *Analysis,* provides documentation and insight into the user experience of the object. Reviewing outcomes and their alignment with the objectives of a Human Biological Interaction. The analysis considers the development of the prototype as biological procedures are introduced into the design. The degree to which these processes are revealed and concealed to the user is also understood in terms of prior camera developments.

Chapter 6, *Conclusion,* synopsizes the conclusions of the thesis work, objectives for continued development, and presents possible futures for Human Biological Interaction.

1.3 Summary of Contributions

The objective of this thesis is to develop a model for interaction design with biological materials, for the investigation of experiences that extend human perception through the design of instruments. By implementing biological materials and procedures into an existing instrument that has undergone a transition from analog to digital, the proposed works can be situated as an extension of this development. In this way, the advances of Human Computer Interaction form the basis for what will become a Human Biological Interaction.

The contributions of this thesis, with respect to this objective, include:

- A critical survey of interaction design.
- A critical survey of synthetic biology.
- A proposal for Soft Exchanges and Human Biological Interaction.
- A design case study for Soft Exchanges.
- An analysis of the instruments and user experiences.
- An outline of possible futures for continued research.

2. Background

"...it will be soft and hairy."
-Salvador Dali, in response to Le Corbusier, regarding the future of architecture.

As the convergence of information theory and biological engineering advances, new interfaces are needed to interact with organisms that not only carry information, but produce it by design. Where Synthetic Biology has been transforming our interaction with organisms from an information theory point of view, the forms of interaction analogous with Human Computer Interaction have not yet been developed. This thesis is the application of one to the another, to create a novel operation that begins to reveal these new opportunities.

The applications will focus on interactions that exist outside of laboratory contexts and experimental protocols, but rather seek to enhance the relationship of oneself to their environment. An environment mediated by microorganisms, exhibiting complex behaviors amongst themselves and their hosts as they sense the world around them.

Increasingly, interactions of this type will be situated as part of synthetic ecologies, wherein humans both actively participate and are subject to the outcomes occurring at scales that regulate internal microbiota to [3]bioengineering the biosphere. Once a new channel for interaction is opened, new modes and behaviors emerge for considering this biology.

This chapter divides the relevant background into three sections. The first, *Interaction Design*, examines key developments in *Origins*, *Artifacts*, and *Applications*. In *Origins*, the need for a Human Computer Interaction is reviewed and examples of unintended outcomes are explored. In *Artifacts*, the digital camera serves as an example of how Human Computer Interaction has led to the development of new objects and procedures while maintaining its core tenants. In *Applications,* examples are given of how recent developments in digital photography and computation are combined.

The second chapter, *Synthetic Biology,* examines key developments in *Origins*, *Artifacts*, *Applications, and Ecology*. In *Origins*, the use of biology as a material is reviewed and examples

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[3] Sole, R., Bioengineering the Biosphere? Retrieved May 2, 2015, from http://www.santafe.edu/research/working-papers/abstract/b7cf8ec933ff0fc7040892b915ef196b/

of unintended outcomes are explored. In *Artifacts*, the use of microfluidic devices that facilitate genetic transformation are reviewed. In *Applications,* examples are given of how recent developments in Synthetic Biology have been applied to a range of subjects, from de-extinction to education. Lastly, *Ecology,* reviews how different models of both perception and experience have coincided with new technological advances, at once informing them while also being informed by their use.

2.1 Interaction Design

2.1.1 Origins

The origins of the computer took a considerable step forward into the general public from its defense origins in the form of the IBM 701 Electronic Data Processing Machine. Unveiled April 29, 1952, it was the first mass produced commercially available scientific computer in which programs were stored in an internal, addressable, electronic memory. The mainframe computer occupied entire rooms where they were being used by teams of experts. They were machines for calculating that required teams of users to understand the processes occurring inside them in order to effectively operate them.

FIGURE 4: MAN AND WOMAN WORKING WITH IBM TYPE 704 ELECTRONIC DATA PROCESSING MACHINE USED FOR MAKING COMPUTATIONS FOR AERONAUTICAL RESEARCH. NASA

Though this was the beginning of a generalizable computer, it is more so for its use of electrical memory, than for the user experience necessary to operate it. It would take over a decade for a deliberate user experience to be created, as the computer transitioned from a laboratory instrument to a domestic one. At that moment it was not yet the humans who were computing but the machines, this would later follow.

At the Fall Joint Computer Conference on December 9, 1968 in San Francisco, Douglas Engelbart gave a 90 minute demonstration of a complete, integrated computer hardware and software system. The result of research begun in 1962 by a team of 17. At the center of the demonstration was the user, in this case Engelbart, but as we now know this would come to be any individual, manipulating physical objects that subsequently manipulated imperceptible electrical impulses into registers to compute information.

This exchange and manipulation of protocols, experiences, and interactions has established the foundation of Human Computer Interaction. [4]The "Mother of all Demos", as it has come to be known, featured the oN-Line System, or NLS, and was demonstrated live. Live, in that the relationship of the elements Englebart manipulated over the course of the 90 minutes, were responsive, and participated in feedforward and feedback interactions with the user.

FIGURE 5: THE MOTHER OF ALL DEMOS, SRI INTERNATIONAL

During this event the computer mouse made its public debut. Notably, it has remained the instrument with which graphical user interfaces are most often manipulated. What persists is the ability

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[4] Headline: Tech Time Warp of the Week: The Mother of All Demos, 1968. (2013, December 13). Retrieved May 2, 2015, from http://www.wired.com/2013/12/tech-time-warp-engelbart/

to manipulate pixels, which manipulate electrical signals, toward the computation of information. This provides the general public a method with which to participate with this material, and has resulted in novel forms of experiences and the creation of new artifacts.

FIGURE 6: THE COMPUTER MOUSE, SRI INTERNATIONAL

In this way, Englebart and his team created a set of interactions for how the general public would come to interact with almost all objects that have embedded computation, later becoming an essential part of the everyday experience. These interactions created the user, and persists today.

2.1.2 Artifacts

The advancement of Human Computer Interaction went on to accelerate the embedding of computation in any device that could accommodate it. While many of the devices are novel, many are not, and in fact draw upon rich histories of development in domains outside of computation. Though some of the most interesting design problems to solve have been those that embed computation into existing models of interaction. The history of its effects on the development of the camera, a technology that has been transformed more than once, will be traced.

The camera had been in existence in its modern form for approximately 150 years before computation was introduced in the digital camera. Since it is an object that has played a significant role in human culture, the ways in which Human Computer Interaction are applied to it are of special interest. This makes the camera a useful object to examine as a test case in understanding the transition from one method of imaging to another and the associated interactions. It is therefore a useful model for how to transition towards a Human Biological Interaction.

FIGURE 7: VIEW FROM THE WINDOW AT LE GRAS, 1826 OLDEST SURVIVING PHOTO TAKEN FROM NATURE

The foundational processes and interactions of creating photographs have remained largely unchanged beyond the development of the first recordable photo etchings by Nicéphore Niépce. Light is chemically recorded onto a media that is later processed and used to create the photographic artifact. Beyond the camera lucida, the camera produced a lasting, fixed image, the result of an exposure of time, in a repeatable process. This criteria of photography would remain unchanged until its integration with computation.

Amongst the most pervasive forms of interaction enabled through advances in Human Computer Interaction has been the

development of photography created through digital imaging. Today more than ever billions of images are taken and billions more are shared electronically. The transition from film to pixels has been successful as users experience conventional interactions that predate computers, as well as entirely new interactions.

In 1975, while at Eastman Kodak, engineer Steven Sasson took the first digital image in black and white with a camera that weighed 3.6 kg at a resolution of 0.01 megapixels. It took 23 seconds to process, and was recorded onto a cassette tape. That the technologies used to create the first digital image are no longer commonly used is less important than the process that has remained and the opportunities it has created.

FIGURE 8: KODAK DIGITAL CAMERA

Digital photography, that is the creation of images through computation, implements Human Computer Interaction and has unlocked forms not before seen, such as image analysis, facial recognition, and object character recognition making what the analog camera could not. It is no longer a matter of creating images with light, but using the light as a material with information to create new uses, understandings, and meanings for users. Once a channel for interaction is opened, new modes and behaviors emerge, and that is the promise of designing for experiences.

FIGURE 9: KODAK DIGITAL CAMERA

[5]Core to this technology is the charge-coupled device (CCD), a

[5] Charge coupled semiconductor devices., Retrieved May 2, 2015, from http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6768140

device which allows for the manipulation of electrical charges by shifting the signals between takes within the device. Developed in 1969 by Willard Boyle and George Smith at AT&T Bell Laboratory, the CCD is effectively a shift register allowing for light data to be digitally recorded and stored. The CCD used by Sasson was the first commercially available model made by Fairchild Semiconductor, 100 x 100 CCD201ADC. This departure from photochemical sensitivity to photoelectric sensitivity for the recording and fixing of light data enabled the inclusion of computational procedures in the creation of photographic images, thereby expanding the field of opportunities for what photography was to become. The initial design of digital cameras however, retained much from their analog precedents.

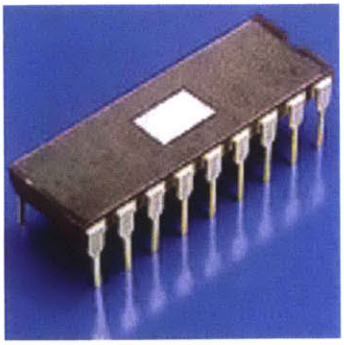

FIGURE 10: FAIRCHILD SEMICONDUCTOR, 100X100 CCD201ADC

2.1.3 Applications

Though atavistic in its implementation by replacing silver halide pieces with pixels the digital camera has created new forms of interaction and made possible new types of artifacts. This transition, and the application of computation has led to the imaging of everything from X-ray to ultrasound. Moreover, what can be computed from this data has more significantly impacted the field. Advances in image analysis, editing, and transmission are possible now because of the pixel and the digitization of the photograph.

The process of digital photography draws significantly from the development of Human Computer Interaction, by adopting existing forms and procedures and adapting them in a manner that the user may implement with a degree of familiarity. That the pixel makes possible yet unknown opportunities in photography is embedded in a process of taking photographs reminiscent of the earliest experiences in the field. For this reason, it is useful to focus on the pervasive form of the camera, an object with analog origins that has been impacted significantly by Human Computer Interaction.

FIGURE 11: CUBESAT

[6]An estimated 2 billion cameras of various types were sold world wide in 2014. This explosive growth is indicative of moments in which new forms of exchange and new forms of information are accessed. Consider similar advancements in communications, and those followed by connectivity from the telephone to electronic mail. Digital imaging is being used today in everything from real time imaging of Earth with CubeSats, piloting

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[6] Presse, A. (2013, December 24). About 880 Billion Photographs Will Be Taken In 2014 - Including A Lot Of Selfies. Retrieved May 2, 2015, from http://www.businessinsider.com/selfies-and-2013-2013-12

autonomous vehicles, and sharing moments via mobile phone through the application Instagram.

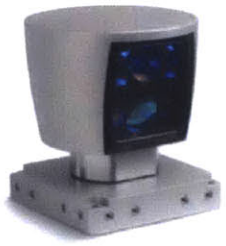

FIGURE 12: VELODYNE LIDAR

The goal of realtime imaging of the Earth is being realized with the use of CubeSats, a standard for satellites measuring one liter by volume and 1.33kg by mass. Developed in 1999 by Jordi Puig-Suari at California Polytechnic State University, as a method for university students to design, build, and test objects in space. First launched in 2003, CubeSats have since increased the accessibility of space exploration. Today, SkyBox Imaging, a company whose mission is the deployment of CubeSats for realtime imaging of Earth, has partnered with Google for internet services and products, demonstrating the intersection of photography and computation in a way previously unimaginable.

Digital imaging has made possible the development of autonomous vehicles. Providing critical information about the environment of vehicles to the computers and algorithms which plan their paths and navigate them through their environments. Made possible by the use of increasingly affordable Lidar instruments that optimize the computation of the Simultaneous Localization and Mapping necessary to direct the vehicle. The initial development of autonomous vehicles by The Defense Advanced Research Projects Agency followed by Google, not only signals its tendency towards applications for the general public by also reinforces this as an extension of Human Computer Interaction.

In 2010 Kevin Systrom and Mike Krieger created the mobile photo sharing, video sharing, and social networking application Instagram. Instagram has over 300 million users as of December 2014, and continues to grow, allowing users to share images taken in a square format reminisce of traditional Polaroid instant film, and apply digital filters to customize their images with the use of a mobile phone. Today the general public can make digital images and share them with millions of other users across the world, all from their mobile phone.

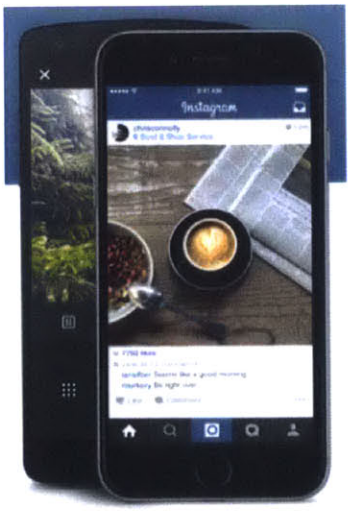

FIGURE 13: INSTAGRAM APPLICATION

An immeasurable number of forms of Human Computer Interaction have emerged and continue still to form. It is useful to focus on the pervasive form of the camera and process of image creation. The camera is an object with historical precedent, existing prior to electronic computation though subsequently transitioning to embed it.

By tracing the ways that computation and Human Computer Interaction changes how we image the worlds around us, with the camera, we being to imagine how a future Human Biological Interaction not only change how we make image, but the way we

see. This example of how Human Computer Interaction worked on an existing model, but expanded the possibilities of its application serves as a template for future developments with biology.

2.2 Synthetic Biology

2.2.1 Origins

[7]In 1910, Stéphane Leduc published the *Théorie Physico-Chimique de la vie et Générations Spontanées,* outlining the potential to manipulate biology through physical and chemical means. Understanding that biology was subject to these processes, Leduc posited that by altering them the biology would also be subject to change stating:

> *"Finally, when the mechanism of a phenomenon is understood, it becomes possible to reproduce it, to repeat it by directing the physical forces which are its cause—the science has now become synthetical."*

This manipulation of biology ultimately lead to the integration of systems thinking and computation.

Initially research by D'Arcy Wentworth Thompson in *On Growth and Form*, from 1917, focuses on the study of the cell, rates of change, and theories of biological transformations. This work began quantifying biological forms, relating them to mechanical interactions with their physical environments. This quantification informed his comparison of biological forms, where different organisms were analyzed and transformed to demonstrate their formal and biological relationship.

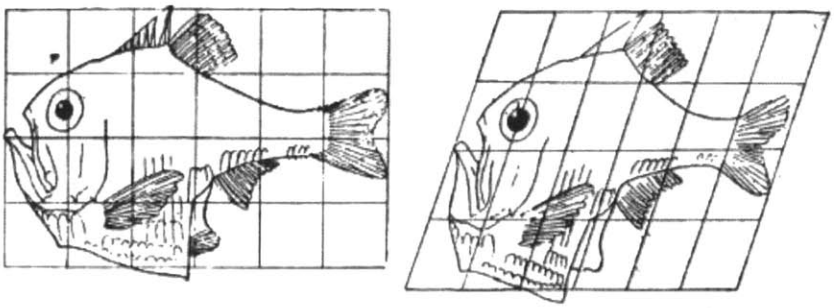

Fig. 517. *Argyropelecus Olfersi.* Fig. 518. *Sternoptyx diaphana.*

FIGURE 14: TRANSFORMATION OF ARGYROPELECUS OLFERSI INTO STERNOPTYX DIAPHANA FROM ON GROWTH AND FORM

At odds with contemporary views of technology designed to compensate or augment nature, biological engineering has rather enabled the creation of a new nature. Everything from the development of vaccines to biofuels is being investigated through

[7] Leduc, S. (1910). Théorie physico-chimique de la vie et générations spontanées. Paris: Poinat.

the manipulation of living systems at the genetic level. Cutting, copying, and pasting, bits of genetic code to run biological programs in organisms has extended computational interactions into the biological domain.

The manipulation of these genetic parts to create biological devices and systems that operate within organisms, has led to the standardization, abstraction, and modularity of parts that reliably replicate procedures that can be designed, modeled, and implemented. The International Genetically Engineered Machine (iGEM) competition maintains the Registry of Standard Biological Parts which consists of various types of genetic components that are distributed to participants in the competition. iGEM has led to the development of many synthetic biology kits that are accessible to the general public. Complemented by open source online repositories of protocols for biological engineering, synthetic biology is readily accessible by the general public today.

[8]Furthermore, entire genomes can be sequenced for less than 1,000 USD, as with the Illumina HiSeq X Ten, leading not only to increased access to biological material, but to the expansion of the sources being sequenced that would have otherwise been cost prohibitive. Additionally, these services can be outsourced, and genetic code can even be manufactured to specific designs and returned to the user for use. The parallels with Moore's Law are clear, [9]with DNA sequencing now surpassing it since 2008. What was once the relegated to laboratory research backed by institutional funding, today can be done in a domestic kitchen.

FIGURE 15: ILLUMINA HISEQ X TEN

2.2.2 Artifacts

The scales of human experience which can be impacted by synthetic biology range from the interior of the body to the environment which we inhabit. [10]Advances in cancer research today, have genetically modified the HIV virus for use in fighting lymphatic leukemia. Taking a virus that has lead to the death of approximately 1.5 million people since its discovery, and

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[8] Human whole-genome sequencing power., Retrieved May 2, 2015, from http://www.illumina.com/systems/hiseq-x-sequencing-system.html

[9]DNA Sequencing: Beating Moore's Law Since January 2008., Retrieved May 2, 2015, from http://www.forbes.com/sites/matthewherper/2011/05/13/dna-sequencing-beating-moores-law-since-january-2008/

[10] Chimeric Antigen Receptor–Modified T Cells in Chronic Lymphoid Leukemia — NEJM, Retrieved May 2, 2015, from http://www.nejm.org/doi/full/10.1056/NEJMoa1103849

transforming it into a potential cure for cancer. [11]While the biological engineering of genetic circuits for bioengineering the biosphere, includes the design of microorganisms to decompose plastic as a remediation measure for the biosphere.

In both instances, modified microorganisms are sufficient to impact the human experience. Harnessing this reality is what designers have to contend with, an imperceptible layer of material that can be modified and employed to work with the challenges of life itself. In this way, more of the fundamental processes underlying our lives may be recognized as opportunities, whether or not we are aware of them. New approaches are facilitating these opportunities, principally advances in the development of microfluidic devices. Microfluidics have diverse applications from the development of dispensers for ink jet printers to lab on chip devices for modeling human organs. Microfluidics provides researchers and designers alike the opportunity to model, test, and implement biological designs.

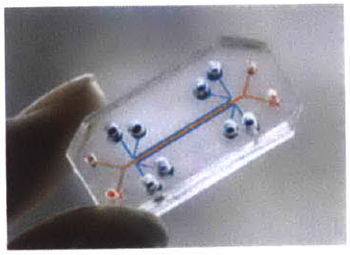

FIGURE 16: WYSS INSTITUTE LUNG ON A CHIP MICROFLUIDIC

2.2.3 Applications

From de-extinction, to gene therapy, to kits for education, Synthetic Biology is seeing a transformation similar to those reviewed in the development of Human Computer Interaction. [12]In 2003, a bucardo, which had been extinct since 1999, was born to a surrogate hybrid between a Spanish ibex and domestic goat. Led by Fernandez Aria and Jose Folch, the buccardo DNA was introduced into goat eggs, whose own DNA had been removed. It lived for ten minutes after birth, having previously been extinct for four years.

FIGURE 17: CELIA THE LAST IBEX

[13]CRISPR/Cas9 has become a promising editing protocol for DNA, creating opportunities to selectively, with high throughput multiplexing and increased precision, remove genes which may become harmful, preempting disease. [14]Even making possible the use of DNA as a data storage and computational device, literally storing repositories of information in genetic material.

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[11] Sole, R., Retrieved May 2, 2015, from http://arxiv.org/pdf/1503.05043v1.pdf

[12] Church, G., & Regis, E. (2012). Regenesis: How synthetic biology will reinvent nature and ourselves. New York: Basic Books.

[13] http://www.sciencedirect.com/science/article/pii/S0092867413012142

[14] Next-Generation Digital Information Storage in DNA, Retrieved May 2, 2015, from http://www.sciencemag.org/content/337/6102/1628

Computer Aided Design software company Autodesk, has developed an advanced research unit, Bio/Nano/Programmable Matter, to investigate the intersection of Synthetic Biology with CAD/CAM processes. The software to create with biology is being made accessible enabling new processes for the designer from writing genetic code to printing cells. [15]Project Cyborg is cloud based meta-platform that includes modeling, simulation, and fabrication computation.

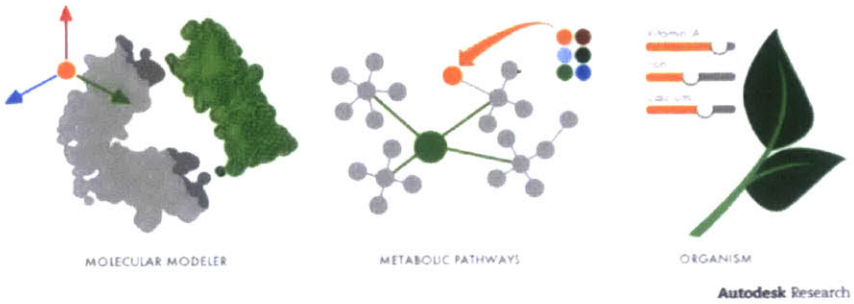

FIGURE 18: PROJECT CYBORG WORKFLOW, AUTODESK

[16]Kits such as BioBuilder, developed by Natalie Kuldell, provide the tools and protocols to create synthetic biology and educate a new generation. That the most advanced protocols and equipment is being reformatted into a general way that the public can engage with is perhaps a sign that the most impactful advances are still to come. Though promising in many varied domains, Synthetic Biology as a field is only in its "mainframe" phase, though rapidly moving towards a new more personalized future in which the procedures developed will lead to varied applications.

2.2.4 Ecology

Interaction Design and Synthetic Biology have each in their own manner situated the user within a set of relationships that it both effects and that effect it. This interconnectivity enables a systems based dependency on the components that constitute each experience. That is to say, it is neither the computer nor the user alone that create the interaction, but rather their exchanges, in the way that systems are characterized by Actor-Network Theory. These exchanges lead to the creation of artifacts and experiences

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[15] Project Cyborg, Retrieved May 2, 2015, from http://www.autodeskresearch.com/projects/cyborg

[16] Home - BioBuilder. (2013, October 30). Retrieved May 2, 2015, from http://biobuilder.org

that in and of themselves also carry information. [17]In the work of James Gibson, *The Ecological Approach to Visual Perception*, an individual's perception is understood to be the synthesis of their environment and how they interact with it:

> *"The environment of animals and men is what they perceive. The environment is not the same as the physical world, if one means by that the world described by physics. The observer and his environment are complementary. So are the set of observers and their common environment. The components and events of the fall into natural units. The units are nested. They should not be confused with the metric units of space and time. The environment persists in some respects and changes in other respects. The most radical change is going out of existence or coming into existence."*

Today, the digital camera and the computation that reinforces its performance contribute to our overall perception in a manner that is integrated with our experience. When the Voyager 1 space probe made an image of Earth on February 14, 1990, from a distance of 6 billion kilometers, Earth was captured in less than one pixel. *Pale Blue Dot* was the last image taken before exiting our solar system. It remains a reference for our experiences from the farthest point of our observation.

FIGURE 19: PALE BLUE DOT

Much as we do not separate the individual signals and process them, but rather use the camera to create images, we operate at a level of interaction which incorporates within it additional scales of interaction. This effect of [18]punctualisation, as described by Bruno Latour, means that the instruments with which we engage allow us to experience what they produce by concealing their internal interactions. This enables the user to participate in the outcomes of their exchanges and attribute value to them.

With Synthetic Biology, we can now begin formulating the realization of Human Biological Interaction. Experiences which emerge when exchanges with biological devices are made possible, devices managing scales of interaction necessary to produce user defined experiences and artifacts. The intention is for a human legible dialogue, differing from the unilateral experience of the microscope or Polymerase Chain Reaction, and

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[17] Gibson, J. (1979). The ecological approach to visual perception. Boston: Houghton Mifflin.

[18] Latour, B. (1999). Pandora's hope: Essays on the reality of science studies. Cambridge, Mass.: Harvard University Press.

towards one in which the biology may influence our own perception. From this experience a new type of user will emerge, one who participates in an ecology they make and from which they are made.

3. Soft Exchanges

"Whatever we call reality, it is revealed to us only through the active construction in which we participate."

-Ilya Prigogine, Order Out of Chaos: Man's New Dialogue with Nature (1984)

This chapter develops Soft Exchanges are as a foundational construct for Human Biological Interactions. *Proposal*, reviews parallels with Human Computer Interaction as a precedent in transitioning to new forms of interaction, as well as the overall approach adopted. In *Objective*, the preliminary goals are explained. The work is contextualized in *Related Works*, both in terms of technical advancements and cultural milestones.

3.1 Proposal

The field of Human Computer Interaction has developed various interfaces to enable communication between the incompatible systems of human perception and electrical signals with the aid of physical peripherals, and serves as an initial reference for how to approach the development of biological interfaces. Relying not only on methodologies and process, but on the physical design and discrete actions associated with intended outcomes, Interaction Design brings together behavioral and perceptual factors into an overall experience. An experience in which hidden signals are rendered at a scale that may be understood and further manipulated by humans.

Whereas the hidden signals that have transformed the human experience have recently been electronic, they have also always been biological. The transition from the initial development of the computer to the advent to Human Computer Interaction is being paralleled by the programmability of biological materials made possible by advances in Synthetic Biology. It is now feasible to consider and begin the development of a basis for Human Biological Interaction. [19]In *The Reconfigured Eye, Visual Truth in the Post-Photographic Era*, William Mitchell opens this opportunity:

> *"Today, as we enter the post-photographic era, we must face one again the ineradicable fragility of our ontological distinctions between the imaginary and*

[19] Mitchell, W. (1994). The reconfigured eye visual truth in the post-photographic era. Cambridge, Mass.: MIT Press.

the realization, and the tragic elusiveness of the Cartesian dream. We have indeed learned to fix shadows, but not to secure their meanings or to stabilize their truth values; they still flicker on the walls of Plato's cave."

It is now possible to consider creating and participating in a series of synthetic ecosystems of human design that serve to extend the boundaries of human experience. Operating from the internal most microscopic layer of existence in our environment to a layer which is now deliberately responsive. Soft Exchanges are a model of interaction with an interface made of and subject to biology. Situated between the collective interactions of microbes in, on, and in the context of the body, these are instruments and procedures designed for human perception.

3.1.1. Approach

Soft Exchanges provide access to microbial interactions, and consider signaling of this type a sensory extension for human perception. That bacteria typically found in the human intestine can now be transformed to create photographic signals, prompts the development of a camera instrument to begin developing Human Biological Interaction. Much as Leeuwenhoek discovered microorganisms, and Tabor instrumented them, we know it is possible to interact with them. The question is how will we interact with them? What instruments will enable the exploration of this space? To this end, this thesis will develop a biological camera.

The biological interface used is based on the "E. coloroid" protocol initially developed by Anselm Levskaya, wherein Escherichia coli are engineered to have photoreceptors (phytochromes), not naturally occurring in enterobacteria and sourced from cyanobacteria. This transformation renders the organism responsive to 650nm wavelengths of light. Forming the first part of a two part system, the light triggers the inhibition of autophosphorylation turning off gene expression. For the areas which are not exposed, the LacZ reporter is expressed by a dark (black/indigo) color, resulting in the processing of images into light and dark regions as the bacteria population grows. Programming light regulation in this manner enables the gene expression to be spatially and temporally controlled, similar to both chemical and digital based photographic methods.

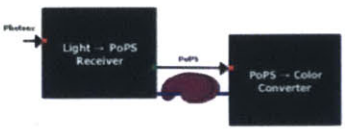

FIGURE 20: E. COLOROID DEVICE DIAGRAM, IGEM

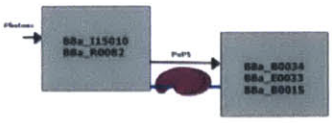

FIGURE 21: E. COLOROID PARTS DIAGRAM, IGEM

The objective is to deliberately stimulate microbe interactions and render them for human use, in a manner once familiar but in a biological regime. This will require the translation of familiar human interactions through an interface to reveal unfamiliar

microbial behaviors, making them legible across scales. These are behaviors which are occurring constantly in the environment and indeed in human bodies, but remain imperceptible until manipulated and amplified.

For these reasons the prototype instrument to engage in Soft Exchanges is a camera that employs biological materials and methods to create human legible photographs. The camera is unique in its capacity to reveal experiences which were always already present.

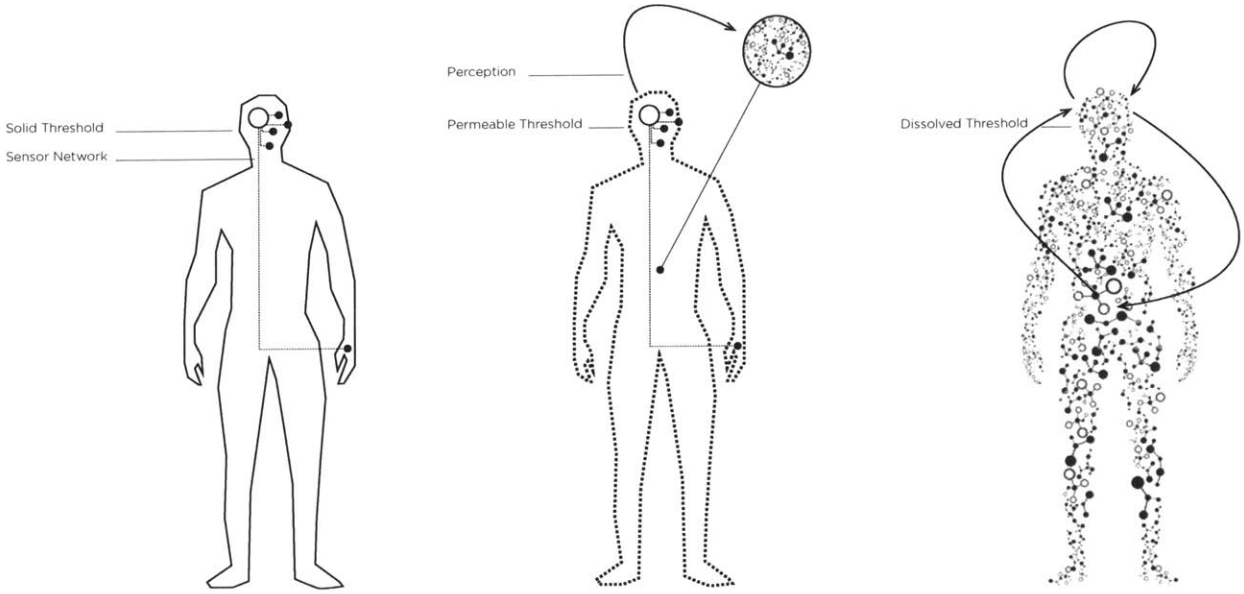

FIGURE 22: DISSOLVING PERCEPTION BOUNDARIES WITH SOFT EXCHANGES

3.2 Objective

The proposed works introduce a model of interaction in which the microbiome is an extension of the human sensory system, accessed through a biological interface that enables exchange. A biological interface is one which transfers discrete behaviors of microbe populations into information across scales, where they may be manipulated. In this way, a Soft Exchange is one in which these behaviors, occurring among microbes, translate to signals that inform human perception and form the basis of a novel form of interaction design.

To achieve this an instrument will be designed to implement the "E. coloroid" protocol and the more generalizable "Bactograph" protocol to yield an interaction that impacts human perception. The object is a hybrid, functioning simultaneously as both a camera and laboratory, to serve the dual purpose of creating the image as well as supporting the microbial life employed to do so. The object completes the entire genetic transformation, resulting in a "photographed" image, and incorporates a discrete human interaction as an integral part of the process. [20]Matthew Fuller, explores these objects in *Media Ecologies Materialist, Energies in Art and Technoculture:*

> *"An apparatus is never necessarily taken as the composite or the sum of all the programs that compose it. Any one or any combination of these programs, themselves the result of others, can be pursued as a compositional imperative. This problem is partly to do with the way media technologies are understood to form wholes rather than assemblages."*

Furthermore, the object will make visible images out of invisible interactions, by harnessing both natural and synthetic biological reactions into visual and tangible products. These types of interactions are significant in their ability to provide access to imperceptible microbial processes, creating the initial components of a model of biological interaction. Initial prototyping and engagement in interactions, will be followed by an exploration of the interaction design space as a novel form of symbiosis in a synthetic ecology. This evaluation will examine the user experience, the role of the user input, the role of the object, and the opportunities and constraints dictated by biological processes. These interactions form the basis for demonstrating a future in

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[20] Fuller, M., & Malina, R. (2005). Media ecologies materialist energies in art and technoculture. Cambridge, Mass.: MIT Press.

which we more actively manipulate the material that forms our environment and participate in it.

3.3 Related Works

The use of biology as a material for the transmission of information in both technical and cultural productions, has been accelerated by advances in synthetic biology. By making possible the targeted manipulation of gene expression, microorganisms have been recombined and implemented to achieve designed outcomes from predetermined stimuli. The mapping of input and output has led to a diversity of applications, amongst these strategies, the following examples are of note in terms of their use of biology a means for communicating information across scales.

[21]*E. coloroid*
Developed by Anselm Levskaya, and a team of iGEM researchers from the University of Texas, Austin and University of California at San Francisco, Escherichia coli have been engineered to switch between states in the presence of red light, creating a "photograph" of a light pattern as a high definition chemical image. The system consists of a synthetic sensor kinase that allows a lawn of bacteria to function as a biological film, such that the projection of a pattern of light on to the bacteria produces a high-definition (about 100 megapixels per square inch), two dimensional chemical image.

FIGURE 22: E. COLOROID

[22]*Cultures*
Developed by Lia Giraud from L'école Nationale Supérieure Des Arts Décoratifs in 2011, along with Claude Yéprémian, from the Muséum d'Histoire Naturelle de Paris, microscopic algae are implemented in a manner reminiscent of silver halide gel impulsion film, to create images from algae growth. The process involves placing the algae in a culture dish in solution, where it is in turn exposed to an image, and the cells react to the light growing in different densities. The photosensitivity of the algae is used to increase the contrast of the image over a period of four days.

FIGURE 22: CULTURES

[23]*E. chromi*
Developed by Alexandra Daisy Ginsberg, James King, and the 2009 Cambridge iGem team, Escherichia coli have

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[21] "Synthetic biology: Engineering *Escherichia coli* to see light", *Nature*, (2005), http://www.nature.com/nature/journal/v438/n7067/full/nature04405.html

[22] Giraud, Lira, Cultures, http://liagiraud.com/videos/cultures/

[23] "E. Chromi", Ginsberg, D. King, J. and the Cambridge iGEM Team, *E.Chromi*, http://www.echromi.com/

been engineered with standardized sequences of DNA, known as BioBricks to express color. Used in combination, the bacteria could be programmed for the detection of toxins or other stimuli, creating a biosensor or indicator whose genetic manipulations are perceived at the human scale as a change in color. Applications include personalized medicine, food additives, and weather amongst others.

FIGURE 23: E. CHROMI

[24]*Ambio*

Developed by Teresa van Dongen, at the Design Academy Eindhoven in collaboration with B.M. Joosse and R.M.P. Groen, from TU Delft, marine photobacteria are agitated to stimulate bioluminescence, providing a light source, in a human scale form factor. Emphasizing interaction with the system, the lamp requires human input to move the tube an begin the process that will provide illumination.

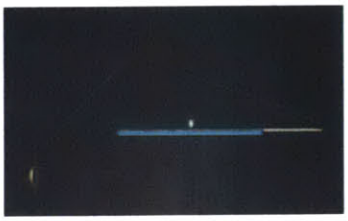

FIGURE 24: AMBIO

[25]*Microbial Home Probe*

Developed by Jack Mama, Creative Director of Phillips Design Probes Program in 2011, the microbial home is a concept for interconnected domestic devices that define the "Biological Age". Together, they create an ecosystem of microorganisms working to replace conventional mechanical and electrical devices that include a bio-digester island, larder, urban beehive, bio-light, apothecary, filtering squatting toilet, and paternoster plastic waste up-cycler. The probe is an exploration of systems level engagement with the domestic microbiome, it describes an alternate future and set of interactions based on dependent cycles.

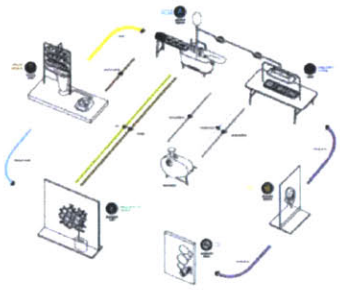

FIGURE 25: MICROBIAL HOME PROBE

The following related works represent cultural artifacts that involve experiences in which users interact with implicit and intangible systems. Whether procedural or formal in their expression, they serve to question the users relationship with the system, and as such suggest a shift from the context in which they operate.

FIGURE 26: FARADAY CHAIR

[26]*Faraday Chair*

Designed by Anthony Dunne and Fiona Raby in 1995, the Farday Chair is a proposal for a space of retreat into which an individual can escape to be protected from

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[24] "Ambio", Teresa van Dongen, (2014), http://teresavandongen.com/Ambio

[25] "Microbial Home", Phillips Design Probe Program, (2011), http://www.design.philips.com/about/design/designportfolio/design_futures/microbial_home.page

[26] Faraday chair, Retrieved May 2, 2015, from http://collections.vam.ac.uk/item/O63805/faraday-chair-chair-dunne-raby/

electromagnetic emissions. The comfort provided differs from conventional chairs in terms of ergonomic support, but rather supports the individual from the invisible transmissions with which there electronic devices interact.

[27]Polaroid Land Camera Model 95
Created by Edwin Land and first demonstrated on February 21, 1947, the Polaroid Land Camera Model 95 was the first commercially available instant camera with self developing film. Within the object the chemistry necessary for the processing the image was supplied in the form of a pod of developing chemicals. As the film was advanced, the reagents spread evenly between two layers of paper and moved out of the camera. After a minute of development time the paper is peeled to reveal a black and white image.

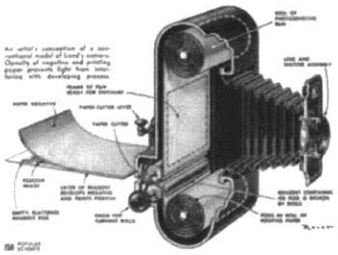

FIGURE 27: POLAROID LAND CAMERA MODEL 95

[28]Fox Theater Detroit Michigan 1979
Created by Hiroshi Sugimoto, the *Theater* series captures in a single photographic image the entirety of a cinematic film. Taken throughout the United States of America during the 1970's this series demonstrates the recording of an entire film in a single image. By utilizing long exposure times, Sugimoto is able to reveal a new point of view, that does not display the content of the film, but instead illuminates the context of the theater.

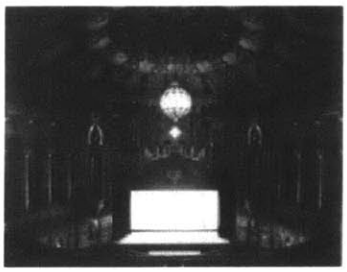

FIGURE 28: FOX THEATER DETROIT MICHIGAN

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[27] Polaroid introduces the instant camera, February 21, 1947, Retrieved May 2, 2015, from http://www.edn.com/electronics-blogs/edn-moments/4407362/Polaroid-introduces-the-instant-camera--February-21--1947

[28] Hiroshi Sugimoto, Retrieved May 2, 2015, from http://www.sugimotohiroshi.com/theater.html

[29]Camera Recording its Own Condition (7 Apertures, 10 Speeds, 2 Mirrors)
Created by John Hilliard in 1971, the piece is both about photography and produced with photography. 70 images produced by exposures that combine 7 different apertures and 10 different speeds. The result is a matrix of representations that in their assembly questions the very nature of representations.

[30]Moyasimon: Tales of Agriculture
Created by Masayuki Ishikawa from August 2004 to June 2013, the serialized Japanese manga series follows protagonist Tadayasu Sawaki. He is a first year college student with a unique ability to view bacteria and communicate with the microbial world. The narratives explore the experience of participating simultaneously in human and microbial scales.

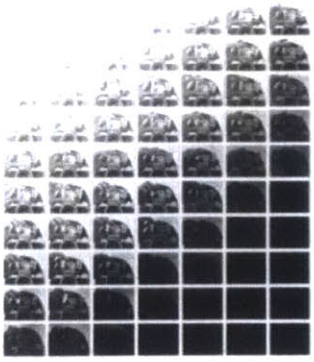

FIGURE 29: CAMERA RECORDING ITS OWN CONDITION (7 APERTURES, 10 SPEEDS, 2 MIRRORS)

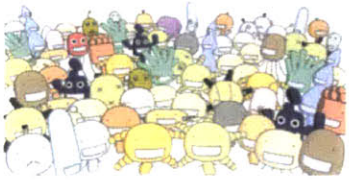

FIGURE 30: BACTERIA RENDERED IN MOYASIMON: TALES OF AGRICULTURE

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[29] John Hilliard, 'Camera Recording its Own Condition (7 Apertures, 10 Speeds, 2 Mirrors)' 1971, Retrieved May 2, 2015, from http://www.tate.org.uk/art/artworks/hilliard-camera-recording-its-own-condition-7-apertures-10-speeds-2-mirrors-t03116

[30] Ishikawa,Masayuki, Moyasimon, Book 1, 2009

4. Design Experiment

"The camera is an instrument that teaches people how to see without a camera."

-Dorothea Lange

To create an experience in which Soft Exchanges occur, various prototypes of instruments to enable users to interact with biological material were designed and implemented. [31]The instruments were designed as a series of cameras that utilized the *Bactograph* protocol as a basis, as later developed by Jeffry Tabor from the original *E. coloroid* protocol developed by Anselm Levskaya. In *Protocol,* the underlying biological mechanism for the instrument is explored. In *Prototype,* the evolution of the camera instrument is reviewed, from its basis in existing camera typologies to its realization as hybrid camera and biological laboratory in an object. In *Procedure*, the experience of using the camera instrument in reviewed and its implications towards a Human Biological Interaction.

4.1 Protocol

The foundational biological mechanism used for the camera instrument is the *Bactograph* protocol. This protocol was selected for meeting two criteria, its novelty in repositioning the use of synthetic biology in terms of existing procedures, in this instance a photograph, as well as the robustness and reproducibility of the protocol.

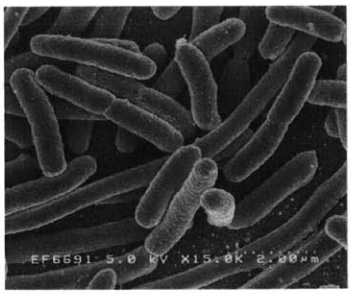

FIGURE 31: SCANNING ELECTRON MICROGRAPH OF ESCHERICHIA COLI, GROWN IN CULTURE ROCKY MOUNTAIN LABORATORIES, NIAID, NIH

[32]In 2005 at Anselm Levskaya at the University of Texas, Austin, successfully engineered Escherichia coli, typically found in the human gut, to respond to light. This protocol, re-engineers a native Escherichia coli two component signaling system to sense the absence of red light, an subsequently trigger a pigment production. This type of two component system to regulate gene expression and intracellular activity is common in prokaryotic cells as a response to environmental factors. In this system, histidine kinase is a sensor which detects an input stimulus and response by phosphorylates a response regulator, either promoting or repressing the transcription of specific genes.

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[31] Tabor Lab, Retrieved May 2, 2015, from http://www.taborlab.rice.edu

[32] Bactograph, Retrieved May 2, 2015, from http://www.bactograph.org/science.html

This protocol creates hybrid a of Cph11, a protein made from Synechocystis PCC6803 cyanobacteria, a light sensor histidine kinase that senses the absence of red light and EnvZ, a two component system found in Escherichia coli that responds to cell stress caused by changes in salinity. The hybrid protein is Cph8.

An additional biosynthetic pathway is introduced that uses the genes pace and ho1 to produce phycocyanobilin so that the Cph1 photoreceptor can detect light. Escherichia coli phosphorylates the OmpR response regulator via the EnvZ system, binding to the OmpF promoter and causing transcription. The output was is linked to the lacZ enzyme converting the S-gal molecule into a black pigment. This singular genetic circuit operating within the transformed Escherichia coli, propagates to millions of Escherichia coli during culturing to produce the bacterial photograph.

Following this protocol, Jeff Tabor and the Tabor Lab at Rice university, further developed it, by implementing optogentics and replacing the lacZ gene with the bFMO gene. These new cells convert tryptophan into indole using the Escherichia coli gene tnaA. Resulting in the the phosphorylation of OmpR by EnvZ if red (650nm) light is not detected by the system. This promotes the expression of the bFMO enzyme resulting in the conversion of indole into an indigo pigment.

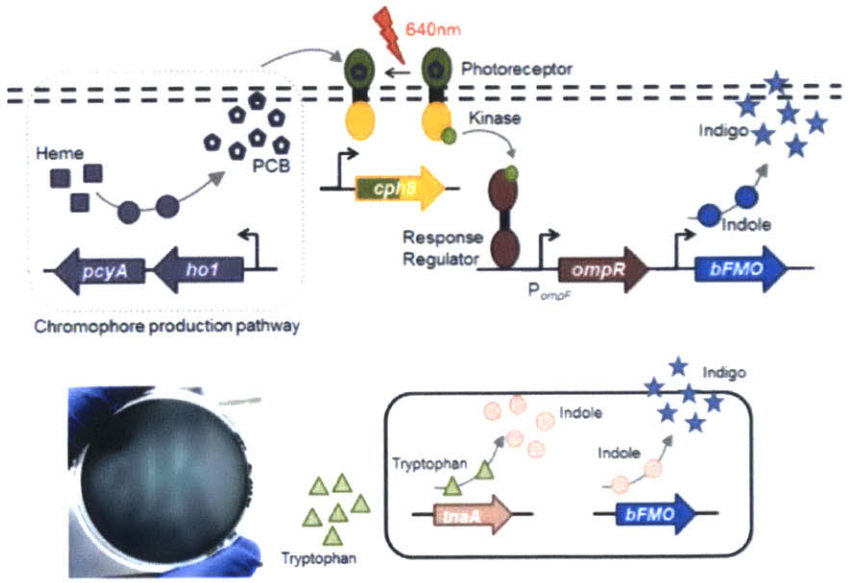

FIGURE 32: BACTOGRAPH TWO SYSTEM PROCESS, TABOR LAB

The protocol has been optimized by the Tabor Lab, and made into a kit that can be used for instruction in synthetic biology. Originally developed at at cost of 15,000 USD, it is now accessible for use by the general public in the kit form.

The kit includes photography media, sample cultures of Escherichia coli, and tryptophan solution. The photograph media is prepared by melting it into liquid form at 37°C. Once cooled sample of the Escherichia coli is introduced into the media and culture for 24-48 hours in a 37°C incubator. Once grown, introduce the culture into the photograph media and add the tryptophan solution. Mix and dispense on a culture dish. Once cooled, the culture dish may be exposed to begin the creation of the bacterial photograph. For more precise images, the protocol outlines the use of stencils on the culture dish.

The *Bactograph* protocol is being further developed to reduce the number of steps required. The inclusion of low melting agarose facilitates the transformation of the organism when combining it with the photographic media and reduces user error.

4.2 Prototype

Three prototype instruments for Soft Exchanges were developed. These explorations represent a refinement of the biological processes required, the scale at which they occur in relation to the user, and the materials and methods employed. They take as their basis existing camera types and modify them as required. The procedures to operate them are defined and implemented. The resulting user interaction is explored and a development towards Human Biological Interaction.

The resulting prototypes are instruments that combine aspects of cameras and miniaturized laboratories, a hybrid instrument designed to accommodate biological processes while presenting them to the user in a familiar set of experiences. *Instrument Type CO* is based on a camera obscura form of the camera. *Instrument Type SLR1* is based on a single lens reflex camera. *Instrument Type SLR2* is based on an optimized version of the *Instrument Type SLR1*. *Instrument Type SLR2* approaches the most complete form, integrating the camera with the majority of *Bactrograph* protocol in a user oriented design.

The prototypes developed share a core application of the [33]*Bactograph* protocol, but differ in the degree of user interaction to complete the creation of a bacterial photograph. As is typical of any technology subject to optimization, it is anticipated that the *Bactoraph* protocol will continue to be updated. Similar to the way in which the original *E. coloroid* protocol has been developed into the *Bactoraph* protocol, the design of the instrument should be able to accommodate the changing procedures associated with these protocols.

Moving the execution of the *Bactograph* protocol from the laboratory into the instrument considers two key criteria, the ability to complete the protocol and the appropriate environmental conditions for the microorganism to grow. The protocol can be categorized into three main parts, the preparation, the transformation, and the incubation. The extent to which these parts of the protocol are performed in the laboratory or in the instrument directly impacts the form of the instrument and the experience of the interactions created for the user.

The integration of the biological process within the customs of creating photographic images, facilitating Soft Exchanges is an initial approach towards a Human Biological Interaction.

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[33] http://pdfs.taborlab.rice.edu/Bactograph_Manual.pdf

4.2.1 Instrument Type CO

The initial instrument prototype was developed from the model of a camera obscura, using readily available light to render an image on a projection surface. The camera obscura is a stationary object that brings an image of the external environment inside of the object, transforming it into a scale visible to the user.

The instrument is organized around three principal components:

- the optical chamber introduces a light source for the creations of the image
- the exposure chamber focuses light and exposes the bacteria culture
- the incubation chamber houses the culture dish and provides the necessary environmental conditions for the growth of the bacteria

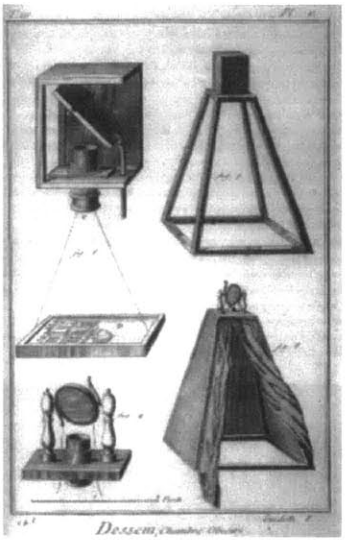

FIGURE 33: CAMERA OBSCURA IN ENCYCLOPÉDIE, OU DICTIONNAIRE RAISONNÉ DES SCIENCES, DES ARTS ET DES MÉTIERS

The optical chamber consists of two key parts, a pinhole opening in the exterior of the camera to admit light into the instrument, and a larger mirrored surface to direct the exposure onto the projection plan where the bacterial photograph will be made.

The exposure chamber houses the culture dish onto which the bacterial photograph is made. It is insulated from light and temperature by foam, to ensure the transfer of the light and that proper conditions are maintained for the growth of the bacteria as the image is grown. The exposure chamber is also connected to the micro controller that manages the power resistor heating element and incubation of the culture dish. This is manually operated by the user at the start and finish of the protocol. An additional 650nm wavelength LED is introduced into the chamber and triggered with the start of the incubation to provide the necessary stimulus for the development of the bacterial photograph.

The incubation chamber interfaces with the exposure chamber through the projection plant for the image. It is insulated to maintain temperature control from the heating element.

Instrument Type CO implements the use of the *Bactograph* protocol in two parts. The genetic transformation is performed external to the instrument, resulting in the preparation of culture dishes that will be used similar to film cartridges. These prepared dishes, primed for exposure, are kept ready until the user is prepared to create a bacterial photograph. To create the image, the culture dish is inserted into the exposure chamber, the camera instrument is directed towards the subject of the bacterial photograph, and the user manually initiates the incubation process for a duration of 24 hours.

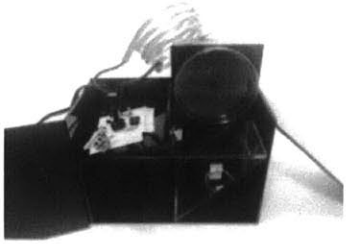

FIGURE 34: INSTRUMENT TYPE CO PROTOTYPE

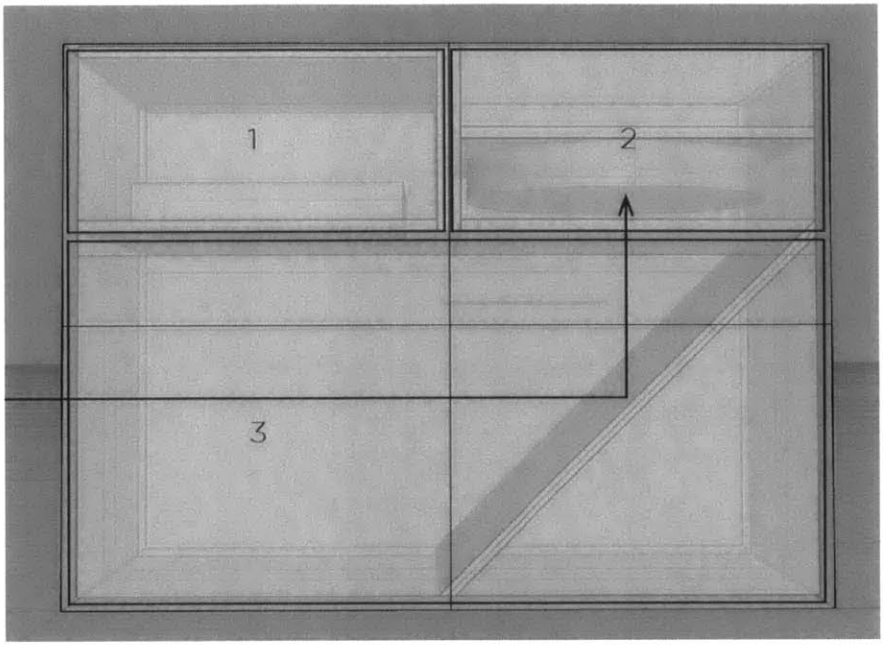

FIGURE 35: INSTRUMENT TYPE CO CHAMBER DIAGRAM

For Instrument Type CO the basic protocol is performed in two parts, in laboratory and in instrument. The preparation of the protocol is performed in the laboratory setting.

The user isolates the microorganism from a sample, culturing it in growth media in preparation for the genetic transformation. Once grown, the microorganism is genetically modified according to the protocol, transforming it into its final form to be used, where it is then prepared into culture dishes that will subsequently used in the instrument. The prepared culture dishes are then inserted into the instrument, wherein once exposed to light, are left to incubate at temperature for 24 hours to grow the transformed culture into a bacterial photograph.

The user experience is divided into conventional laboratory practices for the preparation and transformation, and into a novel experience for in instrument exposure and incubation of the bacterial photograph.

4.2.2 Instrument Type SLR1

The subsequent instrument prototype was developed from the model of a single lens reflex, enabling the viewer to see what the camera sees for the exposure of the photograph. The single lens reflex introduces a viewing aperture from which the user can see the same light that will be exposed onto the photographic media. This is achieved by moving a mirror kept at a 45 degree inclination, momentarily interrupting the users view and thereby allowing the light to directly expose the photographic media behind it.

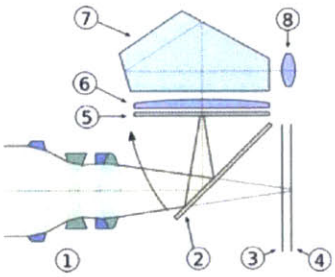

FIGURE 36: SINGLE LENS REFLEX MECHANISM CROSS-SECTION VIEW OF SLR SYSTEM: 1: FRONT-MOUNT LENS 2: REFLEX MIRROR AT 45-DEGREE ANGLE 3: FOCAL PLANE SHUTTER 4: FILM OR SENSOR 5: FOCUSING SCREEN 6: CONDENSER LENS 7: OPTICAL GLASS PENTAPRISM 8:

The instrument was reorganized around four principal components: an optical chamber that introduced a light source for the creation of the image, an exposure chamber into which the light was focused and exposed both to the user through a viewing aperture and to the bacteria culture via a moving mirror, and an incubation chamber which housed the culture dish and provided the necessary environmental conditions for the growth of the bacteria, differing from those in which the object is placed.

The optical chamber consists of three key parts, a 650nm optical bandpass filter at the opening in the exterior of the camera to admit light into the instrument. An additional magnifying lens with a 20mm focal length was used to amplify the image and project it onto the mirrored surface in the exposure chamber.

The exposure chamber is more notably in line with the optical chamber and houses the culture dish onto which the bacterial photograph is made, the rotating mirror, and viewing aperture for the user. It is insulated from light and temperature by foam and mirrored surfaces to ensure the transfer of the light and that proper conditions are maintained for the growth of the bacteria as the image is grown. The exposure chamber is also connected to the micro controller that manages the Peltier thermoelectric device thermoelectric device and incubation of the culture dish. The heat is distributed internally with by a fan connected to a heat sink attached to the Peltier thermoelectric device. This is manually operated by the user at the start and finish of the protocol.

Instrument Type SLR1 implements the use of the Bactograph protocol in two parts. The genetic transformation is performed external to the instrument, resulting in the preparation of culture dishes that will be used similar to film cartridges. These prepared dishes, primed for exposure, are kept ready until the user is prepared to create a bacterial photograph. To create the image, the culture dish is inserted into the exposure chamber, the camera instrument is directed towards the subject of the bacterial photograph, and the user adjust the image composition through

the viewing aperture. Once set, the internal mirror is manually repositioned to expose the culture dish to the photographic subject and manually initiates the incubation process for a duration of 24 hours.

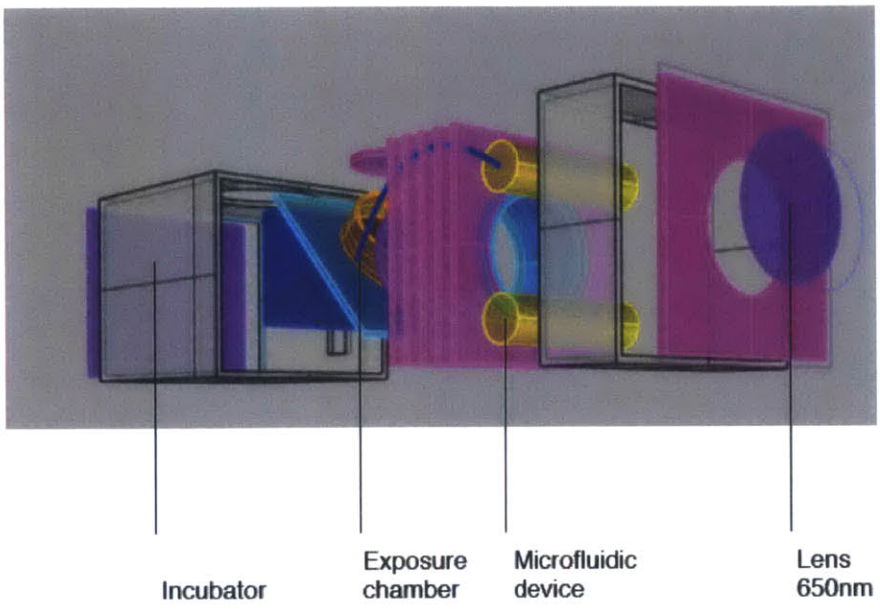

FIGURE 37: INSTRUMENT TYPE SLR1 DIAGRAM

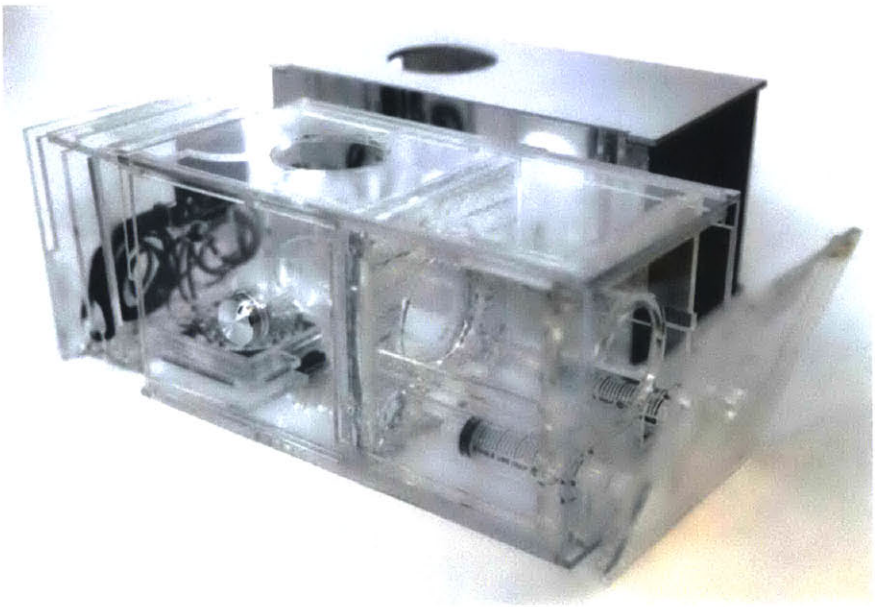

FIGURE 38: INSTRUMENT TYPE SLR1 PROTOTYPE

For Instrument Type SLR1 the basic protocol is performed in two parts, in laboratory and in instrument. The form factor developed for this prototype emphasizes further user engagement with the introduction of a mechanism for repeatedly opening and inserting the culture dish, as well as a viewing aperture enabling the user to view what the camera views prior to exposing the culture dish.

The preparation of the protocol is performed in the laboratory setting. Here too the user isolates the microorganism from a sample, culturing it in growth media in preparation for the genetic transformation. Once grown, the microorganism is genetically modified according to the protocol, transforming it into its final form to be used, where it is then prepared into culture dishes that will subsequently used in the instrument. The prepared culture dishes are then inserted into the instrument, wherein once exposed to light, are left to incubate at temperature for 24 hours to grow the transformed culture into a bacterial photograph.

The user experience is divided into conventional laboratory practices for the preparation and transformation, and into a novel experience for in instrument exposure and incubation of the bacterial photograph.

FIGURE 39: INSTRUMENT TYPE SLR1 BACTERIAL PHOTOGRAPHS DEMONSTRATING EXPOSURE CONTROL

4.2.3 Instrument Type SLR2

The subsequent instrument prototype was developed from the Instrument Type SLR, but introduces more of the biological processes required to complete the *Bactograph* protocol within its design. Design optimization is seen in three key areas, materiality of the instrument, the electronic controls of the instrument, and the introduction of a microfluidic device to perform the genetic transformation in the instrument.

The material development of the prototype consists of appropriately attributing degrees of transparency and reflectivity to both the extra and interior surfaces. This provided accurate direction of the light from the exterior of the instrument towards the instrument. Additionally, it server to conceal and reveal portions of the process to the user involved in the creation of the bacterial image. Acrylic was used for the internal structure in both transparent and mirrored applications. The exterior housing of the instrument was fabricated out of mirrored Aluminum 6061 alloy.

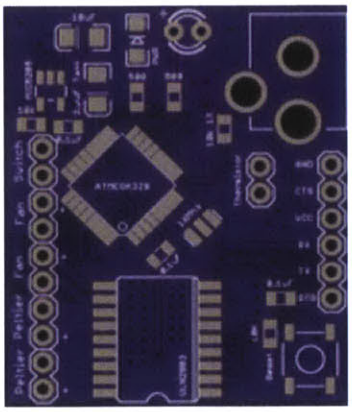

FIGURE 40: INSTRUMENT TYPE SLR2 ELECTRONIC CONTROLS

The electronic controls accommodated three advances. The first was the inclusion of a feedback loop for temperature control with a thermistor. The second was a timer and LED indicator of the incubation period. The third was a switch linked to the starting trigger for the development of the bacterial photograph. The electronic controls also managed the incubation heating with the use of a Peltier thermoelectric device element and fan powered heat sink. This assembly is connected to a 9 volt power source.

The microfluidic device was introduced in this prototype to move a portion of the protocol performed external to the instrument, to the inside of the instrument. The design of the microfluidic device accommodate input from two distinct chambers housing the microorganism and media solutions. Once pumped through, the microfluidic channels are arranged in a manner so as to increase the mixing of both solutions, to dispense them as a single solution in the output of the device. As this is being done in at temperature within the instrument, the protocol can then be continued to create the exposure.

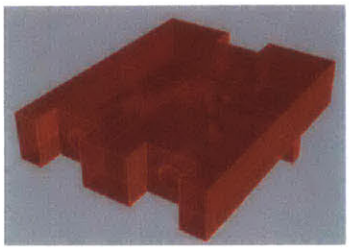

FIGURE 41: INSTRUMENT TYPE SLR2 MICROFLUIDIC DEVICE FOR MIXING TWO SOLUTIONS INPUTS INTO ONE OUTPUT

Instrument Type SLR2 implements the use of the Bactograph protocol in one part. The genetic transformation is performed internal to the instrument, resulting in the preparation of culture dishes that will be used similar to film cartridges within the exposure chamber. The microorganism and media solutions are loaded into two chambers in the optical chamber that feed into a microfludic device situated between the optical chamber and the exposure chamber. The solutions are pumped through the microfluidic device in a singular action by the user, where they are

mixed and subsequently deposited onto a culture dish in the exposure chamber. The user focuses the instrument on a subject and exposes the culture dish, triggering the incubation and growth of the bacterial photograph for a duration of 24 hours.

FIGURE 42: INSTRUMENT TYPE SLR2 650NM BANDPASS FILTER APERTURE

For Instrument Type SLR 2 the basic protocol is performed in two parts, in laboratory and in instrument. The form factor developed for this prototype emphasizes further user engagement with the introduction of a mechanism for repeatedly opening and inserting the culture dish, as well as a viewing aperture enabling the user to view what the camera views prior to exposing the culture dish. The prototype further consolidates more of the protocol within the instrument itself.

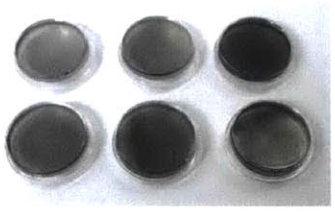

FIGURE 43: EXPOSURE TESTING OF THE INSTRUMENT TYPE SLR2

The preparation of the protocol is performed in the laboratory setting. Here too the user isolates the microorganism from a sample, culturing it in growth media in preparation for the genetic transformation. Once grown in the growth media, however the solution is placed into one of two designated chambers in the instrument for subsequent mixing in the microfluidic device. The additional chamber is designated for the photographic media. In a singular action, the user closes the instrument, and by so doing moves both solutions through the microfluidic device. Here it is transformed into its final form to be used. Upon exiting the microfluidic device, the combined solution is deposited onto a culture dish, awaiting exposure to light. The user then adjusts the instrument towards the subject to be photographed. This process is managed through the viewing aperture. Once set, the user inserts a culture dish and closes the instrument triggering the switch that initiates the incubation process. The instrument regulates the necessary 37°C temperature in the incubation chamber via a feedback loop with the thermistor. This action also begins a timer that can be set by the user.

The user experience is divided into conventional laboratory practices for the preparation of the protocol, but a novel experience is created in instrument for the transformation, exposure, and incubation of the bacterial photograph.

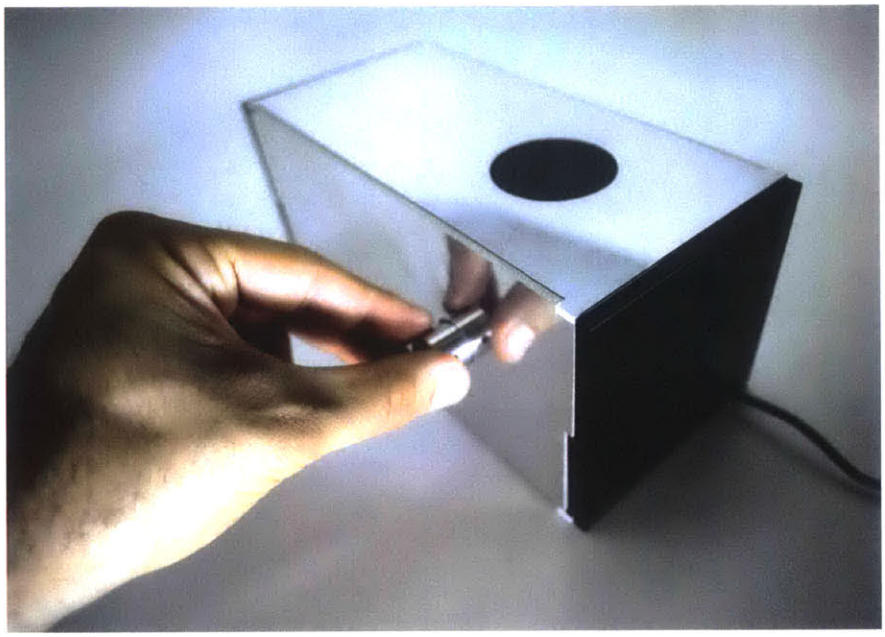

FIGURE 44: INSTRUMENT TYPE SLR2 INTERNAL MIRROR ADJUSTMENT

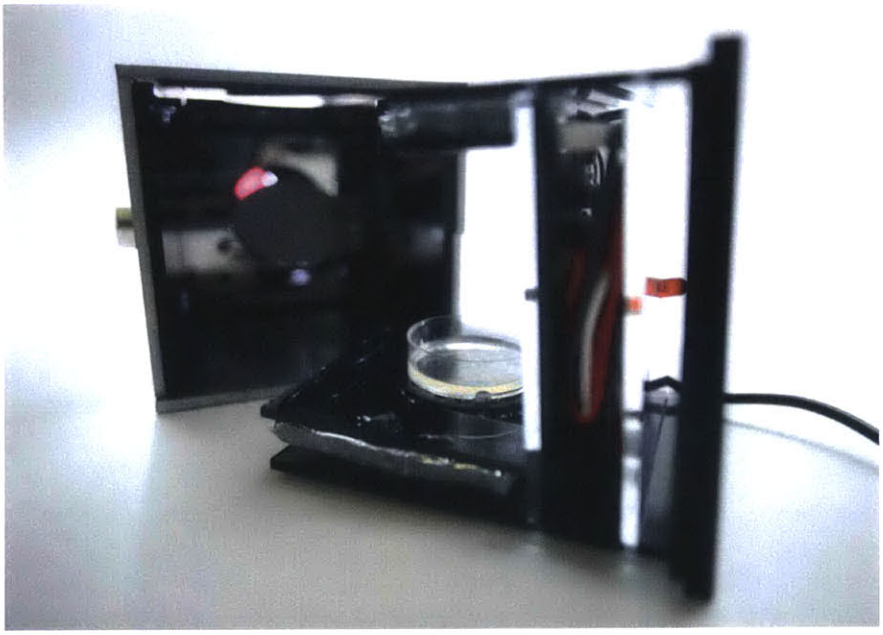

FIGURE 45: INSTRUMENT TYPE SLR2 INCUBATION CHAMBER

The complete bill of materials implemented during prototyping for each instrument type:

- acrylic: 3.175 mm (mirrored, clear transparent, grey transparent)

- acrylic: 6.35 mm (mirrored, clear transparent, grey transparent)
- acrylic: 40 mm tube
- acrylic: 10 mm tube
- aluminimum: alloy 6601, 3.175mm
- lense: 650 nm optical bandpass filter
- lense: 20 mm focal length
- photo-cured resin: custom microfluidic device
- 100 ml disposable syringes
- 15 ml disposable culture dishes
- mirror foil bubble insulation, cut to size
- industrial grade felt: 6.35 mm
- custom printed circuit board
- peltier thermoelectric device heating element
- fan powered heat sink
- 10k thermistor
- indicator LED (red)
- 9 VDC 1000mA regulated switching power adapter

Fabrication and assembly of the prototypes was achieved by utilizing rapid prototyping technologies that included the use of stereolithography 3D printing, laser cutting, water jet cutting, and outsourced PCB fabrication.

The design experiments emphasize an approach to creating Soft Exchanges in the implementation of biological processes as a constructive material. By design, conventions used in photography for making photographs are used to enclose the biological practices that would otherwise reposition the entire act fit for a laboratory. This permits a set of user interactions, at once based in existing photographic practice and laboratory protocols, to be combined into a singular instrument, a singular experience.

5. Analysis

Evaluation of the thesis rests at the intersection of science and design, in that the proposed work builds upon important advancements in both to present a novel approach to interaction design. As a design probe, questioning established notions in both domains, the works present in support of the thesis are used an initial attempt at questioning a new space of inquiry, that of Human Biological Interactions. This is explored in this chapter in *Patterns and Opportunities* and *Challenges*, with each section analyzing key characteristics of both the design and experience of the Soft Exchanges created in support of the thesis.

5.1 Patterns and Opportunities

The Soft Exchanges and the instruments prototyped to experience them reveal how systems towards Human Biological Interaction may begin to work and how they may fail. The basic criteria used to design all of the instruments was the adoption of typical conventions in creating a photograph with a camera. By doing so, unfamiliar and less accessible processes with biology would be understood to be occurring, but as a result of the act of making a photograph. In this way the user is presented with a singular action and objective.

The conventions include loading the media, composing the image, exposing the image, and processing the image. All three prototypes accomplished this, however the more seamless experience was presented in *Instrument Type SLR2* where the materiality of the grey acrylic, mirror acrylic, and mirror aluminum further concealed these steps from the user, enveloping the process in a formal design.

The area of greatest potential variation is in the application of the biological protocol. As many critical factors are typically controlled in the laboratory, their application in the prototypes requires an almost production line sequencing approach to how the instrument will be used. This led at times to the coupling of functions, such as the turn on the incubator with the singular action of loading the bacterial film into the exposure chamber. The switch triggered by the user is concealed, and presented as a continuation of the action of loading the film. As the user is composing the image and stabilizing the camera, the incubator chamber is being brought to temperature. These are areas of opportunity in the evolution of the user experience, that of combining novel processes with established customs.

The act of creating bacterial photographs necessitated conditions external to the instrument as well. These included a constant light source for a period of 12-24 hours. Variations led to images without resolution, though bacterial growth continued.

Conventional cameras operate independent of their context in their ability to create photographs. They are by design able to isolate themselves from their environment to create images in divers contexts, differing exposures, and climates. The instruments that facilitate Soft Exchanges are inextricably linked to their context in way not previously experienced. The conditions of the environment is which these instruments are used is critical to the successful creation of bacteria photographs. Adequate conditions need to persist for a constant exposure with little deviation for the duration of the incubation period. Future investigations will consider precisely the impact of these contextual conditions on the creation of the bacterial photograph, both in terms of technical performance, but also, and perhaps more significantly on the nature of the artifact created.

The type of bacterial photographs created can be characterized as still lives, that is images of inanimate objects. This is due to the nature of the media being used, in that the bacteria require time to grow, and if the subject is not stationary, the light information transmitted into the instrument will be lost by each generation of the bacteria. The still life allows multiple generations of bacteria to be transformed by the light resulting in heightened image contrast. This may be considered a limitation when compared to current photographic methods, but it remains to be seen what new form of representations will be created from this unique behavior of the media.

The media itself has a life cycle, starting with the instruments role in providing favorable conditions for creating microbial life. In conventional photography the media used to create the image is fixed in the instrument, while in this instance it is quite literally the start of life of the image. How these bacterial photographs are subsequently manipulated, presented, and archived, for cultural exchange presents a further opportunity for development.

What these patterns represent is an approach to adopting existing models for interacting with new materials. The way in which culturally accepted methods for making photographs were appropriated for performing Synthetic Biology protocols to create bacterial photographs, demonstrates a method for furthering the applications of Soft Exchanges, while opening new opportunities for Human Biological Interaction to emerge.

5.2 Challenges

The design experiments and prototype development for each of the three instruments presented the following challenges in terms of optics, temperature control, power source, stabilization, duration, and protocol.

Optics

The *Bactograph* protocol requires 650 nm wavelengths of light to trigger the reaction, necessitating either the use of supplementary illumination at that frequency within the exposure chamber, or an optical bandpass filter at the light source for the instrument. While the preferred method, adopted in *Instrument Type SLR1* and *Instrument Type SLR2* is the use of the optical band pass filter, it requires that the external illumination source maintain a constant intensity. Fluctuations in intensity impact the legibility of the final bacterial photograph.

FIGURE 46: UNCLEAR IMAGE DUE TO VARIATIONS IN LIGHT SOURCE

Though supplementary optics were used for internal magnification of the light source introduced in the instrument through the optical bandpass filter, additional use of mirrors and more complex optical configurations may be explored for future applications. The aim of which is to provide a constant and intense passive source, as over exposure is not a concern in the development of thermistor bacterial photograph. Image contrast will continue to be present and reflected in the bacterial growth, given the different intensities of reflected light entering the instrument. Separately, the duration of the incubation impacts the overall contrast and development of the bacterial photograph.

Temperature Control

The *Bactograph* protocol requires a stable incubation at 37°C for 24 hours for the development of the bacterial image. *Instrument Type CO* utilized a heating element and temperature control from a repurposed incubator, with preset settings and different temperatures. This was used to determine the initial feasibility of the incubation within the instrument with a reliable source. High density insulation foam was used. This foam did not allow for a more compact form factor, and was subject to melting when exposed directly to the heat source.

FIGURE 47: EXTENDED INCUBATION

The incubation heating mechanism was later prototyped in *Instrument Type SLR1* with a Peltier thermoelectric device in conjunct with a fan driven heat sink. For this iteration and the subsequent version, software was implemented to

control micro controller and device to achieve stable temperatures. The insulation used was mirror finished bubble insulation that proved effective and more stable when placed adjacent to the heating element.

Instrument Type SLR2 proceeded to the fabrication of a custom designed printed circuit board, which accommodated a more desirable form factor and included the addition of a switch, indicator LED, and 10k thermistor for a feedback loop for temperature regulation. It also accommodates expansion of one additional Peltier thermoelectric device and fan powered heat sink. While this achieved the objective of a stable self regulating 37°C internal temperature in the incubation chamber, expanded functionality of the instrument can be achieved with physical temperature control that can be adjusted manually by the user, similar to the adjustment of aperture or shutter speeds in conventional cameras. This added control would enable manipulation of the bacterial photograph results, as the image can begin to be viewed prior to the recommend 24 hour incubation period of the protocol. Additionally, increased temperatures can fix an image after a stable incubation period, while still in the instrument.

Power Source

The power required to drive the incubation of the instrument in all three prototypes was provided by a 9 VDC 1000mA regulated switching power adapter. This criteria reduced the overall mobility of the instrument. Integrating a battery to provide continuous power for 24 hours while providing adequate thermal isolation from the incubation chamber would increase the portability of the instruments and increase the scenarios in which bacterial photographs can be created.

Stability

The design of each prototype focused on portability in a hand held operable instrument. This presents two challenges in regards to the creation of the bacterial photograph, mainly the need for instrument to remain in place in relation to the subject being photographed for the full duration of the incubation period, and the need for the culture dish to remain in place. The design of the *Instrument Type SLR2* was stable due in part to its external aluminum construction and weight distribution, and contained a guard for the culture dish to prevent movement.

Time
Reconciling the expectations of human centered experiences when compared with biological processes if an area for further development. Conventional photography operates at intervals of fractions of seconds to create images and reveal meaning. Bacterial photography operates at intervals of hours. While different catalysts may be utilized to accelerate biological processes, the order of magnitude difference in times scales remains.

Protocol
Protocol optimizations, such as in the use of low melting melting agarose in the *Bactograph* protocol may impact the formal design of the instrument. In this instance, the development of the *Bactograph* in fact enables the consolidation of the protocol within the instrument, however this may differ and need to accommodated accordingly with different protocols.

Sterilization
The use of renewable culture dishes, syringes, and proper sterilization of the microfluidic device is generally sufficient for the sterilization requirements of the *Bactograph* protocol. Though foreseeable applications include direct sampling of microorganisms for culturing and increased user interaction which may require adjustments to the sterilization necessary for successful completion of protocols. Increased need for sterilization may be accommodated by using sterilized renewables where possible. Additionally, more robust protocols can be designed when considering Human Biological Interactions, to not only reduce user error but also provide consistent outcomes under varying conditions.

Culturing
The preparation of the *Bactograph* protocol requires culturing of the microorganism from a controlled sample. This inevitably requires a portion of the protocol to be performed in the sterile environment of the laboratory. Future developments would enable the direct sourcing and culturing of select microorganism from the environment of the user. That Escherichia coli thrives in the human gut crates the potential for future bacterial photographs to be created directly from the users microbiota.

In many instances the challenges referenced will lead to new design opportunities for both the physical instruments, the protocols they implement, though of greatest impact in the Soft

Exchanges they create. These challenges continue to shape Human Biological Interaction.

6. Conclusion

[34]*"Similarly, our individual bodies and minds are mere coagulations or decelerations of in the flows of biomass, genes, memes, and norms. Here, too, we might be defined both by the materials we are temporarily binding or chaining to our organic bodies and cultural minds and by the timescale of the binding operation."*

Manuel De Landa, A Thousand Years of Non Linear History

6.1. Possible Futures

This thesis proposes constructing new interactions with the design and implementation of biological instruments towards the development of Human Biological Interactions. The space in which Soft Exchanges are experienced creates new opportunities for designers and users in the form of Synthetic Ecologies. The processes and artifacts produced by these interactions enable new cultural value to be created.

The prototypes for camera instruments were designed and implemented to explore user interactions with Soft Exchanges. The instruments expressed differ in formal and procedural priorities as they developed towards a more consolidated hybrid of biological and technical procedures, sharing the application of the *Bactograph* protocol. This investigation revealed opportunities to further the design of Human Biological Interaction in differing contexts and with an increased catalog of protocols.

This investigation presents possible futures for new types of cultural artifacts to be created, and in so doing reveal new experiences to users about their world. Furthermore, that which is revealed to the user is made from the same material from which their world is made, creating a unique linkage in a Synthetic Ecology. Materials are designed to create experiences, merging with the processes to do so. The initial steps in defining this space presented by the works in support of this thesis suggest that this is not only possible, but inevitable.

If we learn nothing from biology, it is that nature will find a way. In a non-anthropocentric, materialist view, it is only reasonable to understand the development of Human Biological Interaction as a biological evolution. While it may not serve human needs directly, it may serve nature, and the synthetic ecologies we create.

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[34] De Landa, M. (1997). A thousand years of nonlinear history . New York: Zone Books.

7. Bibliography

How Many Ebola Patients Have Been Treated Outside of Africa? (2014, July 30). Retrieved May 2, 2015, from http://www.nytimes.com/interactive/2014/07/31/world/africa/ebola-virus-outbreak-qa.html

Mali, P., Esvelt, K., & Church, G, Cas9 as a versatile tool for engineering biology. Retrieved May 2, 2015, from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4051438/

Sole, R, Bioengineering the Biosphere? Retrieved May 2, 2015, from http://www.santafe.edu/research/working-papers/abstract/b7cf8ec933ff0fc7040892b915ef196b/

Headline: Tech Time Warp of the Week: The Mother of All Demos, 1968. (2013, December 13). Retrieved May 2, 2015, from http://www.wired.com/2013/12/tech-time-warp-engelbart/

Charge coupled semiconductor devices, Retrieved May 2, 2015, from http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6768140

Presse, A. (2013, December 24). About 880 Billion Photographs Will Be Taken In 2014 - Including A Lot Of Selfies. Retrieved May 2, 2015, from http://www.businessinsider.com/selfies-and-2013-2013-12

Leduc, S. (1910). Théorie physico-chimique de la vie et générations spontanées. Paris: Poinat.

Human whole-genome sequencing power, Retrieved May 2, 2015, from http://www.illumina.com/systems/hiseq-x-sequencing-system.html

DNA Sequencing: Beating Moore's Law Since January 2008, Retrieved May 2, 2015, from http://www.forbes.com/sites/matthewherper/2011/05/13/dna-sequencing-beating-moores-law-since-january-2008/

Chimeric Antigen Receptor–Modified T Cells in Chronic Lymphoid Leukemia — NEJM, Retrieved May 2, 2015, from http://www.nejm.org/doi/full/10.1056/NEJMoa1103849

. Retrieved May 2, 2015, from http://arxiv.org/pdf/1503.05043v1.pdf

Church, G., & Regis, E. (2012). Regenesis: How synthetic biology will reinvent nature and ourselves . New York: Basic Books.

Next-Generation Digital Information Storage in DNA, Retrieved May 2, 2015, from http://www.sciencemag.org/content/337/6102/1628

Home - BioBuilder. (2013, October 30). Retrieved May 2, 2015, from http://biobuilder.org

Project Cyborg, Retrieved May 2, 2015, from http://www.autodeskresearch.com/projects/cyborg

Gibson, J. (1979). The ecological approach to visual perception . Boston: Houghton Mifflin.

Latour, B. (1999). Pandora's hope: Essays on the reality of science studies . Cambridge, Mass.: Harvard University Press.

Mitchell, W. (1994). The reconfigured eye visual truth in the post-photographic era . Cambridge, Mass.: MIT Press.

Fuller, M., & Malina, R. (2005). Media ecologies materialist energies in art and technoculture . Cambridge, Mass.: MIT Press.

"Synthetic biology: Engineering *Escherichia coli* to see light", *Nature*, (2005), http://www.nature.com/nature/journal/v438/n7067/full/nature04405.html

http://liagiraud.com/videos/cultures/

"E. Chromi", Ginsberg, D. King, J. and the Cambridge iGEM Team, *E.Chromi*, http://www.echromi.com/

"Ambio", Teresa van Dongen, (2014), http://teresavandongen.com/Ambio

"Microbial Home", Phillips Design Probe Program, (2011), http://www.design.philips.com/about/design/designportfolio/design_futures/microbial_home.page

Faraday chair, Retrieved May 2, 2015, from http://collections.vam.ac.uk/item/O63805/faraday-chair-chair-dunne-raby/

Polaroid introduces the instant camera, February 21, 1947, Retrieved May 2, 2015, from http://www.edn.com/electronics-blogs/edn-moments/4407362/Polaroid-introduces-the-instant-camera--February-21--1947

Hiroshi Sugimoto, Retrieved May 2, 2015, from http://www.sugimotohiroshi.com/theater.html

John Hilliard, 'Camera Recording its Own Condition (7 Apertures, 10 Speeds, 2 Mirrors)' 1971, Retrieved May 2, 2015, from http://www.tate.org.uk/art/artworks/hilliard-camera-recording-its-own-condition-7-apertures-10-speeds-2-mirrors-t03116

Ishikawa,Masayuki, Moyasimon, Book 1, 2009

Tabor Lab, Retrieved May 2, 2015, from http://www.taborlab.rice.edu

Bactograph, Retrieved May 2, 2015, from http://www.bactograph.org/science.html

De Landa, Manuel (1997). A thousand years of nonlinear history . New York: Zone Books.