Mycorrhizal Networks, or How I Hack Plant Conversations

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Introduction

In this project, I introduce the idea of intermediary elements that translate information, allowing communication between elements of different kinds. In one case, the translation appears in a natural environment where fungi act as an interface between plants; in the other case, I introduce an electronic interface between organic elements and a computer to translate chemical activity into digital information. The idea of intermediary interfaces is represented within a kit that includes diverse organic and inorganic elements, along with tools to execute the experiments described (Fig. No. 5).

Within the scientific context, the kit introduces various discourses around fungi. First of all, fungi are able to biodegrade organic and inorganic elements, including slowly degradable elements such as cellulose, toxins and heavy metals (Stamets 2005; Singh 2006). In such a way, fungi become important organisms for cleaning soils and supplying chemical elements to other organisms. Fungi are also known for being able to transport chemical elements within their networks and their ability to exchange chemical elements with plants (Stamets 2005; Willis 2010; Fleming 2014).

The title *Mycorrhizal Networks, or How I Hack Plant Conversations* is a direct reference to the use of fungal mycelium for interaction between plants. This interaction is introduced through an electronic interface that translates chemical signals into electronic signals and outputs them as digital information on a computer screen. The discourse around the decomposition of slowly degradable elements is introduced through an explanation of how to grow mycelium on cardboard (see section “Workshop No. 1. Growing Mycelium” below).

Although not directly introduced, other essential topics for discussion around fungi could come up while executing the experiments provided. These additional topics include the DIY production of antibiotics, such as penicillin (Inglis-Arkell 2013), the ability to use space radiation as a food source (Dadachova et al. 2007; Dadachova & Casadevall 2008), and the production of vegetarian vitamin D.

Related Artworks

There are a number of artists and artworks worth mentioning. Among other artists working with plants, fungi, and/or electronic interfaces, bridging these subjects are Martin Howse, Saša Spačal, Laura Popplow, Gediminas and Nomeda Urbonas, Leslie Garcia, and Miya Masaoka. For the sake of diversity, I have chosen to introduce four artworks: *Pieces for Plants* by Miya Masaoka, *Radio Mycelium* by Martin Howse, *Fungutopia* by Laura Popplow and *Life Box* by Paul Stamets.

Miya Masaoka, *Pieces for Plants*[1]

Because of the methods used, Miya Masaoka's *Pieces for Plants* project from 2007 is probably the most direct reference to *Mycorrhizal Networks, or How I Hack Plant Conversations*. In her piece, Masaoka uses electronic interfaces attached to the plants to generate sound (as well as text, appearing in a video performance) (Fig. No. 1). While changing her body position in relation to the plants (approaching, touching, retreating), Masaoka changes the physical properties of the space, which, in turn, affects the plants. Plants sense the changing environment and further transport the captured changes in the form of electrical signals to the electrodes attached to them. The electrical signals captured are then translated into digital signals and transferred into the computer for further manipulation.

Fig. No. 1. Miya Masaoka. *Pieces for Plant* (2007). Photo: Donald Swearington. Available at http://www.miyamasaoka.com/media_files/photos/ (Accessed 26 February 2017).

Using the measurements captured from the interaction between herself and the plants, Masaoka, on the one hand, acts as a performer and, on the other hand, lets the machine generate sounds. Here, the machine becomes an interface between the plants and the performer, while, at the same time, a collaborator for the artistic piece. The final performance could be described as a translation of physical environmental properties into sonic, visual and haptic experience.

*1. http://www.youtube.com/watch?v=1AHOEcAprc8 (Accessed 23 February 2017).

Martin Howse, *Radio Mycelium*[2]

As in Miya Masaoka's *Pieces for Plants*, Martin Howse's *Radio Mycelium* (2011) introduces interaction between the physical properties of an environment and living organisms. In both cases, living organisms and electronic elements are enclosed in a system. On the other hand, the artworks are of different approaches and narratives. While Masaoka explores, from a poetic perspective, the ability of plants to sense the environment, Howse examines connectivity and interaction between the physical properties of the environment and mycelium networks from a scientific, cultural and technical perspectives. Moreover, Masaoka "performs" her piece, whereas Howse holds a "workshop" (Fig. No. 2).

Fig. No. 2. Martin Howse, *Radio Mycelium* (2011). Photo: Nik Gaffney/foam (CC BY-SA 2.0). Available at https://www.flickr.com/photos/foam/6459095083/in/album-72157628288022139/ (Accessed 26 February 2017).

This is how he describes his Radio Mycelium:
The Radio Mycelium workshop aims to actively examine the cross-spore-germination between two parallel wide area networks; between radio-based communication technologies and the single organism network of the mycelium. Fungal transceivers sprouting mycelial antennas form an imaginary underground network. Diversity of human networks is mapped across fungal diversity in the urban environment. The influence of electromagnetic carrier wave on the mycelial network is to be examined.[3]

Proposing the workshop format as artistic means, Howse also proposes research and educational frameworks. Howse and the participants seek understanding of how the environment functions, how species interact with their surroundings, how much cultural charge there is in what is being approached (Howse gives references to Terence McKenna, Paul Stamets, Charles Darwin) and how science and cultural charge complement each other. Through research, doing, sharing, and envisioning, Howse's artwork becomes multilayered.

*2. http://libarynth.org/parn/radio_mycelium (Accessed 23 February 2017).
*3. http://www.psychogeophysics.org/wiki/doku.php?id=mycelial (Accessed 25 February 2017).

Laura Popplow, *Fungutopia*[4]

Laura Poplow's *Fungutopia* from 2011 is an installation, a workshop, a prototype kit and a community project (Fig. No. 3). Being a multifaceted artwork, it also serves as an educational platform. The artist herself describes the project in the following way:

> *As an installation fungutopia shows the different possibilities that mushrooms offer to help to make the world a better place: Mushrooms are open source medicine, food, fertilizer and soil-recovery-method. They can be cultivated quite simply even indoor and are perfect for urban fungiculture. The workshop shows simple techniques to grow mushrooms in cities, whereas the prototype MUSHroom tries to combine Open Source Electronics with Biology to grow even more rare medicinal species year round indoor. As a community-project fungutopia tries to bring together people for urban fungiculture and share knowledge and experience. The Online Community grow.fungutopia.org is the web equivalent of the f2f experience.*[5]

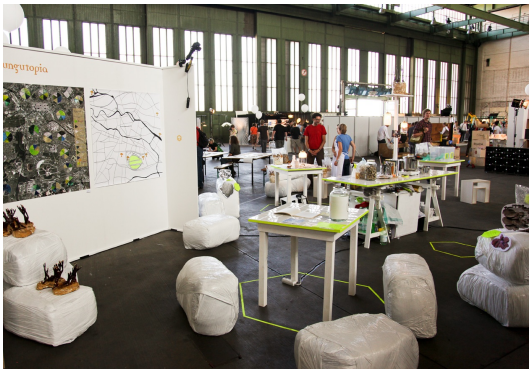

Fig. No. 3. Laura Popplow, *Fungutopia*, 2011. Photo: Martin Schlecht. Available at http://www.fungutopia.org/index.php?/ppp/test/ (Accessed 26 February 2017).

As a very complex project, *Fungutopia* becomes a platform to discuss a variety of topics related to posthuman aesthetics. Along with the reference topics covered by Paul Stamets, *Fungutopia* is also about cooking, DIY electronics, open-source initiatives, sustainability, social practices and, of course, contemporary aesthetics.

*4. http://www.fungutopia.org/ (Accessed 23 February 2017).
*5. http://www.fungutopia.org/index.php?/about/ (Accessed 23 February 2017).

Paul Stamets, *Life Box*[6]

Related to *Mycorrhizal Networks, or How I Hack Plant Conversations* is the project *Life Box*, by mycologist Paul Stamets, started in 2010. Although not exactly an artwork, but rather a commercial product, the project deserves to be listed among other related artworks. First of all, Stamets' ideas regarding mycelium and fungi are often referred to by artists working with fungi (Gediminas and Nomeda Urbonas, Laura Popplow, Martin Howse, TARO). Furthermore, the idea behind the project is well shaped conceptually.

In 2010, Stamets came up with the idea of producing cardboard boxes that could be used for at least two purposes: as packaging material and for the collection of plant seeds. Cardboard boxes of different sizes (Fig. No. 4) can be purchased and used for shipping goods. At the same time, these boxes also serve to combat deforestation and climate change.

The idea behind the *Life Box* is simple: Cardboard, which is made of cellulose, is a good source of nutrients for mycelium and fungi. Through biodegrading processes, the cardboard will turn into soil, and soil containing decomposed chemical elements will, in turn, become a basis for plant growth. The cardboard from the *Life Box* is filled up with plant seeds and fungal spores, so, if watered, they would start interacting with the cardboard and would likely grow into trees.

Interesting in this project is the process of learning how plants grow. The project also involves taking care of living organisms – in this case, fungi and plants. Finally, if trees are nurtured and continue to grow, they could grow into a forest, consuming carbon dioxide and producing oxygen, and, in such a way, again making the environment user-friendly.

Fig. No. 4. Paul Stamets, *Life Box*, 2010. Courtesy: Life Box Company. Available at http://www.thalo.com/thumbnail/040212_1efa29d-586244594-4f79e58e-a7f0-b1c6d6db/o.jpg (Accessed 26 February 2017).

*6. https://www.youtube.com/watch?v=Q8CMsB4jLLc (Accessed 23 February 2017).

Concept

Plants interact with each other. One of the scientific terms defining this interaction is called *allelopathy*, a phenomenon wherein compounds produced by one plant limit the growth of surrounding plants (Fitter 2003). The compounds produced are released into the soils or taken in by symbiotic fungi and further transported over mycorrhizal networks to the target plants within the same community in order to resist invasive species (Barto et al. 2011; Fleming 2014). Using allelopathy as a metaphor for plant interaction, this project suggests interfering in this interaction by adding an electronic interface to lettuce and translating (or hacking[7]) chemical activities into output understandable to humans. In such a framework, chemical activities are captured and converted into electrical signals by the electrodes attached to the lettuce. The electrical signals are in turn converted into digital signals with the Arduino microcontroller.[8] The converted signals may further be used for visual, sonic or haptic output, and finally perceived by human senses.In order to explain chemical reactions between different organic and inorganic elements, the project suggests growing mycorrhizal networks on the cardboard provided.

All the organic and inorganic elements, as well as the electronic tools, are provided in the project toolkit, which acts as an educational framework and a basis for executing the experiments described within this paper.

*7. In this project, the use of "hacking" refers to a shift in the initial meaning of chemical activities between plants; chemical activities here are a metaphor for communication.
*8. http://arduino.cc (Accessed 24 February 2017).

Interaction Between Elements of Different Kinds

This study provides an introduction to symbiotic relationships between fungi and plants, their interaction and their ability to transport chemical elements across distances.[9, 10] Why would fungi and plants interact with each other? How would that happen? And what further picture could be drawn from this interaction?

*9. For a more in-depth discourse on symbiotic relationships between organisms, please refer to another chapter of this project, My collaboration with bacteria for paper production. This chapter was published in Mustekala, http://mustekala.info/node/37799 (Accessed 25 February 2017).

*10. For a more in-depth discourse on symbiotic relationships between organisms, please refer to another chapter of this project, My collaboration with bacteria for paper production.

Fungi, Plants and the Transport of Chemicals Between Different Species

Fungi and plant kingdoms belong to the Eukaryota domain and have an eukaryotic-type of cells that differs from prokaryotic cells (bacteria and archaea) in membrane-bound organelles, which contain genetic material enclosed by a nuclear envelope. According to Nic Fleming, around 90% of land plants are in mutually-beneficial relationships with fungi. These partnerships are usually described as “mycorrhiza,” where the fungus colonizes the roots of the plant (Fleming 2014). The colonization is either intracellular (arbuscular mycorrhizal fungi) or extracellular (ectomycorrhizal fungi), where both sides interact with each other, exchanging chemical elements as well as differently charged protons and electrons.

Most fungi grow as mycelium, consisting of a mass of branching, thread-like hyphae, which are cylindrical, thread-like structures 2–10 µm in diameter and up to several centimeters in length. Together, hyphae may form extremely large organisms, such as, for example, *Armillaria ostoyae*, which occupies 965 hectares of soil found in Oregon's Blue Mountains in the US (Casselman 2007). While able to form net-like structures, this fungus has been called “Earth's natural internet” (Stamets 2008). Fungi expert Paul Stamens has even compared mycelium to ARPANET, the US Department of Defense's early version of the internet (Stamets 2008).

The exchange of chemicals within mycorrhizal networks has been explored by Kathryn Morris, formerly Kathryn Barto (Barto et al. 2011), Nancy Stamp (2003), and Rick Willis (2010). Morris and her team tested, for example, the soil for two compounds made by the marigolds. In the samples where the fungi were allowed to grow, levels of the two compounds were two-to-three times higher than in samples without fungi (Barto et al. 2011). That suggests that the mycelia transport chemical compounds.

As a result of this growing body of evidence describing the communication services that fungi provide to plants and other organisms, many biologists have started using the term “wood wide web” as a reference to the World Wide Web, or simply the internet (Fleming 2014).

Electrical Signals in Living Organisms

As in all matter, the differently charged protons, neutrons and electrons of atoms generate electrical signals. Electrical signals, according to Nick Lane, are the basis for all living organisms and life forms (Lane 2015). How does that work?

The cytoplasm of plants or fungi has, among other chemical elements, potassium (K) and sodium (Na) salts, which provide the correct ionic environment for metabolic processes and, as such, function as regulators of various processes, including growth regulation. Potassium ions (K+) provide protein synthesis and interaction with the external environment, for example, the exchange of gas or nutrition (Leigh et al. 1984). Potassium and sodium ions in plants also generate electrical charges, which are delivered over the cell membranes and ion channels (Fromm & Lautner 2007; Layton 2008; Lane 2015). The delivery of electrical charges in plants is well described by Julia Layton (2008):

The cell membranes practice a trick often referred to as the sodium-potassium gate. It's a very complex mechanism, but the simple explanation of these gates, and how they generate electrical charges, goes like this: At rest, your cells have more potassium ions inside than sodium ions, and there are more sodium ions outside the cell. Potassium ions are negative, so the inside of a cell has a slightly negative charge. Sodium ions are positive, so the area immediately outside the cell membrane is positive... When the body needs to send a message from one point to another, it opens the gate. When the membrane gate opens, sodium and potassium ions move freely into and out of the cell. Negatively charged potassium ions leave the cell, attracted to the positivity outside the membrane, and positively charged sodium ions enter it, moving toward the negative charge. The result is a switch in the concentrations of the two types of ions... This impulse triggers the gate on the next cell to open, creating another charge, and so on.

Electrical charges could be captured by intracellular or extracellular measurements. Both methods have their positive and negative sides. For example, the intracellular measurements are localized and can perform measurements within one cell. At the same time, intracellular methods wound the plant. Extracellular measurements sum up the total of bioelectrical activity in large groups of cells at the surface of a leaf or stem and do not wound the plant (Fromm & Lautner 2007). Within this project, the use of extracellular measurements is suggested because the experiment can be performed for a longer period of time. Meanwhile, the plant will not be damaged by invasive electrodes.

To sum up, the interaction between symbiotic fungi and plants is an exchange of electrical signals and chemical elements between different species. The next question concerns the interpretation of the signals to forms legible to humans.

Interfaces Between Plants and Machines

Noting that differently charged protons, neutrons, and electrons of atoms within organisms generate electrical signals, and knowing that electronic circuits and machines operate on electrical signals as well, the next step is to combine organisms with electronic elements into a biointerface and to translate (or hack) electrical signals passed into humanly perceptible sonic, visual or haptic outputs.

The interface between plants and machines within this project consists of transcutaneous electrical nerve stimulation (TENS) electrodes for capturing extracellular activity, an electrical circuit for high accuracy, an instrumentation amplifier AD620 for amplifying the electrical signals captured, and an Arduino microcontroller for the conversion of electrical signals into digital information. The endpoint is a Windows, Mac or Linux computer.

The electrical signals captured with TENS electrodes are further directed to an electrical circuit in order to amplify those signals and to further deliver them for conversion into digital information. Within this project, I propose using a circuit for the AD620 amplifier, which is also used to measure the electrical activity of the heart. This amplifier is also used by Martin Howse in his *Radio Mycelium* project.

The digital data received by the computer is further manipulated with a Pure Data programming environment for audio, video and graphical processing.[11]

*11. https://puredata.info/ (Accessed 25 February 2017).

Fig. 5. A kit for capturing signals between plants. Photo: Mindaugas Gapševičius.

Toolkit

The kit (Fig. No. 5.) includes components for two workshops. The first workshop introduces the idea of biodegradable elements, which, in turn, become soil and a food source for living organisms. The second workshop introduces an electronic circuit for capturing electrical signals in plants. Altogether, the proposed toolkit introduces interaction between interconnected elements of different natures. This includes living organisms (plants and fungi), nutrition (cellulose and water), and electronic circuits. The use of the kit is divided into an array of different phases. The first phase introduces the cultivation of mycorrhizal networks and lettuce using the provided fungi spores, lettuce seeds, and sheets of cardboard. This phase should last for at least a couple of months, until the cardboard starts to biodegrade into soil and the lettuce is big enough to attach to the electrodes provided. During the second phase, the user is invited to build an electronic interface and bridge it with the mycorrhizal fungi and the computer in order to hack the interaction between the cultivated heads of lettuce.

Workshop No. 1. Growing Mycelium

To prepare the base for mycelium growth, use the following items:

- Cardboard sheets
- A plastic container
- Mycorrhizal spores or oyster mushrooms

Cut the cardboard into pieces that fit well into a petri dish or other sealable container (a plastic one from the supermarket, a glass container or any other dish resistant to boiling water and sealable with fresh aluminum foil will work). Stack them up inside the container and fill it with boiling water. Soak for a couple of minutes until the layers of the cardboard separate easily. Then, drain and separate the layers so you have sheets of corrugated layers and sheets of flat card.

Take your oyster mushroom and cut the inner part of the head into small pieces (1 mm^2 will work well). This is the place where spores reside and where they will grow into the mycelium.

Add flat and corrugated layers of cardboard to the bottom of the container. Place your oyster pieces on top and add an additional layer of a corrugated sheet of cardboard, so the mycelium has space to grow. You can add as many cardboard layers as you want. Place a couple of lettuce seeds on top of the pieces of cardboard. Close the dish with fresh foil, leaving holes for air circulation. Store in a dark place at room temperature and inspect after 2-3 days. Once the mycelium has reached a level you are happy with and the lettuce has grown enough to be attached to electrodes, it is time to proceed with the second phase of the project.

Workshop No. 2. Bridging Plant and Computer

This workshop was inspired by a series of experiments conducted by Leslie Garcia in her *Pulsu(m) Plantae* project (2010) and Martin Howse in *Radio Mycelium* (2012), as well as the scientific discoveries introduced earlier (Stamets 2008; Fleming 2014; Barto et al. 2011).

To bridge plants and a computer, you will need the following items:

- An AD620 amplifier
- A breadboard
- A 100 µF capacitor
- 1 kΩ resistors – 3 units
- An Arduino microcontroller
- Jumper wires
- An A-B USB cable
- TENS electrodes – 2 units
- Software – Arduino, Pure Data, and Piduino

Place the AD620 amplifier on the breadboard with its legs bridging the middle gap in the breadboard. Connect the 100 µF capacitor between pin 4 and pin 7. The capacitor smooths the power supply from the Arduino. Place the 1 kΩ resistor between

pin 1 and pin 8. This resistor sets the amplification of the organism's signal to a factor of 50. Connect pin 5 to the pin marked as ARef of the Arduino microcontroller (as an alternative, plug the patch cable directly into the soil) and add the two other resistors at pin 5 (reference) with one ending at pin 7 (power) and the other at pin 4 (earth). This sets the ground reference for the amp. Then connect pin 7 to the power source and pin 4 to the ground of the Arduino microcontroller. Connect the analogue input A0 of the Arduino to pin 6 (Howse 2013). Pins 2 and 3 of the amp are then connected to the TENS electrodes and further to two different plants.

Connect the Arduino microcontroller to the computer using the USB cable provided, and set the port and the board in the Arduino preferences (install the software provided if it is not already installed). Load the standard Firmata sketch into the Arduino microcontroller. If not yet available, install the extended version of Pure Data, and add its Piduino plugin to the patch library. Open the AnalogIns sketch provided. Turn on the select box of the sketch.[12] Activate the "toggle" box of the sketch so that the sketch updates the values captured on the Arduino object. If everything is done correctly, the scale at the bottom of the patch should start moving left and right. The changing values could be sonified or visualized.

Conclusions and Further Discourses

While providing organic elements (plant and fungi seeds) and inorganic elements (cardboard and electronic elements to bridge the organic elements with the computer), I have laid the practical groundwork of and briefly introduced the discourse on the interaction between elements of different kinds and, along with that, the idea of translation (or hacking). Chemical processes happening within living organisms, in the symbiosis of different living organisms, and in the connection between living and nonliving matter such as electronic elements, suggest that interaction between different kinds of matter is possible. Electronic signals that trigger this interaction could also be translated into information understood by different species; for example, chemicals produced by one plant could be transported to another plant using mycorrhizal networks, or the growth of the plants could be sonified or visualized.

*12. If you do not know which port listens to the Arduino microcontroller, let the sketch output it by clicking on “Devices.”

In the paper, I have described how electrical signals travel through organic matter and how they transfer information. In addition, I have briefly come up with the idea of (mycelium) networks and their similarity to computer networks, which had not yet been introduced or analyzed. Important to computers is computation driven by electrical signals, but what is the electrical signal and where does it come from? These questions propose yet another thread on electricity, which will be illuminated in the other project part, tit led *Ultra-Low-Voltage Survival Kit*, which is devoted to electrical signals.

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This paper is part of a broader body of research within the *Introduction to Posthuman Aesthetics* project, initiated in 2016. The discourse introduced in the paper and the *Toolkit* invite the reader and Toolkit user to think about the interaction between elements of different kinds, for example, different species or organic and inorganic entities. The paper is organized in four parts. The first part introduces related artworks and the contexts where the interaction emerges. The second part introduces the concept of this project. The third part brings the reader deeper into the discourse of the project and the idea of translation (or hacking). The last part is about the Toolkit, which comes along with a manual for practical experiments related to the discourse introduced.
Keywords: hacking, mycorrhizal networks, aesthetics, workshop, interaction.

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