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Polymorphic Plant Architectures: A Pathological Approach to Growing a Building

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Abstract

Considering the prospects of Engineered Living Materials (ELMs), a parallel can be drawn between a building and a tree. How we might grow a living building follows nearly the same processes as how we grow a healthy productive forest. Agential systems such as plants and fungi must respond to and navigate in their environment, naturally resulting in the polymorphic growth of architecture defined by the local stimuli. A symbiotic relationship between two systems provides a ready means to shape the natural plasticity during plant growth using pathogenic agents capable of inducing morphogenesis. Exotic infection morphologies from pathogens are examined from the emerging perspective of a growing building. Transitioning from forest pathogen to biodesign agent of a living botanical building, host-pathogen symbiosis intrinsically links the growth and management of both. How plant pathogens maybe employed in the growth of a building is uniquely transferable across research disciplines from forest to building.

Introduction

The question “Can We Grow a Building?” is rather provocative for it excites our imaginations and becomes a personal experience to each reader (Dade-Robertson 2023).

Invoking a flash forward vision of a seed growing into a tree as the seasons and years pass. Until in age and diameter, the tree’s trunk begins to swell up in size as internal tissues begin forming hallow spaces. Compartments that continue to enlarge becoming the rooms of a building, envisioning the metamorphosis from tree into building. A building that was grown and could remain living throughout its use, and yet such a vision is more mirage than oasis. The growth of a living building via metamorphosis is not on the horizon, for on closer inspection we find the engineering of complex behaviours to push our capabilities. Designing for development has been the traditional concern, while in the following we consider how working with morphogenic agents is more in line with our current capacities to design for the growth of botanical architecture.

Timing is a critical component in the construction or growth of a building and is a primary limiting factor in either process. Designing for the metamorphosis of a singular Oak Tree (*Quercus*) may take 30-50 years before reaching a state of reproductive maturity as is the case for acorn onset (Paul P. Kormanik 2004). Metamorphosis (Bishop *et al.* 2006), is a change in form naturally arising from within the plant and may proceed via a regular or irregular process additionally Goethe describes an accidental process (caused by pest and pathogen) which in the following work is called as morphogenesis (Johann Wolfgang von Goethe 2024). Morphogenesis is also biological process but differs in that the shaping signal may arise from outside of the original organisms as well as from within (Marconi and Wabnik 2021; Silva *et al.* 2019).

Designing for metamorphosis to occur under specific conditions based on an internal timing mechanism, such as in the oak tree is out of sync with our desired building time frame. Therefore, another approach was developed to make use of the innate agency in trees. In response to, the foundational work by Ludwig and Schönle (2023) as summarized in their book “Growing Architecture – How to design and build with trees” which provides a clean and simplified introduction to the following concepts. Under the concept of Baubotaniks, the natural agency of trees is manipulated without genetic modification to construct a living building framework from multiple small trees grafted together forming a scaffolding.

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Construction time may be reduced by an aggregate grafting approach, but this alone does not eliminate the time bound to growth and development required under a metamorphic design approach. Metamorphosis relies on the internal mechanisms of an organism to change states, resulting in an autogenic change in form. It is these mechanisms to which we have approached the design of plants in the past, whereas the following looks to morphogenesis from an exogenic source. Morphogenesis is induced by the exposure of the plant host to a signal, causing the plant to change shape in response. A morphogenic signal can arises from another organism such is in the case of plant pathology. Targeted symbiosis between plant and pathogen is purposed in three examples, covering a range of morphogenic potential.

Specifically looking at the expanding cambium and developing callus at the point of contact between two stems in the grafted building framework (Mylo et al. 2023). A graft is considered as complete when the vascular networks (xylem and phloem) between the two plants fuse into one unified system (Jewell 1968; Webb and Patterson 1983). It is here that plant pathogens offer considerable control potential over when and where growth will occur within a plant.

"Can We Grow a Building, and Why We Would Want to?" (Dade-Robertson 2023) is also provocative for clearly, we have at least been growing the biological components of a building in the form of log cabins to straw roof since antiquity. Jumping forward to modern construction by robotic arms (Achim Menges *et al.* 2016), the scaling of mass timbers for buildings (Ayanleye *et al.* 2022), and finetuning of mechanical properties by engineered wood products (Arriaga *et al.* 2023; He *et al.* 2023; Kuzman and Sandberg 2023). We have developed multiple methods and wonderful feats of engineering biomaterial to meet our needs from the forest nursery to the wood itself used into constructions (Arriaga *et al.* 2023; Evans 2001). Nevertheless, modification of material properties after harvest falls short of the envisioned growth of a building from a single tree.

Engineering material properties of living system without the death of the hosting organism, better capture the sprit the concept a growing building evokes. Engineering of biomaterials post-harvest and the engineering of living biomaterials while the host is actively living are quite different. The former approach has proceeded to shape material properties by mostly external environments or mechanical means, while the latter intends the shaping by internal or interactomics during symbiosis (Osborne *et al.* 2023). While either direction may make use of genomic technologies to study or engineer an organism, the following offers a more holistic biological systems approach on how plant pathogens may be directly used to induce growth on demand. Omitting the genetic engineering of either the host or the pathogenic agents, living biomaterial can be grown to specifications. Where the symbiotic interactions between living systems becomes the primary shaping element in the polymorphic growth of a plant, we need only define our goal and select a suitable symbiotic relationship.

So, our vision of a growing building shifts from the metamorphosis of a single mature tree into a building, towards the morphogenesis of an assembled network of trees by symbiotic interactions. Within this living framework the focus continues to narrow in upon the grafted joint and the potential application of fungal agents at this mechanical joint. Fungal pathogens which are reported as the most economically important forest diseases in the production of biomaterials currently used to build our houses and home, wooden materials that are grown and harvested from the managed forest (Pike *et al.* 2021). Our focus upon the morphogenic capacities that plant pathogens have upon the host is to transition our perspective from the negative to a more positive one, without forgetting the pathogenic nature of the agent. From pathogenic agent to biodesign agent we question how a building may be grown using a pathological approach to elicit the natural polymorphic architectures of plants to meet our needs beyond the agricultural interpretations of growing wooden biomaterial.

Pathology of a Growing Building

Growing building blocks or designing for a change in form by metamorphosis or morphogenesis, all deal with a living system at some point. The use of living systems necessitates a pathological consideration during growth and construction, for we desire the living material to remain healthy and living during its use. How living systems remain healthy and productive depends on their innate ability to handle infection and recovery from any resulting damage. While the botanical sciences have some part of the answer, the considerations from a living and growing building remains to be investigated.

Building pathology currently considers the health of a building from the environmental (abiotic) effects and affects biological organisms have on the material of a building (de Brito and Flores-Colen 2012). For example, in a wooden building the material is affected negatively by water which often leads to moulds growing, or insect damage such as with termites. However, should the house transition into the biotic realm, becoming a living building that can grow and respond to the environment it will have to deal with the pathologies as a living system in addition. Transitioning into the biotic world of living materials for the built environment will undoubtedly raise novel questions.

To begin, we must decide from which branch of life our materials will grow from, as this will influence the limitations for application and restrict the pathological agents we might encounter or employ. In the selection of our primary host organisms, we may limit our choice to either the prokaryotic (bacteria) or eukaryotic (fungi, animals, and plants) branches of life. This limitation is due in reference to the physical scale of a house or building, so we may exclude the bacterial and fungal organisms as the primary host for they alone are not found to meet our requirements on the physical scale to grow a building (Bitting *et al.* 2022; Dade-Robertson 2020). This leaves the branches of living things to that of the animal and plants to become our primary host in growing a living building.

Although animal-based biotechnologies may meet out physical scale requirements, and offer biological structure and mechanisms not found in other organisms (Joachim *et al.* n.d.). To employ animal-based technologies the zoonotic potential between the human and house will become a critical aspect of future building pathologies (Fuller-Thomson *et al.* 2000; Office of the Surgeon General (US) 2009). As our buildings transition into using living biomaterials, we must consider the potential for exchange of infectious agents between the biomaterial and human, such an exchange is called zoonosis. Effects of zoonotic diseases should now be apparent as we have recently been downgraded from a pandemic state of emergency

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after multiple zoonotic events lead to the spread of Covid-19 virus globally (Center for Disease Control and Prevention 2023; Pekar *et al.* 2022; United Nations 2023; World Health Organization 2023). As our houses and homes are built from living materials making that transition, we will as well be affected becoming a sort of endosymbiont to a living building, our health will become intrinsically linked to that of the built environment.

In opposition to the above animal-based living materials and the risk of zoonotic transfer between the human and the house, we are left with the phytological-based building material. Those biomaterials derived from the plant kingdom. Plants, particularly those of the division called vascular plants, such as trees, offer multiple benefits as living host of a growing building. Most importantly, is the lack of any known Phytonotic events. As no known causative agents of a plant disease (i.e. Bacteria, Fungi, Virus) has made the jump between hosts to infect humans our concern is mitigated to some degree but not entirely (de St and van der Riet 1997). When considering the future of a growing building, botanical-based technologies offer the required physical scale of size, human health concerns are reduced, and contain a natural agency of growth. Meaning that wood is again the optimal material from which to grow a building, for after all wood is one of our oldest and most well characterized biomaterials to date (Niemz *et al.* 2023). To which we will review the morphogenic effects that pathogens have on the organization and materials properties, in reference to our grafted mechanical joint.

The symbiotic host-pathogen relationship while familiar to the plant pathology sector, requires a re-evaluation under the biodesign paradigm in the pursuit to grow a living building. Traditionally pest and pathogens are considered in the negative, from the plant host perspective, as their association with the host crop often leads to a reduced harvest yield (Agrios 2004). Contrarily, under the emerging engineering living material research plant pathogen finds new agency in the growth of a botanical building as a plant biodesign agent. Nevertheless, not all pathogens or pests have the desirable morphogenic effects upon plant tissue development and so it is specifically those agents collectively called Gall Inducers that are the most relevant agents for the engineering of living biomaterials.

Engineered Living Materials or Machines (ELMs)

Pathological agents are already employed in the production of biomaterials under the concept of Engineered Living Materials (ELMs) to grow the constructive units of a building (Pike et al. 2021, 2021b; Pohl et al. 2022; Porter and Naleway 2022; Pylkkänen et al. 2023; Sniezko and Dana Nelson 2022; Yamaoka et al. 2022). Where bacteria and fungi are biological machines employed in the growth of materials for the construction industry, such as in self-healing concrete recipes. Upon crack formation the encapsulated biological components become active, growing in response to available water and calcium resulting in a calcification of the forming crack (Bagga *et al.* 2022; Van Wylick *et al.* 2021). In proceeding research, bacteria have been used to mineralize sand rather than concrete cracks to make standard brick shapes as well as to explore the process of architectural form finding (Ednie-Brown *et al.* 2013; H Arnardottir *et al.* 2020). From bricks and mortar buildings to sand dunes, the process of bacterial mediated aggregation of sand have been used in engineering structures (Climatekos gGmbH and United Nations Convention to Combat Desertification (UNCCD) 2020; Larsson 2010).

Fungi as well have novel biotechnological applications as biomaterials to grow alternative food stuff (Amara and El-Baky 2023), Leather (Elsacker *et al.* 2023), Bricks (Bitting *et al.* 2022), Insulation (Pohl *et al.* 2022), and Composite Materials (Pohl *et al.* 2022; Schmidt *et al.* 2023). The recent development of mycological material and the methods to grow them far exceed the breath of this paper, but have been captured and summarized in multiple reviews (Bitting *et al.* 2022; Lantada *et al.* 2022; Vallas and Courard 2017). Although the majority have focused upon the vegetative hyphae (Elsacker *et al.* 2023; Ozkan *et al.* 2022; Porter and Naleway 2022; Pylkkänen *et al.* 2023), which leaves the differentiation of reproductive hyphae and their mechanical properties largely understudied (Porter and Naleway 2022).

Individually as well as under a multi-species relationship, bacteria and fungi have previously been investigated from the biohybrid living materials direction on the fungi-bacteria interactions (Harris and Pitzschke 2020; Sherry *et al.* 2023; Soumare *et al.* 2021). The multi-species relationship is one that has been studied extensively from an agricultural perspective and thus is the basis for most insight of the following into these complex relationships (Agrios 2004; Dundore-Arias *et al.* 2023; Harris and Pitzschke 2020; Wijesinghe 2019). Multi-species and systems level interactions between living and non-living materials of hybrid components, represent a progressive step towards growing a building. So, it is from the grafted scaffolding between trees that we find both cases of biotic-biotic and abiotic-biotic interactions of ELMs within the growing building.

Finally, we have returned to the work by Ludwig and Schönle and their Baubotanik principles, where the tree meets our requirements of the building´s physical scale (2023). In growing architecture with tree, the abiotic-biotic interaction between a stainless-steel screw that mechanically joins the two stems becomes the subject of this type of interaction. While the Biotic-biotic interaction between the two stems is initiated by the fastening, it is the subsequent overgrowth and fusion between them that is the subject of concern. Concerning the effects of mechanical stability at the connection site, and the resulting unified growth have been questioned from an engineering perspective (Ludwig and Schönle 2023; Mylo *et al.* 2023). However, the growth signals and logistical distribution of phyto-biological resource to the connection sight and across the graft union is rather more our concern here (Yin *et al.* 2012). As the prediction of when and where growth will occur is left unanswered in the Growing Architecture book, plant pathogens find new application as growth signal inducing agents.

Nevertheless, it is the growth of plant tissues that we seek to find a means of control, and for that we look to the pathology of infection leading to the process of morphogenesis. Becoming the basis upon which the plant pathogen becomes our design agents capable to induce growth when and where our needs specify. This collaboration between design and biotechnology produces a new generation of biohybrid ELMs. A hybrid where upon inactivation of the morphogenic agent, the primary biomaterial remains living and recovers from infection returning to a stable growth state (Agrios 2004; Harris and Pitzschke 2020; Ludwig and Schönle 2023; Porter and Naleway 2022).

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The Plant Host

Growing our buildings has been possible since antiquity, in the form of straw roofs and log cabins (Ellis 2021). However, the built environment is not limited to the growth of a building but expends to encompass all the land or water that surrounds a growing building. Historically, the natural environment has be shaped by our human activities as forest, savanna, or grasslands have been converted into urban centres or industrialized agricultural systems (Ellis 2021). Shaping the land and plants has caused disruptions, but it has also developed into a knowledge bases for the environmentally responsible management practices by which these straw roofs and wooden walls are now grown to our specifications of today (Evans 2001; Forest Stewardship Council 2023; Lipper Leslie 2018; McGinley *et al.* 2023; USDA Forest Service 2023). Specifications which define the characteristics desired in the stem of either row crop plant for forest tree. Characteristics of material, genetic, or symbiotic nature of which we already design and build these crop plants to our requirements.

Traditionally, the main stem of a plant has been manipulated into elongation by controlling planting density. See figure 1. Close spacing between plants combines the positive phototrophic response of the main shoot to seek light by stem elongation, with the shade avoidance behavior of trees (Sessa et al. 2018). These two behaviors, along with others, produce tall straight trees with few lower branches which produces high quality timbers for construction lumber. These traditional methods work with the natural agency of the tree to respond to the abiotic environment to grow biomaterials to our specifications. Contemporary practices have since delt with the materials properties after harvest to produce engineered wood products (EWPs) (Arriaga *et al.* 2023; Ayanleye *et al.* 2022; He *et al.* 2023; Kuzman and Sandberg 2023). EWPs have been designed in both form and function beyond the natural properties, designing new behaviors to respond again to the same abiotic environment from which they were originally grown.

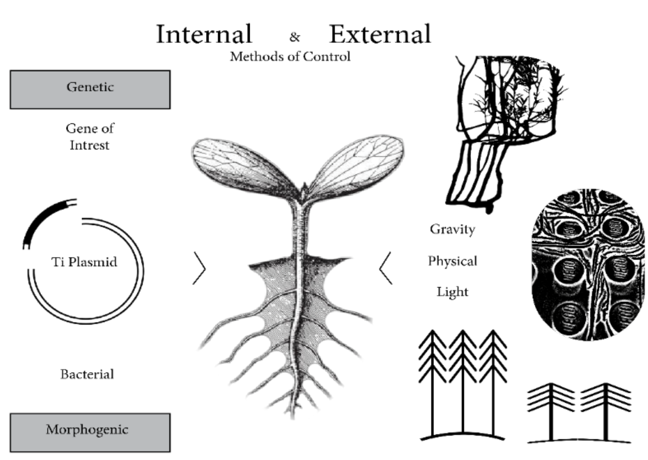

Figure 1. Depicts the external methods to control growth using light and spacing of row crops, physical molds to control the growth of roots, and gravity to strength a shaped structure. Internal methods have employed the bacterial Ti plasmid as a genetic engineer vector, it also naturally induces morphogenesis of an infected plant.

The external shaping environment has profound effect upon the whole plant, from the root to the shoot and from the cell to the organ. In working with gravity and physical barriers the project Rootfull, uses the positive gravitropic growth response of the plant roots to grow downwards combined with the thigmotropic response to touch of the root tip (von Wangenheim *et al.* 2017). Navigating complex moulds with intricate topologies the project Rootfull grows captivating biotextile from wheat roots (Holloway 2023). In scaling this idea of building with plant roots the Khasi tribe in India are the best example as they have built small bridges from adventitious aerial roots previously (Ludwig and Schönle 2023). Moving up the plant, to the shoots we have entered the concept of Arbosculpture (Erlandson 2001; Reames 2005; Wiechula 1921), to which the projects Fullgrow (Munro and Munro 2023) and Growing Architectures resides (Ludwig and Schönle 2023).

Actively shaping a shoot employs the negative gravitropic response of the shoot to grow against gravity, and the positive phototrophic response to grow towards light. Just as in the growth of lumber quality timbers above. Shaping the young flexible shoots of willow tree, the project Fullgrow makes chairs from a single continuous piece of wood (Munro and Munro 2023). Albeit it is only a single unit at harvest, having been grown and grafted together from multiple secondary shoots using physical molds. Employing the same instant shaping method of Arbosculpture, the scaling up step to that of a building has been shown in a more structured and regulated manner with Growing Architecture (Ludwig and Schönle 2023). The use of older mature trees fastened together by a single screw, therefore provide the basis from which we explore the internal response of the plant host by pathogenic attack.

In a counter point against the continued industrialization of EWPs using expensive machinery such as robotic arms to construct materials with desired properties (Achim Menges *et al.* 2016). Shaping the living material into novel form and function seems to be the work of ELMs research (Arriaga *et al.* 2023), and in principle is the concept of Baubotaniks and Arboriculture to work with the natural agency of plants in this manner to which the few recent projects above capture the essence and scaling of the concept. See Figure 1.

Fundamentally, plants are environmentally responsive and have a long history of being shaped as described by the above as well as by Arthur Wiechula (Erlandson 2001; Reames 2005; Wiechula 1921). It is clear by now that the external environment has a profound effect upon the resulting physical form of a plant, and yet it is not solely responsible for the final form a growing plant arrives. As a living organism with inherent agency, a plant has internal mechanisms which also provide important shaping signals. These internal signals work across the entire scale of the plant, from the cellular to the whole organisms, from short- and long-range communication, and by all the omics that make an organism biotic (Canales *et al.* 2018; Elias *et al.* 2018; Milinkovitch *et al.* 2023; Mukherjee *et al.* 2022; Pierre-Jerome *et al.* 2018; Ramos-Cruz *et al.* 2021). Therefore, our plant host must not only respond to the abiotic environment, but it must contend with the biotic signals as well. Biotic signals that arise from the plant itself (autogenically) and those from a pathogenic agent alike (exogenically).

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Agent Pathogen

Plants or buildings are not too different as both must deal with the abiotic elements and biotic agent which cause diseases traceable to a causative agent. These pathogenic agents arise from every branch within the tree of life, and all produce an equally diverse range of effects in their associated hosts. In the above case where plants, specifically trees, are to be the primary host of a living building which plant pathogenic agent would prove beneficial as biodesign agent requires an extensive review. Agents which stimulate growth (Chickarmane et al. 2010), cellular differentiation (Pierre-Jerome et al. 2018), and epigenetic modulation (Maggert 2012; Ramos-Cruz et al. 2021) of the host already exist. Pathogenic agents occur as viruses, bacteria, fungi, insects, and more (Agrios 2004). However, the most inspirational are those morphogenic pathogens also called Gall Inducing pathogens as they offer potential for learning to control plant growth to meet our needs (Harris and Pitzschke 2020). Opening the question of how these pathogens can make the transition from the antagonist in the health of a forest, to the protagonist of morphogenesis for that same tree as a living building?

For now, our question of which agent pathogen is most desirable for inducing morphogenesis of the living plant returns us to the plant-virus relationship to which Gergerich and Dolja provide a great introductory overview (2006). How they might be engineered as design agents of plant growth is reviewed by Zaidi and Mansor (Zaidi and Mansoor 2017). Which virus and which goals are needed to be designed into them are limitations which require far more review than is offered here. However, a survey of plant virologists, produced a top ten list of the scientific and/or economically importance viruses (Scholthof *et al.* 2011). Of these identified viruses the resulting effects on the plant host were only discoloration or slight deformation due to cell death (Scholthof *et al.* 2011). While plant viruses could prove to be more amenable as agents of design under the ELM concept, they lack the inherent morphogenic capacities we seek. This lack of native morphogenic effect, places them into a bottom-up category of engineering agents, as any desired effect would have to be synthetical transformed into the virus (Staufer *et al.* 2022; Tian *et al.* 2019). While a bottom-up approach has to add completely new functionality to the organisms, the contrasting top-down attempts to strip out information to a minimal desired function. The following approach falls somewhere in between these two concepts; in that it directly employs the native morphogenic capacity of an organism (Gergerich and Dolja 2006; Mateu 2011; Scholthof *et al.* 2011).

In similar fashion, bacterial agents are known to vector multiple genetic sequence into their host cells, an insight that became the foundation of genetic transformation techniques (Escobar and Dandekar 2003). Natively, bacteria of the crown gall diseases vector the genes for auxin and cytokine as well as one for food production in the form of a metabolizable sugar for the reproducing bacteria (Gohlke and Deeken 2014). As a founding organism of the biotechnological age, it is fitting these bacteria are considered as potential chassis for morphogenesis. Bacterial morphogens identified and or designed by synthetic biological processes to produce a next generation biotech under the name Engineered Living Materials are already proving useful in the growth of building components (Desnitskiy *et al.* 2023; Korgaonkar *et al.* 2021). While the concept of synthetic living machines (SLMs) (Ebrahimkhani and Levin 2021) is not far from this application of collective intelligence, the bacterium is a disruptive system to the material properties of a host's wood. Disorganized infection tissues leave us to desire a more appropriate system to design for organized growth.

Fungal rust pathogens induce localized morphogenic growth of their hosts tissues without completely disrupting the material properties of infection reaction wood (Gramacho *et al.* 2013; Jewell 1968). Since our desired specification is the controlled and regulated growth of wood withing a living building frame, the resulting wood grain or arrangement of specialized tissues within the affected stem becomes a rather important material property to be considered (Arriaga *et al.* 2023; Ludwig and Schönle 2023). Fungal induced morphogenesis offers a more tangible and readily applicable biotechnology, even without completely dissecting the genetics regulation of either organism during infection (Gramacho *et al.* 2013; Warren and Covert 2004). Interaction between the host pine tree and agent fungal hyphae will produce a typical reaction response during infection that can be monitored without destructive sampling methods. This infection response has been observed between multiple pine species and different fungal isolates, to which each study must use an inoculation step to introduce the fungal agent to the host (Jewell 1968). Consequently, in the context of living architectures of Baubotaniks, and specifically upon the method of fastening tree stems together an application of fungal biotechnology is found.

The resulting plant-fungal interaction during the fastening of stems together introduces a fungal mediated signal for growth which dissipates from point on infection. One important growth quality is the increased quantity and size of vascular elements within galled tissue (Jewell 1968; Jorge *et al.* 2022). Increased vascular tissue withing the graft callus has potential to increase grafting successes. Once union has been achieved the fungal morphogenic agent may be inactivated by application of a locally systemic fungicide, killing the agents without harm to the host tree (Kelley and Rowan 1980). Thereby engineering our living wood materials to meet our architectural designs, without the synthetic biological reductionism required to transfer insect derived morphogens into bacterial vectors (Duplessis *et al.* 2011; Gohlke and Deeken 2014; Ozkan *et al.* 2021).

Pathogens capable of inducing the division, differentiation, elongation of plant tissue during morphogenesis from the wild-type form into exotic forms exist in a spectrum of morphogenesis from basic shapes to highly ordered and structured materials (Harris and Pitzschke 2020). In this respect, insects (pests) hold the greatest control over morphology inducing a process equivalent to complete organogenesis. Drawing from the most recent publications upon the subject of insect-induced galling. The search narrows to a specific set of genes involved from both the host and biological-agent (Cambier *et al.* 2019; Elias *et al.* 2018; Hearn *et al.* 2019). These effector proteins are involved in the cellular division, enlargement, pigmentation, surface texturing and more materials and physical properties of galls. Known as Cecidology, the study of plant galls is a rather understudied subject which leaves the exact mechanism or morphogens still to be discovered (Nastasi and Davis 2022).

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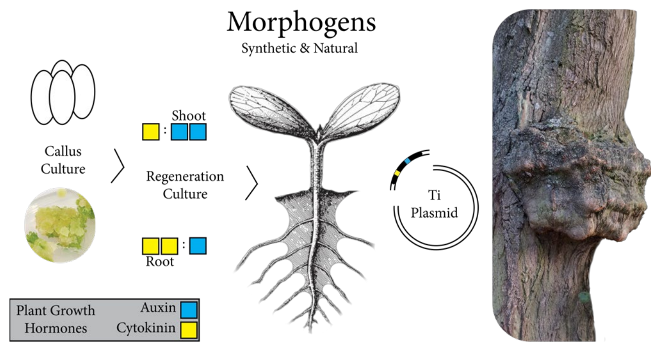

Figure 2. Auxin as a morphogen is naturally occurring in bacteria induce tumour like growth in a host tissue by vectoring auxin and cytokinin via the Ti Plasmid. Those same plant growth hormones are used in plant tissue media during regeneration from callus culture to induce root with low auxin and shoot with high auxin concentration of the culture medium.

Morphogen and the Host

In the following sections the symbiotic relationship becomes our focus wherein we seek to identify the native capacities of pathogens for morphogenesis of the host plant. Naturally a plant has an adaptive organization from the higher body plan and the morphological organization of its tissues (Kaplan and Specht 2022). As host, that natural organization is disrupted during a pathogenic symbiosis, which unlocks the normal limitations of morphogenesis established by the uninfected host. While the mechanisms may differ between host-agent, there is a common plant hormone which acts as morphogens.

Kaplan and Specht have produced a valuable review of the principles of plant morphology, to which chapter one outlines distinctly the topic of plant morphology and how the overall architecture is created from within the plant, autogenic (Kaplan and Specht 2022). At the whole organism's level Darcy Thompson writes from the animal perspective, and both write on the physical or mechanical mechanisms governing growth (Kaplan and Specht 2022; Thompson 1992). These are essentially the leavers or control that we seek to govern but the magnitude of actions, reactions, and interactions that occur within a growing plant are inherently complex. The internal state of the plant becomes yet more complex as it actively responds to pathogenic infection.

Often described as an evolutionary arms race between host and pathogen, the biochemical interactome that occurs during infection originates from within both the host and pathogen. Bioactive chemicals produced by one organism defuse within themselves and are secreted outside of themselves as extracellular metabolites. How these chemicals might defuse and interact with each other became the chemical basis of morphogenesis described by Alan Turing (Turing 1942). Although not originally speaking of biomolecules within living systems, his work can show how the reaction diffusion patterns governing phenotypic traits of animals as well as the morphology of plants (Milinkovitch *et al.* 2023).

Naturally, multi-chemical diffusion rates are computationally complex but in the current age of computers these can be modelled using simulations to some degree. The paper by Marconi and Wabnik on "Shaping the Organ: A Biologist Guide to Quantitative Models of Plant Morphogenesis" reviews the historic progression of digital growth models to reach the present research interest (Marconi and Wabnik 2021). The digitization of growth combines the computational modelling via Finite Element Methods (FEM) processes, as well as advanced microscopy to map and model every plant cell under the plant cell atlas project (Bassel and Smith 2016; Chickarmane *et al.* 2010; "The Plant Cell Atlas" 2023; von Wangenheim *et al.* 2017). Large scale plant anatomy as well as at the individual plant cell have been found to contain bioelectrical patterns, resulting from distribution and concentrations of plant growth promoting hormones (PGPH) (Heisler *et al.* 2010). Hormones such as Auxin and Cytokinin as found in bacterial pathogens (Gohlke and Deeken 2014), and which would become the bases for plant tissue regeneration culture protocols utilizing Murashige and Skoog (MS) medium (Murashige and Skoog 1962; Soumare *et al.* 2021).

These same PGPHs have been found at the infection sites of multiple diseases, where the causative agent repurposes the native cellular mechanism of the host to generate an environment more conducive to their own growth and survival (Brefort *et al.* 2009; Chanclud and Morel 2016; Glick 2012; Rowan 1970b). Botanically, the polymorphic architectures of a single plant are simply astounding as it may host multiple galling species simultaneously. Each species induces a more exotic growth than the one before, in size, shape, colour, texture, function, and material properties (Harris and Pitzschke 2020; Nastasi and Davis 2022; Perea *et al.* 2021). The morphological capacity of that single plant captures the imagination of our future designs, as from one genome arises so many novel forms showing the plasticity of the plant cell (Sultan 2000). A totipotent plasticity that is intrinsically linked to the host, agent and morphogenic signals exchanged during relationship (Su *et al.* 2021). A relationship, that we may now exploit to meet our emerging goals of controlling growth of a host through pathogen derived morphogens and the induction of synthetic morphogenesis.

Hormones as Morphogens

Plant growth promoting hormones primarily arise from the Shoot Apical Meristem (SAM) and is the point from where a plants anatomy is considered to originates (Heisler *et al.* 2010). More pointedly the SAM is one origin of the signal gradients which informs the growth of a plant. Multiple gradients are established from the single cell level all the way up to the whole organism level, these biochemical gradients balance the internal against the external environments (Su *et al.* 2021). Anatomical informing gradients, derived from the SAM in the form of hormones such as auxin and cytokine (Mukherjee *et al.* 2022). As a primary pair these hormones are a major aspect of morphogenesis of a plant.

How these pathogens shape the morphology of a plant, has been found to be in the manipulation of the hormonal signals. In which auxin is one of the most exploited and studied hormone used by plant pathogens and humans alike (Cambier *et al.* 2019; Chanclud and Morel 2016; Glick 2012; Mukherjee *et al.* 2022). To study these hormones and growth the small model plant Arabidopsis is most often used, such as in the visualization of auxin movement within a living plant using fluorescent labelling and confocal microscopy. (Heisler *et al.* 2010) Model organisms for studying a plant growth cycle during infection for bacteria are Agrobacterium (Escobar and Dandekar 2003) and for fungi are Ustilago (Brefort *et al.* 2009). Ustilago maydis is the

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causative agent of the disease known as Corn Smut and the food called Huitlacoche. This fungus also exploits the powerful signals associated with the hormone auxin, to divert phytochemical resources to the point of infection (Djamei *et al.* 2011). Infection which induced the growth of the plant cells and tissues to grow far beyond the normally established anatomical size or shape.

In figure 3, the morphogenic effect of the bacteria (*Agrobacterium tumefaciens*), fungi (*Peridermium harknessii*), and gall wasp (*Andricus kollari*) are compared in cross section. The morphogenesis induced by each of the respective pathogenic agent affects the exterior phenotypic form as well as the interior material properties of the host plant. From the tumorigenesis of the bacteria to create unorganized growth rough, to the complete organogenesis of the insect. How might we employ the native agency of these pathogens to control the morphogenic process to meet our own emerging specificities? To this end, we began in the middle with the simple but organized growth induced by fungi.

Beyond Organogenesis

Growing house and food may capture the idealist sprit of what is envisioned when asked how to grow a building, and why we might want to (Dade-Robertson 2023). Yet organogenesis as induced by the morphogenic galling insects, only reproduces the anatomical elements of the host, albeit in novel and exotic forms. To move beyond this replication and rearrangement of elements into more human centric goals, will require a great deal of research to develop a synthetic induction system independent of an insect-tree symbiosis. For now, such a biodesign process remains a dream beyond our reach, at least until we learn the basis of simple transformation first.

In this regard a focus upon learning to work with the capacities for fungal agents offer a means to induce tangible morphogenesis affect with relevant biomaterial tree hosts. While these fungi may only induce the basic change of the plant stem from a cylinder to a sphere locally from the point of infection, we have already a history of research to draw upon (Gramacho *et al.* 2013; Jewell 1968; Peterson 1960; Rowan 1970b, 1970a; Warren and Covert 2004; Webb and Patterson 1983; Wijesinghe 2019; Yamaoka *et al.* 2022). A history of research that has not yet viewed the tree-rust relationship as more than a pathogen, to which they are now offered as agents for actively shaping plant growth.

In the pursuit of controlling morphogenesis to grow plants beyond their natural anatomical structure using fungal agents represents only a small step in the proceeding direction. An approach which requires the review of previous research under a biodesign discourse of engineering living materials research. As research moves from morphogenesis inducible by natural agents, which generally works within the limits set by the hosts specific grow behaviours. Moving beyond the natural organogenesis into the synthetic will remain, an interesting but challenging pursuit for future research interests.

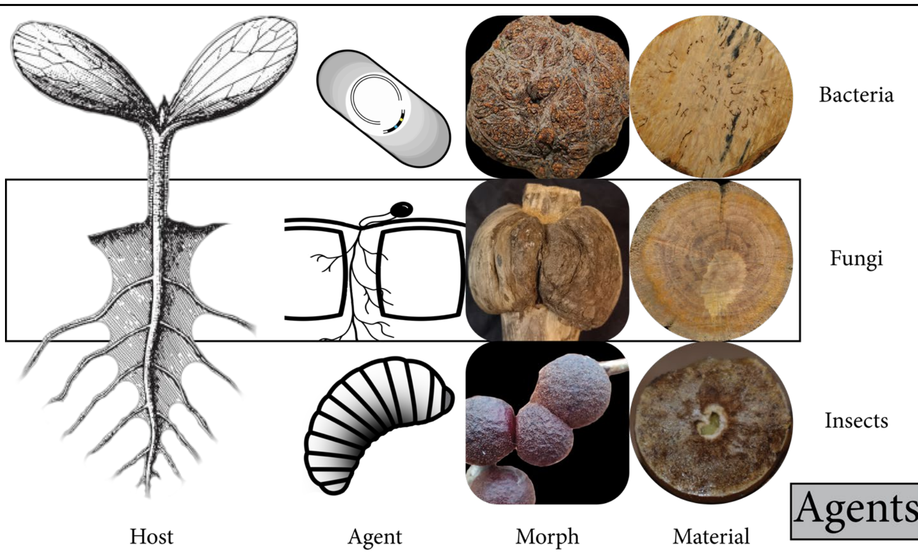

Figure 3. Overview of the host and symbiont agents of morphogenesis. Where the agents are Bacterial, Fungal, or Insect each have a defined external morphology associated with their growth. As well each gall has internal material properties, such as the fungal induce growth appears normal as is highly desirable in ELMs.

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Plant Design Agents

Plant Pathogens – Methods of Morphogenesis Induction

Designing plants is no simple task, but one in which we have achieved some degree of capability. The 2020 Research Road Map for Plant Biosystems Design provides a comprehensive overview on theories, principles, and technical methods of designing plants (Yang et al. 2020). Also, this road map summarizes well the future directions from where we currently are and how emerging synthetic biological principles might be employed to design plants to meet our needs beyond food, medicines, and more. Just as the historic design of plants has focused on the genetic engineering for stress tolerance and resistance to disease so too does this future roadmap, speaking only briefly upon the engineering for beneficial symbiosis citing the considerable potential of future research. This topic of beneficial symbiosis and the impact the microbiome has upon the plant is as well as growing focus in designing with plants (Escudero-Martinez and Bulgarelli 2023). The future of co-opted microorganisms is expanding our toolbox for design.

Moreover, known pathogens are finding new applications as the organism's agency transitions through a role reversal. Such as in the case with *Fomes Fomentarius* which is making that transition, from endosymbiont (Baum et al. 2003) and pathogen to agent species in the production of biomaterials (Schmidt et al. 2023). A transition of perspective, from the traditional view where the pathogen is the antagonist of the plant-host relationship, to the emerging unconventional perspective where they become the protagonist of a sustainable future of engineering new agency into living materials. However, just as the above fungal-based ELMs had to begin with a simple brick shape to transition from the original mushroom fruiting industry to the architectural. So must too the morphogenic agents start with similar basic transformations.

Host manipulation by biological agents exists within a broad symbiotic spectrum. A continuum of biotic organisms, all of which employ an equally diverse range of mechanisms for inducing symbiosis (Harris and Pitzschke 2020). Just as with humans the plant microbiome affects its health (Pagán and García-Arenal 2020), beyond this each pathogen displays a typical symptomatic response from their host. To which the following sections are concerned with those agents which induce a phenotypic polymorphic growth. Rather than complete necrotrophic death of a susceptible host nor the complete resistance against a pathogenic infection, a middle ground of tolerance becomes an interesting future for research upon the host-agent relationship (Pagán and García-Arenal 2020; Pike et al. 2021; Sniezko and Dana Nelson 2022). Microbial induced morphogenesis is the method by which we will explore how to design plants from the abstracted organism level without genetic intervention. See Figure 3.

Fungal Agents – Pine Gall Rusts

In designing the growth of a plant or a building we can start with the architecture, where the main stem is our focus rather than inducing growth of roots or leaves. In the living botanical building the principal component of the tree is the trunk, here we require control over cellular growth and differentiation. In pursuit of controlling when and where growth will occur within the bounds of the main trunk, fungal gall rusts are purposed for transition from the causative agents of disease into agents for biodesign for controlling architectural growth.

First there is the causative agent *Peridermium harknessii* (*P. harknessii*) which causes Eastern Pine Rust (Peterson 1960; Wijesinghe 2019). In the identification of infection by phenotypic expression of symptoms, infection by this pathogen reliably produces a round or globose gall. Internally from the point of infection, intercellular hyphae expand both up and down the stem radially (Peterson 1960). It is by the proximity of these hyphae that the growth of the gall tissue is induced. While it might be a simple control over the growth dynamics of a host, it also has the potential to become a tool to control morphogenesis. See figure 4.

Second, we have the causative agent *Cronartium quercuum f. sp. fusiforme* (*C. fsp fusiforme*), which is the pathogen of the disease Fusiform Rust (Webb and Patterson 1983; Wijesinghe 2019). Producing a localized increased growth rate at the point of infection, the resulting morphogenesis is similar. How the infection extends within the host plant tissues is however slightly different. *C. fsp fusiforme* fungal hyphae display a stronger gravitropic growth response as opposed to that of the P. harknessii with an equal radial growth behaviour, resulting in the downward tapering of the stem from the original point of infection (Rowan 1970a; Webb and Patterson 1983). Again, while this galling of the host tissue is simple, it offers another stable transformation of the host tissues for design goals. See Figure 4.

Both fungi induce localized growth of the host plant in reliable and reproducible morphogenesis, for which we can employ directly in the growth of a building without engineering. Granting that the host species is tolerant to infection by the selected design agents (Gramacho *et al.* 2013; Pike *et al.* 2021; Sniezko and Dana Nelson 2022). Morphogenic behaviour is species specific and dependent on the host-agent relationship. The co-evolution of these organisms in turn places some limitation on the ready application of fungal induced morphogenesis. Such as on the host species for which the Baubotaniks of Growing Architecture are focused upon the Willow and/or Plane Tree, whereas the rust fungi presented are specific for pine trees. In addition, rust fungi have an alternating life cycle where the spore type that infects pine trees, also grows on an alternate host such as oak tree (Peterson 1960).

Counterintuitively, to the traditional view of plant pathology the purposeful infection has value beyond the screening assay for resistance (Sniezko and Dana Nelson 2022), we need only define our new goals as they relate to emerging living building paradigm. Generally, the screening assay observes the interaction between a selected host and competent agent (Yamaoka *et al.* 2022). The study of host response to pathogenic attack has converged upon standard protocols, as both the host must be raised as well as the causative agent propagules must also be grown or collected (Yamaoka *et al.* 2022). Specifically, for our fungal rust agents there is over 50 years of interactions data for review and extraction (Jewell 1968; Peterson 1960; Rowan 1970a; Webb and Patterson 1983; Yamaoka *et al.* 2022). Rather than observing from the host side for a resistance response we might select for a more favourable intermediate susceptibility response, also called tolerance (Pagán and García-Arenal 2020). While screening and scoring a host response for resistance or susceptibility is the more typical assay, targeting a tolerant host response will require only slightly different observational study. We need now only apply our observation to those that would prove applicable to the growth of our building.

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Fungal agent induced morphogenesis offers a means of controlling where, when, and how plant tissue growth will progress. Taking the instant shaping method employed in the growing of architectures book, where two individual stems are brought into contact and fastened together by a single mechanical connection, a screw (Mylo *et al.* 2023). See Figure 4. Under traditional horticultural practices this approach graft and fastening methods would be considered a potential point of infection, due the physical damage of the screw as well as abrasive damage from the two trucks rubbing together (Mylo *et al.* 2023). This approach graft methods becomes our inoculation method to bring our morphogenic agents into contact with the living tissues of the host. In the wild, infection would normally progress via the needles of young branches before the invading hyphae would progress to the trunk (Wijesinghe 2019). The screw now acts as the vector carrying the fungal agents into the main trunk directly. Naturally the two trunks would grow into each other as individuals, until the vascular tissue of the cambium becomes unified into a single stem. Applying this purposeful infection by morphogenic agents would reduce the time until our building design would become one stem from many. Although the mechanical properties of the resulting infection wood would require testing to define its limitations, the work to assess this graft union has already been conducted (Arriaga *et al.* 2023; Mylo *et al.* 2023).

Figure 4 shows the Fungal mediated auto-inosculation in where by two pine stems are fastened together by the mechanical connection of a screw. As the screw vectors the fungal rust spores into the pine tree tissues, the typical infection progression is bypassed. Depending on the causative agent pathogen selected, the resulting infection induced growth proceeds in a more localized manner as with Eastern Gall Rust (EGR) or in a tapering of growth with Fusiform Rust (FF). As the stem tissues within the morphogenic zone of effect which expand outwards from the point of infections, following a species-specific behaviors. The swelling reaction wood expanding faster than the unaffected stem outside of our dissipating morphogenic gradient, we have induced the localized growth (Jewell 1968). This volume of fungal influence, galling tissues typically have increased vasculature. Vasculature becomes critical to the graft union success via fusion of the individual cambium tissues. With increased vasculature the rate of success could be improved.

Engineering living materials is not an easy task often due to the inherent nature or working with living systems, but one that can be controlled to a high degree of reproducibility due to host specificity and co-evolution. A symbiotic history which offers new research interest to study the host-agent relationship of a major economically important pathogen which already infections the ELMs from which we build our houses currently (Webb and Patterson 1983). A relationship that would change as we progress from using the non-living wood to construct our building but transition into using the living wood to build our houses and homes. Where the temporary infection is allowed to grow as to meet our building needs but is inactivated at a later stage. To turn off the galling of the host trees tissues a locally systemic fungicide can be employed to inactivate, kill, the fungal pathogen. As our Engineered living material is the wood of a host as opposed to just the fungal agent, post infection recovery of the host is another topic for future research (Gramacho *et al.* 2013).

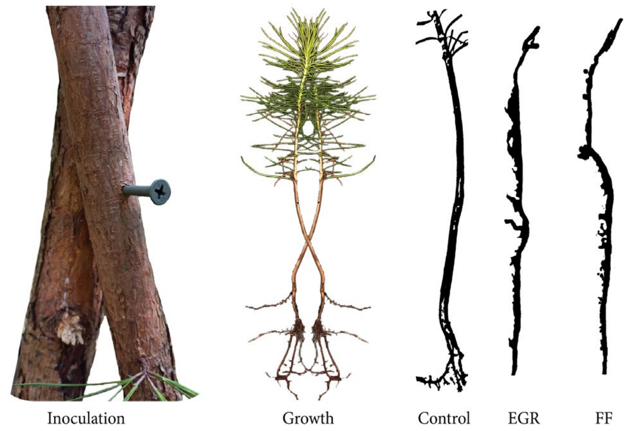

Figure 4. Causative fungal agent growth profiles. As the growth of two approached graft fastened trees are inoculated, the use of host and fungal species can determine the growth morphology, where Eastern Gall Rust (EGR) forms a rounded globose gall, the gall of Fusiform Rust (FF) develops into a tapering cylinder.

Bacterial Agent – *Agrobacterium tumefaciens*

The bacterium is a living machine, capable of delivering a genetic payload into a host plant. Bacterial transformation is now a common practice for engineering other organisms, and *Agrobacterium tumefaciens* (*A. tumefaciens*) became a catalysis for biotechnology of today. Transcending their origins as the causative agents of Crown Gall Disease, the bacterial tumour inducing (Ti) plasmid has been used to engineer multiple other organisms (Escobar and Dandekar 2003). In reference to Figure 3 above our interest is their effect of the plant host where upon infection a morphogenic growth signal is introduced within the internal environment of the plant. In response the plant cells divide and/or expand into a tumour-like growth. The resulting unregulated growth produces wood with poor material properties, such as reduced strength due to the method of inducing morphogenesis (Arriaga *et al.* 2023; Niemz *et al.* 2023). For at the point of infection, the TI Plasmid randomly inserts its payload into the host cell DNA (Escobar and Dandekar 2003). The vectored payload contains multiple genes, such as auxin, cytokinin, and Opine (Gohlke and Deeken 2014). The random insertion of auxin outside of its normal regulatory pathway, and into the indole-3-acetamide (IAM) pathway produces a continuous signal resulting in the gall formation. While auxin affects cell elongation the second inserted cytokinin gene stimulates cellular proliferation, division (Escobar and Dandekar 2003; Gohlke and Deeken 2014). While the third, an Opine gene induces the production of a sugar by the host cell that the bacteria can metabolize as fuel for growth. So, with these three genes inserted into the host the bacteria *A. tumefaciens* induces basic un-controlled morphogenesis of our plant host.

From an ELM biodesign perspective, the resulting material properties of the gall wood fibre alignment does not meet our needs for the growth of a living building (Jorge *et al.* 2022). However, as a potential agent for design for the growth of plant tissues the bacteria is a useful platform. A design platform that is already in use under the synthetic biological approach employing the engineering Design-Build-Test-Learn (DBTL) cycle. So, as a morphogenic agent, what are the limitations of the natural polymorpha and the synthetic

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behaviours we may design remains further definition. Nevertheless, the above and following are given as a comparative example in how such research might proceed in combination with recent identification of candidate morphogens from insects (Korgaonkar *et al.* 2021; Martinson *et al.* 2022).

Entomological Agents – The Wasp and Aphid

Insects have already arrived at the point of biodesign that we seek for the near future growth of our buildings and homes (Harris and Pitzschke 2020; Nastasi and Davis 2022). Producing the most beautiful and exotic forms, the gall-wasp induced the morphogenesis of their host plants cells mostly by mechanisms still unknown. Only recently, have these insects received the research attention needed to identify the mechanisms by which they grow their shelters to protect themselves from the environment and predation (Cambier *et al.* 2019; Desnitskiy *et al.* 2023; Korgaonkar *et al.* 2021; Martinson *et al.* 2022). Additionally, the gall wasp larvae induce the growth of their food stuff just as with the bacteria above within the interior of the species-specific galls (Martinson *et al.* 2022). The more common or iconic insect induced plant gall might be the wasps of the *Cynipidae* family, producing truly exotic morphologies that are seen nowhere else on a host plant. Unfortunately, these insects' life cycle and associated morphogens remain cryptic.

In recent attempts to decipher these morphogenic signals, the venomonic profiles of the adult wasp were analysed for their potential effect on host tissues (Elias *et al.* 2018). During the oviposition of the wasps' egg a small quantity of venom is injected. Although this venom seems a likely inducing agent, it likely has only a short affect meant to subvert the immediate host plant defenses (Elias *et al.* 2018). A more likely source comes from the salivary glands of the wasp larva, as it is observed that gall senescence is linked temporally with the pupation of the larva (Elias *et al.* 2018). As an additional point for support for this purposed linkage, comes from those communal galling insects whereby the number of individuals within a gall affects the overall size of growth. Considering these factors, should the morphogenic signal remain continuous the growth of the gall tissue is thought to continue. A hypothesis that is not without support (Elias *et al.* 2018). As the morphogenic mechanisms of the gall wasp continue to be interrogated, the salivary genes become more interesting as candidate morpho-genes (Martinson *et al.* 2022). Candidate genes for the engineering of living materials of the built environment.

Since the gall wasp mostly remains as a cryptic species, a more amendable insect to study is required one that is easily reared under laboratory settings. For this we now turn to a gall-inducing aphid of the species *Hormaphis cornu*, which affects willow tree leaves. The work by Korgaonkar et al. on this species describes the simple vertically tapering conical galls which often comes in two colour variants (2021). Often these Green and Red galls appear on the sample leaf at the same time, a polychromatic phenotype that is also seen in the galls induced by the midge *Mikiola fagi* on Beech (*Fagus*) trees. This population variance led the researcher to analyse the host tissue throughout the stages of galling using genome-wide association study (GWAS) (Korgaonkar *et al.* 2021). Their findings linked the upregulation of at least seven host plant genes within the red gall tissue to the anthocyanin synthesis pathway. Anthocyanins are colour pigments found in plants. From a pathological perspective these pigments are often linked to infection defense mechanisms, so it is not too surprising to read this result. This upregulation for anthocyanins leads to the deposition of two red pigments within the gall tissue, leading to the observed red galls. Additionally, Korgaonkar et al. identified 8 differentially regulated genes of the host plant in the green gall and similar variance was found for 476 genes of the aphid (2021).

What this means for plant design agents is that our potential biodesign toolkit can and has expanded in colour palette. In finding the Determinant of Gall Colour (dgc) genes in the salivary glands of a gall-inducing aphid, *Hormaphis cornui* (Korgaonkar *et al.* 2021). We have a candidate gene pool to transform into another vector such as the crown gall bacteria. Under the D-B-T-L Cycle of synthetic biology the 476 candidate genes could be evaluated to some degree. See Figure 5. While the identification of these colour associated genes is of interest, their application to the growth of a building leave much to still be desired. When considering the growth of a human habitable space, size, and internal voids would be more desirable early targets rather than that of colour. All the same, induction of morphogenesis would seem a complex regulator task equal to that of engineering a botanical building to grow from the Single Seed Model. Therefore, we return to morphogenesis by fungal agents, as a steppingstone to move beyond phytochrome plant design aspects. See Figure 5.

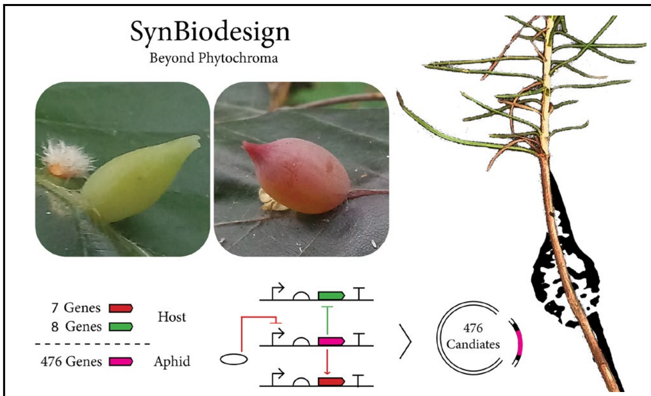

Figure 5. Showing the green and red gall of the midge *Mikiola fagi*, a Synthetic Biological Open Language (SBOL) glyph-based icon of the interaction between the reported 476 Aphid genes suspected in the differential regulations of host genes resulting in either green or red galls is shown to represent the targets of Synthetic Biological applications to target morphogens beyond the Phytochromic controls.

Symbiosis Over the Individual

Symbiosis regularly deals with complex living systems, often with cryptic components that have yet to be identified. However, our lack of knowledge of mechanisms involved during the symbiotic relationship of a pine tree and fungal agent does not prevent its capacity to infect and induce morphogenesis. Rather this lack of understanding necessitates its continued research of their relationship from a new perspective. However, the gene-to-gene research belongs to that of the synthetical biological approach of ELMs as their elucidation typically proceeds in opposition to the holistic acceptance of a naturally symbiosis. Accepting the natural agency of both living systems in a symbiotic relationship, as well as the resulting outcomes from their interactions offers a glimpse towards controlling growth and development.

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Although the pine-fungal relationship remains parasitic in nature, there are varying degrees of susceptibility and resistance reactions between the two organisms. A symbiotic spectrum rich in variety and novel applications in the future of engineering living materials. Selecting for tolerant reactions between pairs of tree cultivar and fungal isolates, known morphologies arise. Rather than designing each living system's behavior independently, image the potential in designing for the symbiotic effects between them. To which the above fungal rust of pine trees presents an interesting opportunity to identify beneficial effects from pathogenic symbiosis during the growth of a tree or building alike.

Perspective and Limitations

Here it must be said that an extensive review of all plant pathogens and disease agents has not been covered, for there may be other host-agent relationships that may prove better systems for the growth of a building. Nevertheless, the above viral, bacterial, fungal, and insect models offer the best connections across the entire living system that is the tree. From the roots, shoots, and leaves these pathogens may infect a host plant, bacterial agents offer a tie to the genetic basis of biotechnology to study the interactomic during symbiosis. Fungal agents offer a basis of morphological transformations from which we may build upon. While the entomological agents offer inspiration as to what is already possible by natural agents. Employing pathogenic agents in growing a building will require the correct selection of appropriate agent, task, and hosting systems to find symbiotic compatibility for desired morphogenic effects.

Conclusion

Plant pathogens have more to offer than to only be considered as pathogen or pest, they offer a chance to do what our technologies have yet to replicate. The pathogens' natural ability to shape the growth of a tree, is unmatched against our current engineering ability. Therefore, it would be unfortunate to continue to view them only in the negative but rather find the positive in the morphogenic capacities these gall inducing agents have on a host plant. As emerging biomaterial research continues to find new applications for botanical biotechnologies, how we will continue to shape the growth of a plant finds new agency in the co-option of pathogens. Working with the natural abilities of the agents to induce growth upon infection as agents for biodesign, a tolerant symbiotic relationship can develop.

Growing a healthy and resilient forest becomes analogous to the growth and maintenance of a living building. The transfer of knowledge between the two provides a critical connection to the pursuit of engineering living materials for a sustainable future. Engineering wood while the tree remains living offers new opportunities to design material properties to meet our specifications. Fungal rust pathogens clearly offer an untapped morphogenic capacity, from which we need not engineer either the host or agent to turn this natural agency to our advantage. Instead, a fresh perspective of plant pathology holds the key to unlocking polymorphic architectures of plants.

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Competing Interests

None

Ethics Statement

The above work was written in response as an impact article type, and so was written from a review perspective only. As a review of literature compiled in response to a question, no physical research or analysis of data was conducted. Since written as an impact article type ethical approval and consent are not relevant to this article type.

Although it was not required in the above case of this paper, should the purposed research be carried out the following authorities are offered as resource for consultation:

United States: United States Department of Agriculture - Animal & Plant Health Inspection Service - Plant Protection and Quarantine (PPQ) (USDA-APHIS-PPQ)
https://www.aphis.usda.gov/aphis/ourfocus/planthealth

European Union: European Commission Food, Farming, Fisheries,
https://food.ec.europa.eu/index_en

If outside of the above Regions please refer to:
International Plant Protection Convention (IPPC) :
https://www.ippc.int/en/

Connections Reference

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