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The SAND Model

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# Innovation from the perspective of a natural scientist: The SAND model.

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**Abstract**

*Engineers and natural scientist are required to suggest successful utilization of their discoveries and secure property rights to their universities whenever possible. Here I develop a novel model that optimizes the process of innovation by dividing it into three separate phases following the pre-innovative discovery; i.e., an application phase, a design phase, and an entrepreneurial phase. The phases are identified in the well-described innovation of the electron tube from Edison's light bulb. Each phase consists of an abductive process, where a large selection of possible solutions is created, followed by selection of viable solutions among them according to their fitness in an entrepreneurial niche. An innovation is described in an evolutionary setting, starting with a novel discovery which becomes the Source (S) of an innovation. In the application phase, a viable application (A) of the Source is selected among a variety of possible applications. This again becomes the basis for a viable design (D) in the design phase. Finally, to become a viable innovation the particular discovery, application and design has to fit into an entrepreneurial niche (N) with a high fitness. To become a successful innovation all four elements (SAN D) need to be optimized by abduction.*

*The present SAND model is different from all other innovative models in its focus on three separate creative abductive processes, yet current innovative theories can be described in the four dimensional innovation space by mapping along its four SAND axes. Analysis of fitness landscapes is in the present report used to visualize the events leading to incremental versus radical innovation, sustaining versus disruptive innovation, as well as the difference between technology and meaning-changes in design. Leading innovation models thus fit in as specialized scenarios under the general model. A low level of redundancy was found between the SAND model and the Stage-Gate model, but the differing theoretical foundations have the effect that the two models are complementary rather than overlapping.*

## Introduction

In this article I present a model of innovations that sets the frame for the initial process of linking a novel discovery to possible applications. It is primarily a visualization model and describes the process of linking the discovery to an application as the identification of the optimal point in a two-dimensional space. Two additional creative processes of linking innovation-elements are needed for creating a successful innovation. The first process is the linking of the discovery and the application to an optimal design, and the second is the linking of the elements to an optimal entrepreneurial and commercial niche. All and all an innovation can be defined as a specific location in a four-dimensional SAND space. Even though the model operates with four phases or levels in the creation of an innovation, the theoretical foundation is totally different from process models like the Stage-Gate model (Cooper, 2001). To identify the areas of redundancy between the SAND model and other innovation models, these have been mapped and visualized using the SAND model. The construction of the SAND model is derived from an analysis of the research and patterns leading to the electronic tubes and their use in wireless telegraphy in the start of the twentieths century. Underlying the model is a concept of creativity based entirely upon the idea of abductive reasoning defined by Charles Sanders Peirce. Taking into account the major line of criticism relating to this idea, an informatics-based definition of abduction is suggested which highlights the importance of a combination of unrestricted idea-generation, mental simulation, and fitness-based selection.

**Abductive reasoning in science and in innovations**

Charles Sanders Peirce defined abduction as the missing creative element in science (Peirce.C.S., 2014), a mental technique that together with induction and deduction is needed to describe the scientific method of investigation. In the following, the process of creativity in science and innovation is tentatively equaled to the use of abductive reasoning. To distinguish abductive reasoning from deduction and induction, a small meta-level definition of the latter two is first outlined.

Deductive reasoning relies on a defined rule-based system and defined premises, such as formal logic and mathematics, and allows one to derive consequences from the premises according to the given rules. Defined in this general way one may state that computer simulations and mathematical modeling use deductive reasoning. Inductive reasoning is a completely different process, as it relies on pattern recognition and allows one to form more or less appropriate co-incidence rules, solely based upon observed co-incidence patterns or frequencies. A well-known example of inductive reasoning is the assumption that the sun will rise tomorrow, because it has risen every day until now. Mathematical curve fitting models, neural network based analysis, and human facial recognition can be classified as inductive since they work by formalizing coincidence-rules. Induction involves no underlying mechanisms of explanation, even though the descriptive models themselves may rely on a network of distributed information. Turning instead to the mechanistic models in classical physical science, such as Newton's mechanics, one may argue that the laws of nature could have been described inductively through the plotting of time and space coordinates for interacting bodies, and the subsequent fitting to the best mathematical formula. According to Peirce, however, the explanatory model was arrived at by abductive reasoning and could not have been produced through induction and deduction alone. In his most dry formulation of the concept, Peirce suggested the following logical path: "*The surprising fact C is observed. But if A were true, C would be a matter of course. Hence, there is a reason to suspect that A is true* "(CP 5.189). These criteria have later been attacked by philosophers who argued that they require that theory A, or a selection of A's is already known by the scientist (Christiane Chauviré, 2005), which effectively reduces abduction to simple deduction of consequences from known theories or models. The argument is very important, and if it is integrated in the concept of abduction, we could propose that the abductive process first consist of a phase that generates a large collection of rules (laws). A phase of mental deduction then follows, where the consequences of each rule are traced, leading to the identification of all rules that result in the consequence C. Abductive reasoning would thus, according to this scheme, be composed of a informatics-type rule-randomization process (random theory generation) followed by a deductive simulation process. The outcome of these phases would be a large number of theories logically linking theory A to the surprising fact C. In addition to this logical selection of useful theories among a random pool, abduction needs to involve a process of theory-decimation to end up with one or a few theories that please the scientist most. The pleasing aspects could be very diverse, but those theories that can be coupled with rules from bordering areas have historically been of highest priority. A semi-tautological concept that encompasses all success-yielding aspects during selections in a defined environment can be found in the term *fitness* from the field of biological evolution (discussed in (Gould, 1998)). To state that an organism has a high fitness is equivalent to stating that its likelihood of success in a given environment or ecological niche is high. So in analogy to biological fitness the fitness of a theory would define its likelihood of success in the scientific environment. The decimation of unwanted theories will thus select those with the highest fitness.

<Figure 1.>

Returning to the abductive reasoning used in the definition of the underlying force in Newton's mechanics and linking gravity to planet movement (Isac Newton, 1687); the idea of force would never have resulted from a process of induction and deduction alone. Induction might suffice to produce enormous complexes of curve fitting model that would reproduce all kinetic behavior; however they would not suggest the idea of an underlying force, and could not with the current computer technology be logically recombined to yield Einstein's idea of a curved space-time continuum or a theory of relativity. Likewise, the suggestion of an underlying heritable gene to explain the color and shape of the offspring of Mendel's peas required abductive reasoning. To be creative, abduction must contain a large component of stochastic imagination, but it also relies on educated guesswork, primarily by trying out the patterns of rules that arise from laws in other areas. It definitely also requires deduction in the form of mental envisioning and mental simulation of the different underlying links between the scientific objects.

The most important prerequisites for abduction according the outline above (see Figure 1) appear to be 1) the ability to create a large number of new theories, i.e., to allow the surfacing of randomized and seemingly unproductive ideas during the first phase; 2) the ability to simulate the outcome of any rule; and 3) the ability to see and argue why one law is more pleasing and has higher fitness than another.

There is a clear analogy between abductive reasoning in science and in innovation. In both fields, the abductive mental process identifies (or rather produces) a more or less random selection of relations, rules, or theories between elements in a defined space, and singles out the preferred ones.

Relations between elements can be viewed as links or representations, as defined by Peirce (Peirce.C.S., 2014). A relation can be entirely mechanical or purely psychological, but in any case we can define that one element is linked to the other through a representation function. Abduction is likely to be subconscious in most researchers and innovators, but may be brought to focus by looking at historical accounts of innovation. In this report I have therefore tried to identify instances of abduction in the history of scientific innovations. Using the well-documented scientific evolution in the field of electronics as an example, from galvanic elements over Edison's commercialization of the electric light and his discovery of the Edison effect, through the diode rectifier, to the mature pentode vacuum tubes that were invented in the twenties, I show that in the process of innovation, abduction is used at four distinct levels.

**A historic overview of the innovation of the light bulb and the vacuum tube**

The history of electronic development is well documented and most innovations are described in patents. I am not educated in the field of electronics but I have a semiprofessional interest in building and repairing vintage valve amplifiers which has nurtured my historical interest in the field. Aside from the patent literature there are a number of sources describing the evolution of vacuum tubes, such as (Cullis, 2014). The field expanded explosively after the innovation of the wireless telegraph, and finally led to the design of integrated circuits and quantum computers. To depart from common ground I will present a superficial outline of the development of the thermionic valve, or the vacuum tube as regular folks named it. After the historical facts are presented, I will identify three different abductive phases and define their respective input and output.

The foundation for the electric and electronic evolution started when Volta in 1796 invented the voltaic pile which could offer a steady electrochemical supply of electricity. In 1802 Sir Humphrey Davy used the voltaic pile for producing elementary potassium and sodium from salts (Sir Humphry Davy, 1812), and he was able to demonstrate that heat and light could be produced from electricity, in the form of electric arcs between carbon electrodes and incandescent light from passing current through a thin metallic filament (L.J.Davis, 2003). Later, in 1820, Ørsted used the Voltaic pile in his discovery of electromagnetism (Hans Christian Ørsted, 1820), and in 1827, Ohm published his work on the relation between electric current and the length of wire, proportional to the electric resistance, inserted between the poles of a galvanic element (Georg Simon Ohm, 1827).

The state of the art in the field of incandescent electric lightning before the 1880's had focused on a light source consisting of a thin filament of platinum wire within a confined glass space (L.J.Davis, 2003). This light bulb emitted bright light, but was extremely short-lived. Emission of light required that air was removed by evacuation and that the electron flow was slowly applied to prevent the absorbed gasses from being liberated explosively from the platinum metal. The use of vacuum in light bulbs had been employed for various other reasons such as avoiding detrimental oxidation of the glowing filament, and for preventing localized heating or cooling. The vacuum pumps were not very efficient before 1900 so the bulbs still contained considerable gas remains, which were actually postulated to be a prerequisite for incandescence.

This was the scene upon which Thomas Alva Edison decided to set up a novel industrial laboratory in Menlo Park, the first of its kind, primarily to screen for the optimal filament material for the incandescent light bulb. After having screened carbonized material from more than 6000 different sources of plant material, his laboratory found that carbonized cotton thread or carbonized Japanese bamboo filaments could last many hours before disintegrating. Platinum wire filaments could only last for a few hours at this candle light strength.

A major drawback using carbonized material was that the interior of the evacuated glass bulb was blackened by the evaporated wire material. Edison was able to show that the deposited material was negatively charged, and in an effort to draw the blackening to a single spot, he inserted a piece of wire in the glass bulb separated from the glowing filament (see Figure 1). When the anode wire was given a positive potential relative to the filament, he observed that a current flowed between the filament and the anode. As electrons were not yet discovered, Edison had no explanation for the effect. He filed a patent in 1883 for the use of the innovation as an "electrical indicator" (Thomas Alva Edison, 1884); one out of many patents he was granted in 1883 and 1884 for controllers of electrical generators. Edison remained fascinated by what was later termed the Edison effect, and demonstrated it to many fellow scientists.

<Figure 1>

One of these was John Ambrose Fleming, who had been a student of James Clark Maxwell in University College in England, and who worked as a consultant, first for Edison and later for the Marconi Wireless Telegraph Company. Like Edison himself, Fleming became fascinated by the Edison effect and finally, as late as in 1904, found its utilization as an electrical rectifier where he focused on the fact that only positive anode voltages resulted in a flow of current between filament and anode (John Ambrose Fleming, 1905). As a rectifier the diode tube could pick up the extremely faint signals from the receiving antennas in Marconi's wireless telegraph systems and enabled easier detection of the signals.

In an effort to improve the diode tube Lee De Forest later added a grid, composed of a flat sheet of folded wire, between the filament and the anode (Lee de Forest, 1907). The grid of the Audion, as he called his triode tube, offered the possibility to control the current between the filament and the anode by changing its electric potential. De Forest believed, at the time of filing his patent in 1907 that the mechanism for the amplification of electronic signals was dependent upon the remaining gas in the tubes. The first patent in which the triode structure is clearly visible was named "Space telegraphy" and suggested the use of the Audion for amplification of an antenna signal (oscillation), enabling it to be detected by a telephone receiver.

After its release in the market, the Audion was refined in several laboratories including the General Electric Research Laboratory where Irvin Langmuir with improved vacuum pumps showed that although ionization of the residual gas in "soft" vacuum tubes were needed for the functioning of the Audion at low voltages it resulted in instability, while “hard” high vacuum tubes were stable and functioned perfectly at much higher voltages (Irving Langmuir, 1925). Langmuir’s “hard” Pliotron tubes could deliver stable output power in kilowatts, where the Audion could only deliver fractions of a watt and were highly unstable.

The subsequent improvements for turning vacuum tubes into efficient amplifiers for radio and telegraph communication and audio signals was achieved by addition of two more grids between the control grid and the anode of the triode. A positively charged grid was first added between the control grid and the (positive) anode to prevent spontaneous oscillations at radio frequencies, when the amplification factor was increased. These tetrodes were highly successful, but suffered from a certain kink in the amplification response, because secondary electrons are kicked off the anode and became attracted to the new positive grid, resulting in a reverse electron flow from the anode, when electrons from the glowing filament bombard the anode. Several innovations were made to correct this flaw, such as a series of highly successful kink-less tetrodes and beam-power tetrodes that are used in present day hi-end guitar and musical amplifiers. Finally, however the insertion of a negatively charged grid between the two other grids resulted in the innovation of the pentode which became the standard in high power amplification tubes.

**Four levels of creativity in the innovation of the light bulb and the vacuum tube.**

If we compare the evolution of the incandescent light bulb and the rectifying diode tube, we will find at least four phases or levels, a pre-innovation phase and three consecutive innovative phases. I will show that the innovation process in the discovery of the Edison effect is of a different type than the innovation process he used in the screening for optimal filament material. This process is again of a different type than the innovation phase leading to Edison’s forceful creation of the urban electric environment for use of the incandescent light bulb.

**Discovery level (pre-innovative).** In the discovery of the Edison effect, Edison identified a previously unknown relation between a filament and an inserted anode in a light bulb. The resulting diode cannot be characterized as a special design of the light bulb, even though it started out as one. The diode has acquired emergent properties that were not present in the light bulb which turned it into the source of totally new innovations with novel applications. Likewise, the triode cannot be characterized simply as a special design of the diode, where a grid has been inserted between the filament and the anode. The triode represents a new discovery because it has properties that are totally different from the diodes, and which permits new applications. We may define the abductive process leading to such discoveries as innovation at the *discovery level*. The discovery level is a pre-innovation level, and the discovery does not turn into an innovation until it is used as a source of an invention with identification of corresponding application, design and niche. As we will see later, a discovery does not have to be linked to an innovation at the time of its publication or its exposure. A discovery can simply be the description of the molecular function of a biological molecule or the properties of a carbon nanotube, and will usually have been pursued for purely academic reasons without ideas of explorations. This appears to be the case for the discovery of incandescent light by Sir Humphry Davy, who was interested in the links between electricity, heat, and light from a scientific standpoint. It is clear from the above that basic research or spin-off discoveries during the design of unrelated innovations has the potential to produce *Sources* of radical innovations, but it does not exclude the possibility that applied research may also in many cases have that potential. The discovery of how to prepare wolfram filaments for light bulbs, which was a discovery with unforeseen affordances, appears to be a case of applied research which in 1903 led to a patent of how to mix wolfram powder with sugar and unite the metal by burning out the carbon (Cullis, 2014).

**Application level.** The application of incandescent light as a general source of illumination was a dream shared by many inventors after Davys discovery, so the innovative process leading to the application of incandescent light as general illumination was more or less public at the time. This innovative phase can be defined as the *Application* phase, where a discovery is linked to a potential application. When the Edison effect was discovered, there was no awareness of the importance of a flow of electricity between electrodes within a light bulb, or the thermionic flow as it was called before the electron was discovered. In order to have the effect patented Edison needed an application of the discovery, and in the application phase he focused upon an independent discovery that he had made. Using a galvanometer for his measurements he had found that the current flowing from the glowing filament to the anode was dependent upon the temperature of the filament. He had also found that the temperature of the filament was determined by the voltage between its two ends, so he linked the two discoveries together and suggested the use of a light bulb with an inserted anode as a controller of the voltage output for electric generators (Thomas Alva Edison, 1884). Using the outcome of the application phase, which I define as the Applicum of the innovation, he actually described the first electronic voltmeter. This application never reached commercial success, and it was Flemings later application for rectifying alternating current into direct current that later realized the true potential of the Edison effect as a Source of innovation. Fleming made the link between the two elements of the innovation because he was constantly engaged in a search for more efficient signal detectors than the current coherer (Ellery W.Stone, 1919) while he was employed in the Marconi Wireless Telegraph Company. In retrospect it appears as a logical extension of the Edison effect to be used in an electronic rectifier, since it creates a net positive voltage that can energize an electromagnet in the receiving end of a wireless system sending Morse codes. At the actual time in history, however, it must have required a spark of Abduction to link the Edison effect to its use in wireless telegraphy. Also the later application of the Audion with a grid for controlling the current in wireless space telegraphy was no less revolutionizing, even though the mechanism was still to be revealed.

**Design level.** In the third phase of the innovation process, where Edison was screening for optimal filament material for the use of incandescent light, he was actively searching for a specific technical solution, which is here defined as the *Designum*, to the known application at a technical or *Design level*. In the design phase during the innovation of the tube rectifier, Fleming likewise tried many different technical layouts, and the actual Designum for his rectifying diode contained a glowing filament as a cathode and a rough cylinder of metal, placed around the cathode as the anode. Both cathode and anode was placed in an evacuated light bulb. The Design phases in these two examples were both very technical and goal-oriented, following an inductive approach, and directed towards optimization and proofs of concept. Edison's exhaustive search for the optimal filament material and his high standards of craftsmanship was much more elaborate that Flemings roughly tinkered designs of diodes. However, despite the apparent inductive approaches both Design phases were innovative phases where new combinations were tried out, i.e., testing of new links between the Applicum and various Designa after imagination and mental modeling of their effects. The technical design of the first Audion triode by Lee de Forest was just as roughly tinkered as Flemings diode, but it was still efficient enough to serve as proof of the revolutionary concept. Later designs by Langmuir resulted in much stronger triodes with new applications, but the first design is still fascinating in its do-it-yourself simplicity.

**Entrepreneural level.** In order to become a successful innovation, it is not sufficient to have a fruitful discovery, a good application, and a great design. A fourth *Entrepreneurial* phase is required for an innovation aside its patentability, to increase its fitness and the possibility of commercial success in a particular niche in society. Invention at the entrepreneurial phase adds this feature and creates the last link between the Source, Applicum, Designum, and the Niche for the commercial realization. Thus the fitness of the final innovation is the result of linking of all ingoing elements in the discovery. All elements are needed because logically there can be no innovation without an underlying discovery, just as there can be no innovation without a practical application.

In his patent of the light bulb, Edison did not mention general household illumination. Nevertheless, the innovation of the light bulb was a commercial success because it fitted into the visions for general illumination, and was developed in parallel with household electrics. Edison thus paved his own way into the niche of general consumers when he developed household electrics for his innovations, ensuring the highest fitness of his light bulb. Accordingly, the electrical rectifier was only a commercial success because it fitted within a newly formed niche in wireless telegraphy where it found its use almost immediately. In Flemings patent, the niche was clearly visible (John Ambrose Fleming, 1905), as it included a figure of the diode tube in a setup where a signal from an antenna was rectified and could be detected by a galvanometer. In de Forests patent (Lee de Forest, 1907) the niche of the audion was also visible as it was shown as an amplifier of antenna signals, for detection by a telephone receiver. His title "Space telegraphy" clearly indicated a promising novel niche for the innovation.

**Definitions of the SAND model of innovations**

Although the different innovative levels were exemplified by only few examples of innovations, my claim is that all innovations require three phases of creativity following the pre-invention discovery phase: An *Application* phase, a *Design* phase, and an *Entrepreneurial* phase. Each phase require the linking of two entities, such as a *Source* and an *Applicum* in the application phase (see figure 3). Figure 4A visualizes the application space as it can be stretched out between a *Source-axis* (S-axis), which maps a succession of all possible discoveries, and an Applicum-axis (A-axis) that maps a succession of all possible applications. The link that was created in the application phase has its own distinct place in application space (SA-space) relative to the S and A axes. Along the same lines, figure 4B shows the AD-space where links created in the design phase can be mapped as a single point between an A-axis and a Designum-axis (D-axis). The D-axis maps a succession of all possible designs. Grammatically the three words innovation, application and design can unfortunately be used both in the form of nouns (e.g., innovation as a product) and in the form of verbs (e.g., innovation as a process). The strange word Designum can however only function as a noun, and defines the particular construction and appearance of the innovation, i.e., the totality of distinguishing traits that characterize it. The word Applicum was coined for identical reasons, but I refrained from proposing a new word for the noun form of an innovation as it would sound even uglier than Applicum and Designum. Visualization of the links between the Designum and the particular niche of the innovation is also possible in DN-space between the D-axis and a Niche-axis (N-axis) as shown in figure 4C. The N-axis maps a succession of all possible entrepreneurial niches. Since the innovation carries links between each of its particular S, A, N, and D elements, the links that were created in the entrepreneurial phase may also be visualized in SN-space or in AN-space.

Mapping of links in AD-space and DN-space may be explained through Krippendorff's definition of the design process (Krippendorff, 1989). A shorted version of his definition can be stated as follows: "The etymology of design goes back to the latin *de + signare* and means making something, distinguishing it by a sign, giving it significance, designating its relation to other things, owners, users or gods". This statement tells that a design has a signifying function which relates to both its environment and its function. A Designum can thus be viewed as a sign that represents the function (Applicum) of the innovation as well as its place in society (Niche), through its established links.

<Figure 2>

To recapitulate and to define the elements in more detail, the Source is a concept describing a discovery (see table 1), such as the "generation of light by electric current running through a filament" (see table 2). The output generated in the application phase is the Applicum and its link to the Source. An Applicum is a concept describing a generalized method of applying or utilizing the source of innovation. For the electrical light bulb the Applicum could be "a durable and commonly applicable light source". The Applicum subsequently serves as the input for the *Design* phase, which generates the Designum and its link to the Applicum. The Designum is a concept describing the actual design of the innovation. For the Edison incandescent light bulb, it could be stated as "a filament of carbonized Japanese bamboo between two metallic poles inclosed in a partially evacuated glass bulb". These three concepts, Source, Applicum, and Designum serve as input for the entrepreneurial phase that generates a niche for the application and links the Source, Applicum, Designum, and Niche. As an example, the Edison light bulb integrates incandescent light as a commonly applicable source of illumination, with the particular design, to be used within an environment of common household electrics.

<Table 1>

In the following three tables (2 to 4) brief tabulated SAND descriptions are outlined for the Edison light bulb, the Fleming rectifier, and the Audion by Lee de Forest.

<Table 2, Table 3, Table 4>

**Incremental and radical innovation, mapped in SAND fitness space**

Verganti and Norman (Norman and Verganti, 2014) recently reported an analysis of the logic behind incremental and radical innovation, where they defined an interesting set of underlying determinants. In accord with a number of other innovation theorists, the authors suggested that incremental innovation can be likened to hill-climbing along surfaces in a two dimensional space. Product quality served as the optimization goal, with increased along the vertical axis while design parameters were aligned along the horizontal axis. Radical innovation, according to the authors is the result of jumping to a new hill in this design space. To analyze these ideas within the frame of the SAND model, we need to define equivalents of design parameters and product quality. Since an evolving innovation has the possibility of either achieving greater success or of dying out, in analogy to the Darwinian evolution of biological species a concept of innovation-fitness may be an appropriate success parameter as discussed above for the fitness of scientific models. The seemingly tautological definition of fitness which states that success is a result of increased potential for success in a particular niche (fitness), has proven very useful for visualization of evolution in biology (Gould, 1998), and biological evolution is frequently described as hill climbing in a fitness landscape (Wright, 1932). In analogy with biological fitness in natural selection we can define innovation fitness as a systems-level characteristic of an innovation that quantifies its potential for success in a specific Niche, whether this success is commercial or otherwise, and no matter if the determining factor is quality or desirability of the product. In this evolutionary setting the incremental innovation by hill climbing would clearly take place in a fitness landscape. After having defined the term innovation fitness, we need to identify the parameter space, analogous to Norman and Verganti's design parameter space, where movement can lead to increased fitness. In the present model we have already shown how any innovation can be uniquely mapped in the four-dimensional SAND-space, or in different two-dimensional parameter-space projections such as SA-space, AD-space, DN-space, etc. Since a particular innovation must have a certain fitness value, it will also have its place in a three-dimensional SA-fitness landscape.  A rendering of a hill climbing and a hill jumping evolution of an innovation is shown in figure 4D in an SA-fitness landscape. The individual hills represent potential successful innovations, and a single hill is comprised of innovations based upon closely related discoveries which have closely related applications.

To fully understand such a fitness landscape, we would need more precise definitions of the concept of closeness within discoveries and applications. Until such definitions are available the graphs function mainly as a visualization tool. At this point yet another concept from biological evolution may be helpful; i.e., the concept of a species. If a biological species changes to much from its fellow species members during evolution, it will not be able to interact with the remaining un-evolved members and may not have to compete for the same resources. In effect it has evolved into a new species by jumping to (or rather creating) a new hill in the fitness landscape. If an innovation has evolved radically and is distinctly different from the rest of the innovations in the hill that it jumped from, it may have changed into a new *Innovation Species*. This new species will most likely have gained its fitness by occupying a new Niche, and will not be in direct competition with its former species members.

Figure 1E shows the AD-fitness space where a specific innovation can be mapped as a single point, according to its design and its application. Also here there are many possibilities for both hill climbing and hill jumping. In this design-fitness landscape the hills are comprised of innovations with similar applications and of similar designs. As a last example the DN-fitness landscape is visualized in figure 4F. Innovations of similar designs, which are likely to have success in similar commercial niches form common hills in this fitness landscape. Any combination of two axes within the S, A, N, and D parameter spaces can be combined with a fitness axis to form a fitness landscape in which innovations may perform hill climbing or hill jumping.

**Technology and meaning-driven innovations, mapped in SAND fitness space**

Verganti recently identified two different modes of changes, technological changes and meaning change (Verganti, 2008;Norman and Verganti, 2014). The meaning of meaning-change in their innovation model came from the design-definition by Krippendorff that was described above (Krippendorff, 1989) defining innovations according to their function as cultural signs (Verganti, 2008). We may gain further insight by considering the definition of a sign by Peirce as something (which he defined as the *Representamen*) that can represent or stand for something else (which he defined as the *Object*) to an Interpreter. He thus defines that a sign is characterized through its dependence on representation-links. As an example of such dependence we can state that the movement of a flag functions as a sign because it represents the direction of the wind to an observer. According to this definition a change in meaning is equal to a change in representation-links. In the present SAND model, there are a number of representation-links, the SA-link, AD-link, DN-link, etc., that may be changed. Each of these links is defined by a representation function where one element represents the other. If we focus on the SA-space (see figure 5, top panel), each point in the space maps a unique link between a discovery (S-axis) and its specific application (A-axis) in an innovation. Since the meaning-aspect of an innovation according to Norman and Verganti relates to the purpose of the design, we can state that re-purposing of an innovation represents a change in meaning. Changes in meaning for a certain innovation while the source is held constant can be visualized as changes parallel to the A-axis (figure 5, top panel). Such movements along the A-axis comes about by the breaking of the link between a discovery and its application, and the formation of a new link to another application. An example of such a meaning change is the innovative re-purposing of an old drug to cure a new illness. During this process, the innovation has performed hill jumping in the corresponding SA-fitness landscape (figure 4D).

<Figure 3>

When Fleming turned the Edison effect into a Source of an electronic rectifier his innovation jumped along the A-axis. His innovation was radical, mostly because it was based upon re-purposing and represented a meaning change in the application of an existing innovation. However when de Forest subsequently added a grid, he made a novel discovery. The discovery made it possible to control the current in the rectifier. This was a jump from one Source to another along the S-axis, while he maintained the application as a detector of telegraph signals.

It may be up for discussion whether the modern development (discovery) of faster and faster central processing units (CPU's), and the parallel use of dual and quadruple cores, represents radical or incremental changes in the evolution of Personal Computers. These changes can be mapped along the S-axis, but at critical points in the evolution the CPU speed crosses thresholds that open up for radical new applications of PC's, so these CPU's become examples of radical innovations where the innovations have moved along both the S-axis and the A-axis.

Jumps along the D-axis are definitely also possible, as visualized in Design space in Figure 5 (middle panel). In Edisons search for the optimal design of the filament in the incandescent light bulb, the evolution was incremental. However, when wolfram alloys was chosen as filament material by his followers, the life span of the light bulbs increased dramatically. The innovation of Wolfram-based filaments must be characterized as radical since they resulted in novel applications that can be visualized as jumps along the A-axis as well as along the D-axis. Design evolution of the Audion triode was done incrementally after its patenting by de Forest. Yet the innovation of efficient vacuum pumps by Langmuir resulted in electron tubes with different applications showing large jumps along the D-axis as well as the A-axis.

Movement along the N-axis in entrepreneurial space (figure 5, bottom panel) is also frequent. Innovations may change incrementally along this axis if the Niche is slowly expanded, but they may also perform jumps from one Niche to a completely different Niche if an innovation is re-targeted to a new group of users. The use of X-ray equipment for safety checks in airports is the result of re-targeting an older innovation, as well as it represents meaning changes by re-purposing of the X-ray equipment.

**Disruptive versus sustaining innovations mapped in SAND fitness space**

Disruptiveness of innovations, i.e., the ability to outcompete total lines of dominant products from the market is clearly related to differences in innovation fitness. The classical analysis of disruptive technologies by Bower and Christiansen (Bower and Christensen, 1995) showed that even though the performance of the disruptive technology often do not reach the level of the dominant technology, it still takes over the mainstream market by targeting the lower performance requirements of the mainstream users, which lag behind the established technology. This was seen clearly in the transition between 14”, 8”, 5.25”, and 3.5” hard disk drives in computers (Bower and Christensen, 1995), and in the transition from electronic tubes to transistors (Cullis, 2014). It appears to be common to disruptive innovations that they compete by targeting the same Niche that is inhabited by an established technology, and does that with a similar type of Applicum (i.e., by supplying products with the same basic function). The dominant and the disruptive innovation species differ in either their Designum or in their underlying Source. Figure 6 shows the trajectories of a dominant Sustaining innovation species that is outcompeted by a Disruptive innovation species.

<Figure 4>

As discussed by Bower and Christiansen, a company with a dominant technology will usually try to increase the performance through sustaining innovation. The company will therefore tend to use the same basic design in their innovation strategy and rely on technological improvements. The normal temporal increase in performance will result in increased expectations in the mainstream market, resulting in a drift of the Niche (movement of the innovation along the N-axis). A disruptive innovation, on the other hand, will focus on a different and superior Designum (different location on the D-axis); but due to an inferior performance in the early stages of its development, it will start out with an extremely low fitness. While the innovation is targeted to the niche created by the dominant company and continuously increases its performance by technological improvements, it will at some point meet the requirements of the mainstream market. These expectations lack behind the increasing performance offered by the dominant companies, but now the disruptive technology is able to fulfill the needs. At this point, the fitness of the disruptive innovation shoots into the sky because the mainstream market now prefers the superior design with the adequate performance offered by the disruptive innovation, rather than the inferior design with the superior performance offered by the dominant product. As a result of this change in Niche, the dominant innovation now loses its high fitness, and a change in design at this point towards the superior design will be too late to have any effect.

**The Stage-Gate model operates partly in SAND fitness landscapes, but has a different focus.**

Because of their process orientation, the SAND model may at first appear to be overlapping with the Stage Gate model. This is however not the case, as the Stage Gate or Phase Gate model (Cooper, 2001) is characterized by a succession of five stages: 1) Scoping, 2) Build Business Case, 3) Development, 4) testing and Validation, 5) Launch. At each Stage decisions have to be taken whether to stop or hold the process, to go to the next stage, or to iterate the processes of the current stage one more time. The Stage Gate model starts, like the SAND model after the discovery phase. However, unlike the SAND model, the product (i.e., the design) and the market (i.e., the niche) have already been defined in the discovery phase of the Stage Gate model. In the Scoping stage, the product and its corresponding market are evaluated. Visualization of this process in the SAND model would correspond to evaluating the location of the innovation in SA, AN, and DN fitness space. The Scoping also involves analysis of threats from competitors, which in the SAND model would correspond to analyzing all the fitness-landscapes for location of large nearby hills. Stage 2 concerning the business case and business plan involves both a detailed product definition and market analysis. This is again related to the location of the innovation in the fitness landscape of design-niche (DN) space. Stage 3 that is focused on development of the innovation relates mostly to marketing issues and final design changes, carrying the product from prototype to its mature design. Also the production plans are developed at this stage. The level of redundancy at this phase, or rather the compatibility with the SAND model would again correspond to analysis of the DN-fitness landscape. Stage 4 that is concerned with testing and validation require Near-testing (related to in-house testing of the product), Field-testing and Market-testing. Neither this stage nor Stage 5 where the product is launched has substantial overlaps with the SAND model except for the possibility of references to DN-fitness landscapes.

All and all it may be concluded that there is no redundancy between the SAND model and the Stage-Gate model as the scopes of the models are altogether different. However, there is a high degree of compatibility between the models, in that many of the tasks in the Stage-Gate model can be visualized using SAND diagrams and fitness landscapes.

**How the SAND model can help natural scientists to become innovative**

In the introduction it was concluded that the current innovation models do not focus on the stages in the innovation process where natural scientists are expected to excel and gain competences for the future innovative university environment. Most innovation models have as their prerequisites, a discovery and its promising application. From this starting point, the innovative process is treated as an intertwined flow of entrepreneurship and business planning with occasional shifts in focus, to target product redesigning and optimization. The SAND model separates the business and entrepreneurial issues from the rest of the innovative process and reduces these issues to fitness-determining border-conditions of the niche. Instead the theory focusses on the stages where links are created between the discovery and its application, its design, and the niche where it has to compete with other innovations. This change in scope results in a model that is very different but complementary to the dominant models. The SAND model may seem less useful to companies where the innovation process involve a high degree of entrepreneurship and business decisions. However it will find its use in more technically oriented settings where consumer expectations and market structure can be treated as conditions from the outside that only dictates the frame for the technical innovative process. It appears safe to propose that the current business-oriented innovation theories in an analogous fashion treat the technical and design issues as conditions from the outside that dictate the frame for what they consider the true innovative process, and which have to be pushed in favor of the innovation of the optimal marketing strategy.

To summarize, the technical “gadget” and its design is at the center of the SAND model. Its evolution is confined by the borders of the entrepreneurial and commercial Niche, where it has to compete as a product. This is totally opposite in current innovation models where “product” is at the center and its evolution in business space is here viewed as being limited by the borders set by the design and technical possibilities of the gadget.

To the natural scientist that has just made an interesting discovery The SAND model may set the frame for solving the task ahead. Creativity is extremely difficult when the target of the effort is not known or if the aim is too wide. The most creative starting point would be, if the scientist knew which type of application to aim for. Using the SAND model it is possible to approximate this fortunate situation by visualizing the surroundings of the novel discovery in Source-Application space. When neighboring discoveries are mapped on the S-axis, and the successful applications of these discoveries are mapped on the A-axis, then a pattern will emerge in SA-fitness space, from which the most straight-forward applications may be derived. Likewise, the patterns in AD-fitness space and in ND-fitness space may suggest the most straight-forward ideas for the novel innovation. These obvious innovations should however be treated as starting points and not as final targets, since the true innovation potential would lie in the less populated regions of SA, AD and ND-fitness space.

Few scientists will ever become proficient in all phases of the innovation process. Edison is one of the few researchers in history that has excelled in all three phases, the application phase, the design phase and the entrepreneurial phase. The biographer Bernhard Carlson shows repeatedly (Carlson, 2013), that Edison’s competitor Nikola Tesla paid attention to the application phase and the entrepreneurial phase, while he preferred to leave the tedious optimization and design work to others; the work that was needed to make the electrical machines work. Different types of scientists may be ingenious in designing and engineering, without the slightest inclination towards creating the illusions for opening an entrepreneurial niche. According to the SAND model, the phase closest to home for the scientist would be the application phase, so that is where the largest learning effort should be placed.

It is not obvious for a brilliant scientist that has just made a new discovery, how it should be used as a potential source for a successful innovation (abduction proceeding from Source towards Applicant). However one may recognize that the industrial designer has to proceed the in the totally opposite direction, by identifying possible discoveries that can be applied to fulfill a required function (abduction proceeding from Applicant towards Source). Human centered designers as an example (Norman and Verganti, 2014), include market analysis and consumer needs in the first phases of the design process when they optimize the design of existing innovations. Since the innovation techniques proceed almost opposite of each other, a cross fertilization between the minds of scientists and industrial designers could be very rewarding. From the standpoint of the scientist, courses or seminars on the design process might nurture some of the desired competences. Of equal importance would be the increase in the ability of the scientist to imagine and identify possible means of practical utilization. As a generic competence this could possibly be trained by engaging scientists in cross-disciplinary discussions about innovation trends and new products emerging from scientific research within distant scientific fields. Such cross disciplinary knowledge about novel and desired innovations could be interesting and could make it easier for scientists to imagine discoveries within their own field as sources of innovations and suggest possible means of utilization of their own discoveries.

At the Design level, where the different means of utilization (Applica) are linked to specific technical designs abduction may well be within reach of some scientists. However it needs competences within design and end-user needs that are not yet part of the curriculum for most scientific educations. The last level in innovation, the entrepreneurial level of invention, where the niche is identified and the full-fetched innovation is fostered will often require advanced spindoctor competences and competences within finance and industrial production which are quite foreign to most scientists at university faculties.

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TABLES

**Table 1. SAND description of a generic Innovation**

| | |
|---|---|
| Source | A concept describing in general terms, the elements in a discovery that are used in an innovation |
| Applicum | A concept describing in general terms an application of the discovery |
| Designum | A concept describing a specific design of the application |
| Niche | A description of the niche of the application |
| SA link (Application level) | A description of the mechanism by which the Applicum relates to the Source (Source-Applicum link) |
| AD link (Design level) | A description of mechanism by which the Designum relates to the Applicum (Applicum-Designum link) |
| DAS link (Entrepreneurial level) | A description of the concepts of the Innovation that brings together the Source, the Applicum, and the Designum into a successful Invention. |

**Table 2 SAND description of the Edison incandescent light bulb**

| | |
|---|---|
| Source | Incandescent light: generation of light by electric current running through a filament |
| Applicum | A durable and commonly applicable source of illumination |
| Designum | A filament of carbonized Japanese bamboo between two metallic poles enclosed in a partially evacuated glass bulb |
| Niche | Common household electrics |
| SA link (Application level) | Electric current through a conducting filament, enclosed in an evacuated glass bulb can be used to generate general illumination |
| AD link (Design level) | Electric current through a carbonized bamboo filament in an evacuated glass bulb can result in extended periods of incandescent lightning |
| DAS link (Entrepreneurial level) | The light bulb can be used for domestic general illumination in areas with electricity |

**Table 3 SAND description of the Fleming rectifying diode**

| | |
|---|---|
| Source | The Edison effect: Current flows in one direction from the filament of a light bulb to an inserted anode |
| Applicum | The Edison effect can result in a signal with a net negative voltage. |
| Designum | A cylinder-formed anode is placed around the filament. |
| Niche | Wireless telegraphic detection of Morse code signals |
| SA link (Application level) | Only positive anode voltages result in current flowing between filament and anode. Alternating positive/negative voltages (AC) applied between filament and anode will produce a rectified (DC) current with a net electromotive power. |
| AD link (Design level) | A cylinder-shaped anode, positioned around the glowing filament result in a highly efficient current flow |
| DAS link (Entrepreneurial level) | Electromagnetic detection of Herzian signals in wireless telegraphy is possible after creating positive voltage from antenna-derived AC signals through electronic rectifying |

**Table 4 SAND description of the The Audion**

| | |
|---|---|
| Source | A voltage applied on a grid between filament and anode in a light bulb can control the current between the filament and anode |
| Applicum | The triode can rectify and amplify an oscillated signal |
| Designum | A grid of metal inserted between the filament and the anode in a partially evacuated light bulb |
| Niche | Wireless telegraphic detection of Morse code signals |
| SA link (Application level) | By an unknown mechanism, an amplified signal can be detected between a glowing filament and a positively charged anode, if a weak signal is applied between the grid and the filament (stated in patent no 879.532). |
| AD link (Design level) | The amplified signal is strongest if the grid is formed by a folded wire. The mechanism for the audion is believed to be dependent upon ionized gasses. |
| DAS link (Entrepreneurial level) | Electromagnetic detection of Herzian signals in wireless telegraphy after creating amplified positive voltage from antenna-derived AC signals |

FIGURE LEGENDS

**Figure 1. A simplified model of abductive reasoning.** When a person is confronted with a surprising phenomenon, a large selection of more or less arbitrary explanatory theories are produced. These are tested by simulation for their explanatory power, and of the theories that give adequate explanations, one (or a few) is selected based on its fitness into the mental environment.

**Figure 2. Evolution of the thermionic valve (electron tube).** The innovative steps from the incandescent light bulb to the Audion

**Figure 3. A process diagram explaining the SAND model of innovation.** In each innovative phase (application, design, and entrepreneurial), a selection of more or less arbitrary links are formed between the input and putative outputs. After testing or mental simulation of their usefulness, some links are found adequate. One link survives the following selection based upon its fitness into the technical environment or its niche.

**Figure 4. Ingoing elements in innovations and their evolution according to the SAND model.** An innovation can be defined by the links between each of its elements in the four-dimensional SAND-space (abbreviation of Source, Applicum, Designum, and Niche). The Source is the underlying discovery; the Applicum is its application; the Designum is the actual design; and the Niche is the entrepreneurial niche for which the innovation fitness is high. The innovation can be visualized in two dimensions: Application-space (panel A and D), Design-space (panel B and E) and Entrepreneurial-space (panel C and F), respectively. Panel A) Shows a rendering of Application-space where the links between discoveries (S-axis) and their applications (A-axis) can be mapped. B) Design-space where links are mapped between A-axis and D-axis. C) Entrepreneurial space where links are mapped between D-axis and N-axis. Panel D) shown a fitness landscape in application-space (SA-Fitness landscape). The red arrow symbolizes a hill-climbing evolution characteristic of incremental innovation. The green arrow symbolizes a hill-jumping evolution characteristic of radical innovation. Panel E) shows a fitness landscape in Design-space (AD-Fitness landscape), and panel F) shows a fitness landscape in Entrepreneurial-space (DN-Fitness landscape).

**Figure 5. Incremental and Radical innovation vs. technology and meaning change.** Small changes along an S-axis, A-axis, N-axis, and D- axis represent incremental innovation. Large innovation changes along either axis represent radical innovations. Radical innovation can be either based upon technology changes or meaning changes as written for application space (top panel), Design space (middle panel), and in Entrepreneurial space (bottom panel).

**Figure 6. Sustaining and Disruptive innovations.** A dominant innovation species slowly changes its Designum (moves along the D-axis) by sustaining innovation, thereby provoking its Niche to change (movements along the N-axis). A Disruptive innovation species that is targeted at the same Niche starts out with a radically different Designum, and moves along the same Niche-trajectory as the dominant species. Despite its superior Designum, the fitness of the disruptive innovation starts out low due to inferior performance, but at some point it has developed the technical performance required by the mainstream users, after which its fitness shoots up. The dominant innovation species loses fitness due to its inferior Designum.

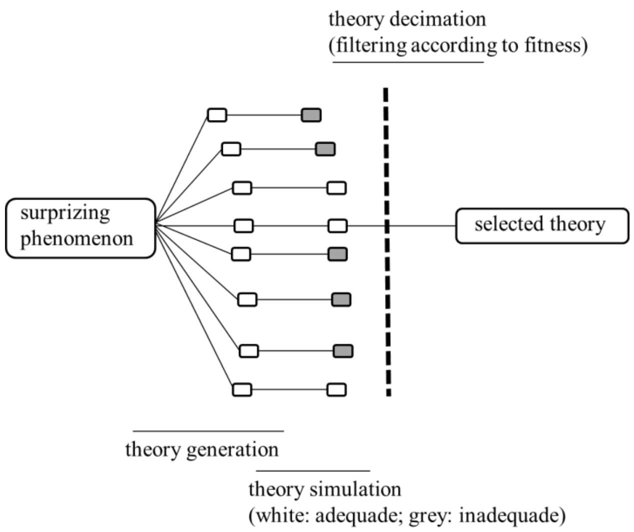



Figure 1.

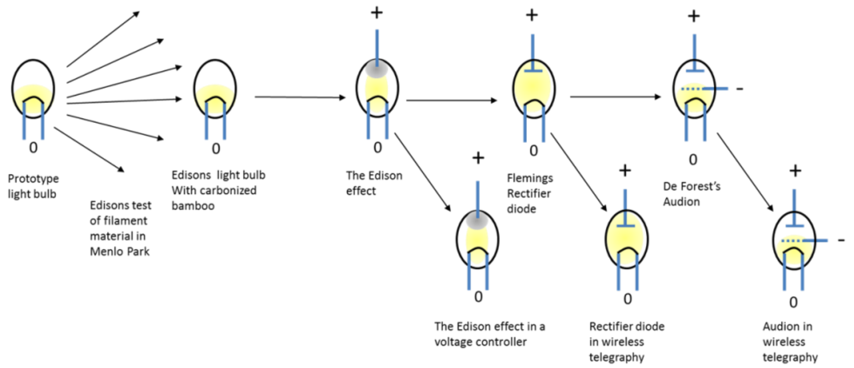



Figure 2

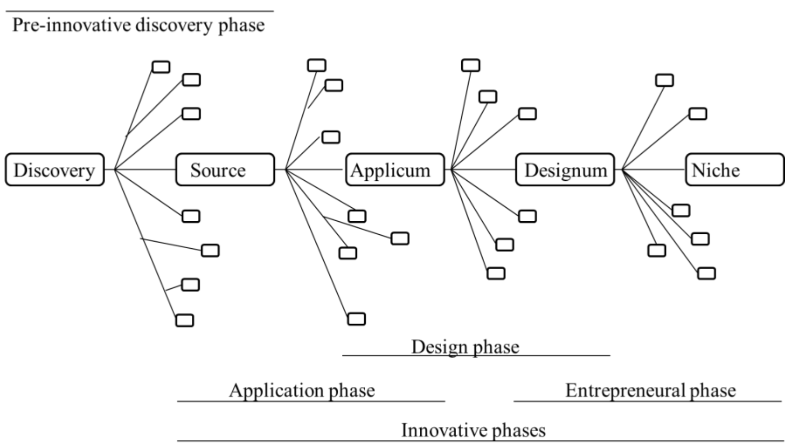
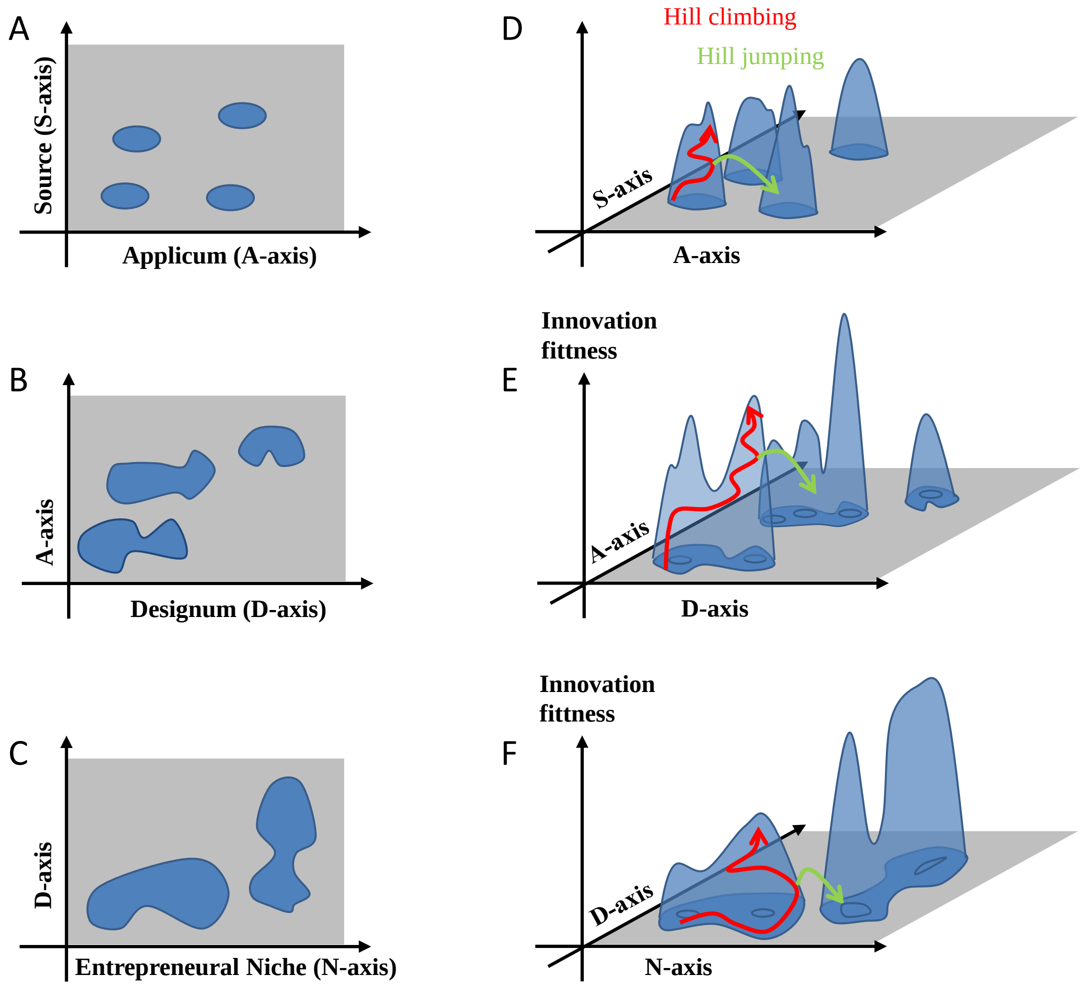


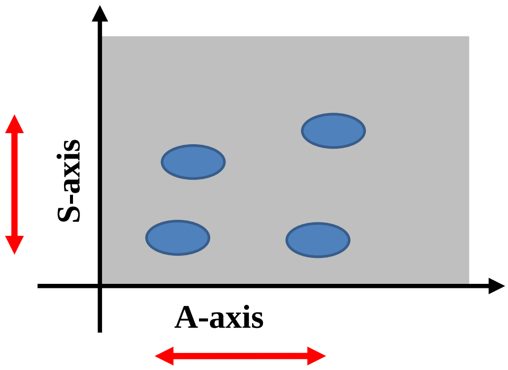

Figure 3



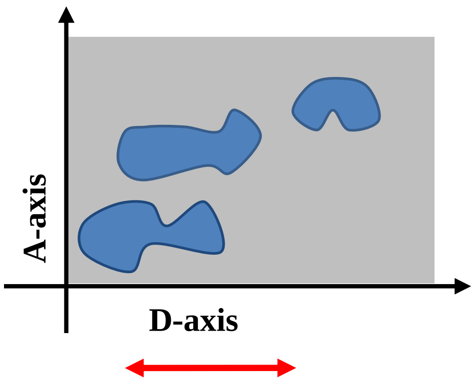
A
Source (S-axis)
Applicum (A-axis)
B
A-axis
Designum (D-axis)
C
D-axis
Entrepreneural Niche (N-axis)
D
Hill climbing
Hill jumping
S-axis
A-axis
Innovation fittness
E
A-axis
D-axis
Innovation fittness
F
D-axis
N-axis


Figure 4.

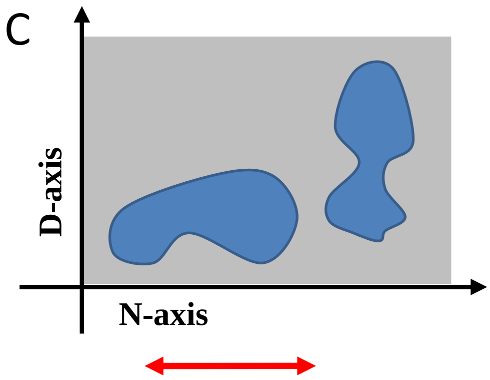
Large changes along
S-axis represent
radical innovation
based upon
technology-change
(new discoveries)




Large changes along A-axis represent re-purposing of
innovations = radical innovation based upon meaning-changes

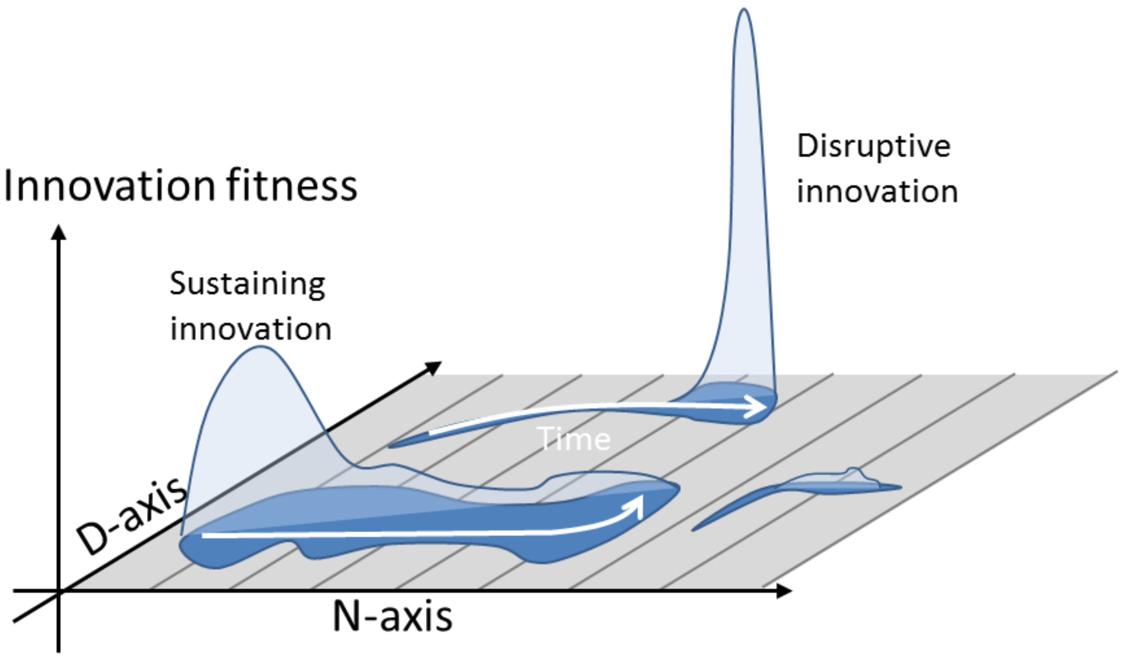



Large changes along D-axis represent radical innovation based
upon technology-change or meaning-changes




Large changes along N-axis represent re-targeting of
innovations = radical innovation based upon meaning-changes

Figure 5



Innovation fitness
Disruptive innovation
Sustaining innovation
Time
D-axis
N-axis


Figure 6