ORIGINAL PAPER DOI: 10.7401/visions.04.03

Circuit-bending and sustainability transitions. Exploring ways of re-thinking and re-using technologies

Michele Cagol[1], Martin Dodman[2]
[1]Free University of Bozen, Italy; [2]Interdisciplinary Research Institute on Sustainability, Italy

Abstract. This paper examines the relationship between circuit-bending - a form of adjustment of technological artifacts involving the modification of circuits in electronic devices - and sustainability. Sustainability is considered in terms of the wider context of socio-cultural and technological change and a necessary shift in patterns of human behavior related to harnessing creativity and innovation. It is argued that from both educational and environmental perspectives circuit-bending offers examples of re-thinking and re-using processes and products that are typical of human activity and which can be used to support a sustainability transition.
Keywords: circuit-bending, technology, creativity, innovation, sustainability

ISSN 2384-8677 **DOI:** 10.7401/visions.04.03

Article history: Accepted in revised form November, 08, 2015; published online as in-press November, 18, 2015

Published online: Final publication, December 21st, 2015.

Citation: Cagol, M., Dodman, M. (2015) Circuit-bending and sustainability transitions. Exploring ways of re-thinking and re-using technologies. Visions for Sustainability 4: 13-21

Competing Interests: The author has declared that no competing interests exist.

Corresponding Author: Martin Dodman, Interdisciplinary Research Institute on Sustainability, Italy.

E.mail: martindodman@libero.it

***Perspective**: Educational vision*

***Fields**: Economy and technology*

***Issues**: Electronic wastes and pollution, Educational processes*

1. Introduction

The importance of considering sustainability transitions from multiple and interdependent perspectives - psychological, social, ecological, technological - is now recognized by an increasing body of literature as a fundamental component of the endeavor to identify necessary and possible shifts in patterns of human behavior. Current research is looking at ways in which human creativity and innovation potential can promote forms of resilience and transformability that are crucial for sustainability (Clark, 2001; Raskin et al., 2002; Walker et al., 2004; Chapin et al., 2010; Folke et al., 2010, 2011; Westley et al., 2011). In this context resilience is seen as "the capacity of a system to absorb disturbance and reorganize while undergoing change", while transformability is understood to be "the capacity to create untried beginnings from which to evolve a fundamentally new way of living when existing ecological, economic and social conditions make the current system untenable" (Westley et al., 2011: 763). This paper examines the activity of circuit-bending as one specific example of a transformative paradigm linking psychological, social and ecological aspects of the evolution of technology while combining elements of resilience and transformability.

Human creativity and innovation potential have always been inextricably linked to technological development. Technology can be seen as a composite made up of tools or appliances used to carry out actions, solve problems or provide recreational pursuits; of types and characteristics of knowledge-building processes for understanding, developing know-how and creating products; of material and immaterial cultural artifacts and corresponding value systems (Vergragt, 2006). Technologies and societies evolve together and there is a clear, albeit complex, correlation between the type and the rate of technological innovation, the scale it assumes and the impact it has on people, societies and their environments.

At the same time, human value schemes and the choices they produce play an important role in shaping technology, together with the social and economic interests that determine the inventions developed and the innovations implemented. Interpretative models such as Social Construction of Technology (SCOT) (Pinch and Bijker, 1987; Bijker 1995) and Actor Network Theory (Callon, 1986; 1987), examine aspects such as social actors and social networks and the definition of desirable visions for the future and responsibilities within innovation processes (Vergragt, 1998). According to SCOT theory, technological innovation is directed by the significance that "relevant social groups" ascribe to a particular technological artifact, giving rise to problem definitions within technological frameworks that in particular circumstances can lead to adjusted technological artifacts (Bijker, 1995).

One thing is the initial motivation for the development of a given technology, while quite another is the use to which it is put and subsequent and diverse uses that may emerge. Transformative paradigms involve innovation potential as the ideation both of new processes and types of production and new ways of re-thinking and re-using existing processes and products, thereby releasing new forms of potential previously hidden or undiscovered. Part of the relationship between invention and innovation must necessarily be finding new ways of using (technology as tools and appliances), but also of understanding and know-how (technology as knowledge-building), as well as of considering and valuing (technology as cultural artifact).

Circuit-bending is an activity which can be analyzed as a form of adjustment of technological artifacts that explores one of the possible intersections between art - principally, but not exclusively, music - and technology, more specifically, analogical electronic engineering. The purpose is to creatively modify small devices, electronic battery-powered games or instruments, so as to obtain novel and experimental sounds and noises or invent new musical instruments. The aim is therefore not only to create new sonorities from simple electronic devices, which could be produced by elaborating on the audio signal emitted by a game keyboard, for example, or from any other kind of game that emits sounds through some analogic or digital effect (a delay, a distortion, etc.). On the contrary, the creative modification of the original sound object is an integral part of the aim. Circuit-bending means modifying an electronic circuit in order to alter its behavior. Indeed, for some, “the products created by the benders are less interesting than the process of their creation” (Fernandez & Iazzetta, 2011: 13).

2. Circuit-bending, innovation and creativity

From a technical point of view, circuit-bending is modifying the electrical circuits within electronic devices - substituting, adding, eliminating components, changing the connections within the circuit and/or connecting different circuits, adding elements which become part of the circuit - in order to obtain sounds and noises that are unusual and novel. This can be done with any of the interconnections between electrical elements and electronic components within the closed track of an electronic circuit: resistances (which slow down the flow of the electrical current), photo-resistances (which vary the strength of their resistance on the basis of the quantity of light they receive), potentiometers (variable resistances), capacitors (which accumulate and release current), integrated circuits or chips (complete integrated circuits encapsulated in a plastic casing), transistors (which control the flow of current between two poles through the current which arrives at a third pole), diodes (which permit current to pass in only one or both directions beyond a given electrical tension), leds (light-emitting diodes). Planning and assembling a functioning electronic circuit requires specific electrical and electronic knowledge together with programming and technical skills, whereas modifying an existing circuit does not necessarily presuppose any such previous experience. Indeed, circuit-bending was born as the result of an accidental discovery and its proponents have always striven to maintain this sense of spontaneity in exploring and experimenting for its own sake.

What is perhaps most interesting and innovative from the psychological, social and ecological perspectives is that “anyone can do it. You don’t need to be an electronics guru or a shop genius. All you need is the ability to solder and to think outside the box” (Ghazala, 2005: 3). Moreover, since such an activity is the prerogative of anybody, every circuit-bender can proceed in potentially infinite creative ways. “Essentially, to bend a circuit you hold one end of a wire to one circuit point and the other end to another point. That’s it! Place the wire upon the circuit in an arbitrary fashion, wherever you want, from here to there on the board. This replicates the pure-chance aspect that launched my first instrument as it shorted out in my desk drawer, and it is still the heart of bending. If you hear an interesting sound, you then solder the wire in place, putting a switch in the center of the wire so that the new sound can be turned on and off. That’s pretty immediate!” (Ghazala, 2005: 4).

Towards the end of the 1960s Ghazala accidentally created a short circuit in a small portable amplifier, which began generating interesting noises and whistles. After a few attempts and experiments, also by adding some switches, he succeeded in controlling the short-circuit and thereby giving birth to circuit-bending, even though he did not coin the name until 1992 (Collins, 2009; Ghazala, 2004).

In my drawer a small battery-powered amplifier's back had fallen off, exposing the circuit. It was shorting out against something metallic, causing the circuit to act as an audio oscillator. In fact, the pitch was continuously sweeping upward to a peak, over and over again. Opening the drawer I discovered the amp, my genie lamp. I immediately thought: If this can happen by accident, what can be made to happen purposefully? If this can happen to an amp, not supposed to make sound on its own, what might happen if one were to short out circuits that already make a sound, such as keyboards and radios and toys? (Ghazala, 2004: 97).

Although Ghazala is the inventor of circuit-bending as we know it today, many others can be seen as working within the same innovative tradition. Particularly significant examples can be identified in Michel Waisvisz, the inventor of Cracklebox, who produced "the first mass-produced electronic musical instrument that incorporated the player's skin as the primary variable component in a sound-generating circuit" (Collins, 2009: 76), Louis and Bebe Barron, who invented a highly volatile approach to electronics in which Louis provided current for circuits built by Bebe so that they produced sounds up to the moment when they caught fire, John Cage, who experimented with mechanical/acoustic-bending at the piano, David Tudor, who experimented with the use of contact microphones, Alvin Lucier and Gordon Mumma[1] .

There is certainly no single genre or style of music that can be linked with circuit-bending. A bent toy instrument can be used in a passage of drone-music[2], a sequence in a piece of pop music or as way executing Beethoven's Für Elise. At the same time, there are some characteristics typical of circuit-bending: the sounds produced by the bent instruments endeavor to be as alien as possible, in the sense that they have not been heard before and are unusual, often inevitably noisy, unstable, unpredictable. This very instability and unpredictability is what characterizes circuit-bending music. "Circuit-bending transgresses the boundaries of what is considered music because it uses unrefined, unstable, and unconventional sounds that are often irreproducible and set in compositions with little discernible structure" (Naficy, 2010: 23). Moreover, "the ethos of circuit-bending entails involvement with an object which is never fully under control […] benders also manifest a disregard for perfectability, appreciation for creative mistakes, and de-centering of intention" (Naficy, 2010: 25).

In the majority of cases, such instruments do not have a defined and stable tuning (since this has been tampered with at the level of the circuit) and so it is more difficult to play melodies that follow precise musical scales. In this respect, there are two principal expressive possibilities for circuit-bending instruments: experimental music, largely improvised and with a strong aleatory component, such as noise, drone and glitch, or repetitive music (from the point of view of melody or rhythm) that use sequences inside the bent instruments or patterns based on samples of sounds. Every bent instrument is as such unique, with its own individual characteristics, which can change in the course of time or indeed cease to exist. At the same time, some electronic devices lend themselves particularly well to modification and offer interesting examples of expressive potential, by now well documented. Examples include "Speak and Spell" from Texas

[1] Important exponents of circuit-bending today include Phil Archer, John Bowers, Nicolas Collins, Joker Nies, Knut Aufermann, Xentos "Fray" Bentos, David Novack, Vic Rawlings, Sarah Washington, Chris Weaver, Dan Wilson, Patrick McCarthy e Tommy Stephenson (Roth Mobot), Tim Kaiser, Kaseo, Steven Buck.

[2] A minimalist genre based on sustained or repeated sounds, notes or tone-clusters known as drones.

Instruments, the sampler keyboard Casio SK-1 and the mini keyboard Casio SA2.

3. Circuit-bending, resistance, resilience, transformability

Circuit-bending has become increasingly widespread principally in those countries "where surplus electronic materials are cheap and widely available in the form of trash" (Naficy, 2010: 2) and has also come to be considered part of the worldwide Do It Yourself (DIY) movement (Fernandez & Iazzetta, 2011). From this perspective, circuit-bending combines elements of rebellion, anti-consumerism, political critique and opposition, transgression, subversion and resistance. In his ethnographic study Naficy (2011) examines the way in which circuit-bending can be considered a form of resistance. Circuit-benders oppose the "built-in limitations" of commercial products, the "rapid product turn-over combined with planned obsolescence", and use their inventive capacity to "circumvent the power of the market to determine access on the basis of income, by producing their own objects" (…). In this way, circuit-bending constitutes a kind of resistance with political implications and particular significance for sustainability transitions:

> *Circuit-bending is trangressive of socio-cultural and economic norms in at least four analytically separate ways: 1) it transgresses manufacturer-designed use, function, and recommendations; 2) challenges popular conceptions of what is an instrument and who is or can be a musician; 3) introduces novel elements producing novel experiences; and 4) expands the horizons of what is considered possible on a personal and social level (Naficy, 2010: 17).*

If we consider in particular the first point, circuit-bending can be seen as a form of transgressive resistance to the corporations and manufacturers of battery-powered electronic devices for sound production. This kind of resistance brings with it an (apparent) contradiction and two benefits. It is often held that benders combat the very productive systems that manufacture the "raw material" on which their activity depends. In fact, the question posed lies at the heart of any process of improvement in that the very action of trying to improve something means that it is considered to be improvable, something less than an original idea or a project to be realized. Circuit-bending simply sets out to modify and improve something that benders believe can be criticized, something which is essential to the very existence of circuit-bending itself and, more in general, to the ingenuity that lies at the heart of human creativity and innovation. The argument is parallel to that proposed by Wittgenstein that philosophy exists only because there are philosophical problems to resolve. Otherwise we would feel no need for it (Wittgenstein, 1953). By the same token, circuit-bending exists because there are circuits to bend, accepted customs and practices to be transgressed and transformed.

The benefits of circuit-bending can be analyzed from the educational and the environmental perspectives. Even though no specific electronic knowledge is necessary, the spread of this activity almost inevitably leads to greater interest in electronic engineering and music through a desire to immerse oneself in projects that are more difficult and complex and therefore motivate learning by involving practitioners in a process of learning by doing. As Collins (2009) puts it: "In contrast to the laborious analytical work that had previously accompanied most electronic engineering, even in hobbyist and musical circles, this philosophy is tremendously liberating for the first-time hacker. But after the thrill of "how" wears off, some of us ask "why?" Accordingly, many younger artists gain access to circuitry through classic bending activities, but then move on to diversify their electronic portfolio: interconnecting toys, combining handmade circuitry with bent toys, hacking other found technology (effect pedals, video circuits, mechanical devices), writing software, etc." (Collins, 2009: 277). In this respect, the dividing line between bending and hacking becomes extremely thin. "'Bent' means you have no idea what you are doing when you open up the circuit; 'hacked' means you have some idea" (Collins, 2009: 106). "Circuit-benders continue to parallel the hacker ethos in their appreciation for knowledge and learning through active engagement, and in their strong association of learning and improvement" (Naficy, 2010: 28).

Circuit-bending is thus a process of active learning through which experimenting promotes the desire for knowledge-building rather than a mere application of what has previously been learnt. Understanding electronics derives directly from its utility in the realization of one's own projects. "Circuit-bending is currently being taught all over the world to people of all ages. MIT has a program teaching grade school kids to bend (imagine kids learning experimental electronic instrument design at the age I was learning in school to play a plastic flute)" (Ghazala, 2005: 4). It is highly likely that children who build their own electronic instruments will be more motivated to learn music than by being required to play a plastic flute. The learning is directed towards the achievement of an objective and the motivation is thus enhanced as children open games they wish to modify, endeavor to change the values of some electronic components, build bridges within the circuits using their fingers and connecting resistances, potentiometers, etc. Initially they may not be fully aware of what they are doing, but gradually the desire to understand and improve the results of their project leads to an information gathering process, asking for advice and explanations from more expert practitioners, seek on-line experiences narrated by others who have modified the same game, eventually buy or download an electronics manual or publication on electronic music.

Very few manuals exist which are dedicated to circuit-bending. The two principal sources are Nicolas Collins, Handmade electronic music: the art of hardware hacking and Qubais Reed Ghazala, Circuit-Bending: Build Your Own Alien Instruments, but there are many on-line tutorials and videos or guides to how to modify particular electronic devices[3]. This too is a specific characteristic of circuit-bending and its approach to learning by doing and cooperating within real and virtual communities. The principal means of spreading circuit-building is through open workshops in which it is very rare to find teachers who tell students what to do, what to connect or what outcome to aim for, but rather, in a similar way to a hackerspace, novices, amateurs, engineers, technicians and musicians meet and share knowledge and experiences.

The environmental benefits concern the re-using of objects destined to become waste that is difficult to dispose of. "Circuit-benders reduce waste related to high levels of consumption and turn-over by reusing and repurposing" (Naficy, 2010: 36). Electronic toy devices are indeed part of a system of production that is unsustainable at the level of waste production. "Old" products are ever more rapidly replaced by new ones, made to be more desirable and with higher levels of performance. The fate of the old devices is generally that of being abandoned rather than recycled. Disposal of plastic and electronic parts is extremely difficult. Thus circuit-bending offers an example of a sustainability transition strategy. Products considered at a

[3] http://www.anti-theory.com/soundart/; http://getlofi.com/blog/; http://cargocollective.com/secretmedialab/SML-Hacking-Manual-v0-3; http://circuitbenders.co.uk/tips.html; http://casperelectronics.com/finished-pieces/circuit-bending-tutorial/

certain point obsolete - which had perhaps a highly dubious function even at the outset (not only for the benders) - are reused, thereby not becoming waste, through being modified and transformed into something better (at least for the benders), an example of up-cycling, the highest form of recycling, which unites reusing to refashioning. Although the actual quantities of electronic waste that can be reduced by circuit-bending as it has thus-far been practiced are inevitably limited, its potential for enhancing relationships between the psychological, social and ecological aspects of sustainability (Rossi & Dodman, 2015a, Rossi & Dodman, 2015b) are considerable when it is seen as a possible precursor of future and diverse ways of bending.

Circuit-bending can therefore be considered a form of resistance to a certain type of market, society and aesthetic. It is transgressive from various points view - economic-productive, social, artistic-cultural - and anti-political - in the sense that it is disinterested, without the commitment or sense of mission of the hackers (Naficy, 2010: 33). At the same time, it produces, almost unintentionally, educational and environmental benefits. Nevertheless, we must be aware of its limits. Technology advances, but the thought processes that are the basis of productive systems, the cultural choices concerning the use and the functions that the technological devices should have (above all, for marketing reasons) do not necessarily evolve and risk remaining within a perverse loop. Today people can enjoy the same unchanging and vacuous television programs with ever more excellent quality video and audio. Internet enables users who wish to do so to switch from pornographic films to videos of enchanting kittens infinitely more quickly than a few years ago. Listeners can access an immense variety of music of the lowest artistic quality. Obviously not everything is to be dismissed as trash, yet it becomes ever more difficult to resist or to avoid that which seems dubious, stupid or even dangerous, ever more easy to become glued to a large, high-definition screen offered through a home-theatre system than with a small cathode-ray tube television set, to remain immersed in an inane video-game, to wander almost indefinitely within immense shopping centers.

Moreover, circuit-bending provides an excellent example of the process of inhibition of resistance through technological advance. The evolution of technology - more specifically, the miniaturisation of electronic components and increasing integration of electronic functions within a single chip - circuit bending becomes more difficult and even impossible. Towards the end of the 1980s the techniques for assembling electronic components on printed circuits changed, moving from Through Hole Technology (THT) to Surface Mount Technology (SMT). With THT components are soldered to the printed circuit by passing “legs” through holes in the circuit board, whereas with SMT components are directly soldered onto the board’s surface. Moreover, the components used in the SMT become increasingly miniaturized. Thus it becomes ever more difficult to find bending points and remove, add or substitute components. Miniaturisation also permits the production of chips that integrate and unite increasing numbers of functions that previously were distributed over different components, thereby reducing the possibilities of modification. Often, the miniaturized circuits are printed directly on the card and covered by a drop of epoxy resin, rendering what is inside the blob impossible to modify. As Collins writes:

> *Circuit Bending has changed since Reed Ghazala coined the term. One factor has been toy technology’s shift toward greater integration of functions onto a single chip. At the end of the last century, control of a toy’s various functions (making sound, blinking lights, reading switches, defining the clock speed, etc.) was typically*

distributed amongst several different integrated circuits and associated components, and benders delighted in messing around with the myriad connections between those components. Now integration has reached the point that everything is controlled by a single malevolent-looking black blob (Collins, 2009: 277).

When it is no longer possible to obtain electronic toy devices from the 1980s - already, for example, it is not easy to find a "Speak and Spell" on a market stall or on eBay - circuit bending, as we know it today, will cease to exist. Not because resistance to a certain type of market, society, aesthetic, is no longer necessary. Quite simply this type of resistance will no longer be possible. Thus the environmental benefit will no longer be possible to obtain, while business will continue to produce ever more unsustainable electronic devices. Circuit-bending will therefore have to reinvent itself, find new ways of bending, or vanish. Hacking and DIY will continue to exist, but the very specific form of resistance created by circuit bending will be inhibited by technological advance.

4. Conclusions

We may draw some conclusions both from the emergence and the fate of current circuit-building, considering it as a relatively small-scale, short-term experiment in resistance, yet with important implications and highly interesting potential for analogous initiatives, an experience which exemplifies the need and the way to find new forms of resistance together with move to more radical ways of changing behaviors and harnessing creativity and invention. Circuit-bending can be seen as an expression - albeit limited - of resilience in terms of the capacity of human and technological systems to absorb disturbance and reorganize as well as transformability in terms of creating new beginnings and ways of living.

From both educational and environmental perspectives, circuit-bending provides models for re-thinking and re-using processes and products typical of human activity. The term itself, with its emphasis on the progressive form of the verb and thereby a vision of reality as dynamic and process-based (Dodman, 2014), provides a powerful metaphor for human activity seen as learning through experimenting and creating, thinking through making (Ingold, 2013) and thereby building new knowledge. If sustainability and its necessary transitions are not points of arrival, but rather ways of being, based on resilience and transformability, then newly-discovered ways of bending will always be a part of human learning processes that are capable of enhancing our awareness of the relationship between technology as the use of tools and appliances, as knowledge-building processes and as value-bearing cultural artifacts.

References

Bijker, W.E. (1995) Of Bicycles, Bakelites, and Bulbs: Toward a Theory of Socio-technical Change. Cambridge, MA: MIT Press.

Callon, M. (1986) Some Elements of a Sociology of Translation: Domestication of the Scallopsand the Fishermen of St Brieuc Bay. in Power, Action and Belief: A New Sociology of Knowledge, edited by Law, J. 196-233. London: Routledge & Kegan Paul.

Callon, M. (1987) Society in the Making: The Study of Technology as a Tool for Sociological Analysis. in The Social Construction of Technical Systems: New Directions in the Sociology and History of Technology, edited by Bijker, W. Hughes, T. and Pinch, T. 83-103. London: MIT Press.

Chadabe, J. (1997) Electric sound: the past and promise of electronic music. Upper Saddle River, NJ: Prentice-Hall, Inc.

Chapin FS, III, Carpenter SR, Kofinas GP, Folke C, Abel N, Clark WC, Olsson P, Stafford Smith DM, et al. (2010) Ecosystem stewardship: Sustainability strategies for a rapidly changing planet. Trends in Ecology & Evolution, 25:241–249

Clark, W.C. (2001) A transition toward sustainability. Ecology Law Quarterly 27: 1021–1076.

Collins, N. (2009) Handmade electronic music: the art of hardware hacking (2nd ed.). New York, NY: Routledge.

Dodman, M. Language, its technologies and sustainability, in Visions for Sustainability 1: 09-19, 2014 DOI:10.7401/visions.01.02

Fernandez, A. M. & Iazzetta, F. (2011) Circuit-Bending and the DIY Culture (Unpublished article). Universidade de São Paulo, Brazil.

Folke, C., S.R. Carpenter, B.H. Walker, M. Scheffer, F.S. Chapin III, & J. Rockstro¨m. (2010) Resilience thinking: Integrating resilience, adaptability and transformability. Ecology and Society 15.4

Folke, C., A. Jansson, J. Rockstro¨m, P. Olsson, S. Carpenter, A.-S., Crepı´n, G. Daily, J. Ebbesson, et al. (2011) Reconnecting to the biosphere. Ambio 40.7

Ghazala, Q. R. (2004) The Folk Music of Chance Electronics: Circuit-bending the Modern Coconut. Leonardo Music Journal, 14, 97-104.

Ghazala, R. (2005) Circuit-Bending: Build Your Own Alien Instruments. Indianapolis, IN: Wiley Publishing, Inc.

Ingold, T. (2013) Making: Archeology, Anthropology, Art and Architecture. Abingdon, Oxon: Routledge

Naficy, S. E. (2010) Agency Through Engagement: Circuit-Benders' Subcultural Resistance (Unpublished paper submitted in partial fulfillment of the requirements for the Master of Arts degree in the Master of Arts Program in Social Sciences). University of Chicago.

Pinch, T. F. and W. E. Bijker. (1987) The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other. in The Social Construction of Technological Systems, edited by Bijker, W., Hughes, T. and Pinch, T. 11-44. Cambridge, MA: MIT Press.

Raskin, P., T. Banuri, G. Gallopin, P. Gutman, A. Hammond, R.Kates, and R. Swart. (2002) Great transition: The promise and lure of the times ahead. GTI Paper Series no.1. Boston: Stockholm Environmental Institute, Tellus Institute and Great Transition Initiative.

Rossi, G. & Dodman, M. (2015a) The contribution of psychology in connecting the civic and environmental dimensions of sustainability, in Visions for Sustainability, 3: 16-24 DOI: 10.7401/visions.03.03.

Rossi, G. & Dodman, M. (2015b) Understanding Young People's Engagement with Sustainability, in Journal of Academic Perspectives, Vol. 2015 no. 4.

Vergragt, P. J. (1988) The Social Shaping of Industrial Innovations. Social Studies of Science 18: 483-513.

Vergragt, P.J. (2006) How Technology Could Contribute to a Sustainable World GTI Paper Series no.8. Boston: Tellus Institute and Great Transition Initiative.

Walker, B.H., C.S. Holling, S.R. Carpenter, and A. Kinzig. (2004) Resilience, adaptability and transformability in social-ecological systems. Ecology and Society 9.5.

Westley, F., Olsson, P., Folke, C., Homer-Dixon, T.,,Vredenburg, H., Loorbach, D. Thompson, J., Nilsson, M., Lambin, E., Sendzimir, J., Banerjee, B., Galaz, V.,van der Leeuw, S. (2011) Tipping Toward Sustainability: Emerging Pathways of Transformation. Ambio, Vol. 40.7

Wittgenstein, L. (1953) Philosophical Investigations. Oxford: Blackwell