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Virtuality and the Discovery of Reality

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Abstract

Definitions of virtuality and the virtual are reviewed. It is shown that virtuality is extending our senses in many ways; that virtuality is closely linked with scientific visualization and thereby opening many visible, invisible, possible and creative worlds. Links with virtual and augmented reality are considered. From a scientific viewpoint it is claimed that the most important contribution of virtuality thus far lies in creating a new simulation – reality loop. In the past, simulations were models that served as abstract hypotheses about reality. Today, the most complex simulations are connected with the physical phenomena they emulate through sensors, which permit a constant correction both of the simulation and of the original objects/processes. This has profound philosophical implications.

Several factors play a role in these developments. One is the enormous increase in computing power. A second is miniaturisation. There are presently at least nine approaches towards computing at the nano-level among them DNA computing. A recent estimate claims that one gramme of DNA will have the capacity of 1 trillion CDs. Knowledge, which was once the almost exclusive domain of great libraries, will increasingly become mobile and portable. The sharing of knowledge will also change as collaborative work evolves through virtual laboratories and collaboratories. These developments are already altering our understanding of traditional disciplines and categories of knowledge. For instance, biology and technology were different fields until the advent of bio-technology. These developments are leading us to re-discover reality. Ultimately, they will change our concepts of reality, knowledge and life itself.

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1. Introduction

The Oxford English Dictionary defines virtuality as: 1. The possession of force or power (Caxton, 1483); 2. Essential nature or being, apart from external form or embodiment (Sir Thomas Browne, 1649) and 3. A virtual as opposed to an actual thing: a potentiality. Sir Thomas Brown (Pseud. Ep., 1649), used virtuality in a way analogous to Aristotle's concept of entelechy and thus combined elements of 2 and 3 when he claimed: "In one graine of corne there lyeth dormant the virtuality, of many other, and from thence proceed an hundred eares."[1] This meaning derived from the mediaeval Latin term *virtualitas* and was linked with the Latin term *virtualis* (i.e.virtual). This mediaeval notion of the virtual serves as a starting point for Pierre Levy's discussions in *Becoming Virtual. Reality in the Digital Age*,[2] perhaps the most extended theoretical discussion of the term in recent times. The virtual, claims Levy:

> should not be compared with the real but the actual….Unlike the possible, which is static and already constituted, the virtual is a kind of problematic complex, the knot of tendencies or forces that accompanies a situation, event, object or entity, and which invokes a process of resolution: actualization.[3]
> Virtualization can be defined as the process of actualization in reverse. It consists of a transition from the actual to the virtual, an exponentiation of the entity under consideration. Virtualization is not a derealization…but a change of identity, a displacement of the center of ontological gravity of the object considered.[4]

Levy's book has chapters on the virtualization of the body, text, economy, intelligence qua subject and object, the ontological *trivium* and *quadrivium*[5]. He identifies virtualization as a particular kind of transformation linked to final causes and eternity and ultimately sees the virtual as part of process which includes the potential, real and the actual (figure 1).

A quite different approach is taken by Milgram, Takemura, Utsumi, and Kishino (1994), who use a combination of three factors, namely, Reproduction Fidelity (RF), Extent of World Knowledge (EWK) and Extent of Presence Metaphor (EPM), in defining a reality-virtuality continuum which applies to augmented reality (figures 2-5).[6] A third approach to virtuality in the realm of organisations is offered in a perceptive paper by Grisholt (1998), who relates it to grids of space, time and organization (figure 6):

> The letters A, B, C and D indicate where in the organisation-space, the following hypothetical examples of virtual organisations might be found:
> A. A team of collaborating high-energy physicists, accessing equipment and communicating on-line on a long-term project. Relatively permanent, capabilities common to all, high degree of virtual presence.
> B. A team of collaborating industrial scientists, accessing equipment and communicating on-line, high turnover of personnel within firm; duty rotation.
> C. A team of collaborating scientists, based at an in-house laboratory, bringing in a significant proportion of 'outside' knowledge (from suppliers, users etc.,) to work on a long term project.
> D. A continually evolving network of scientists (suppliers, customers etc.) accessing equipment at many sites and communicating on-line, i.e. members based at many sites."[7]

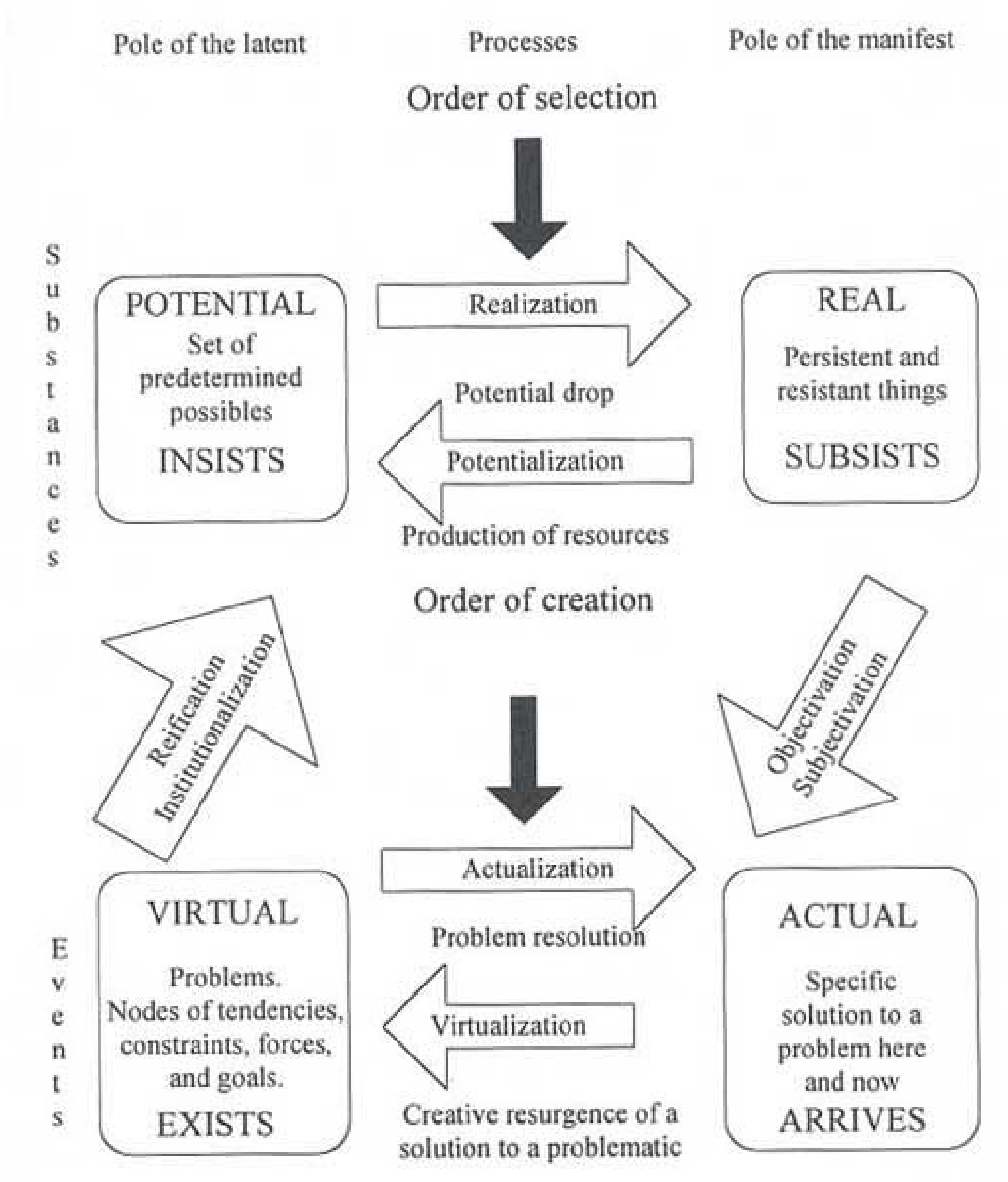
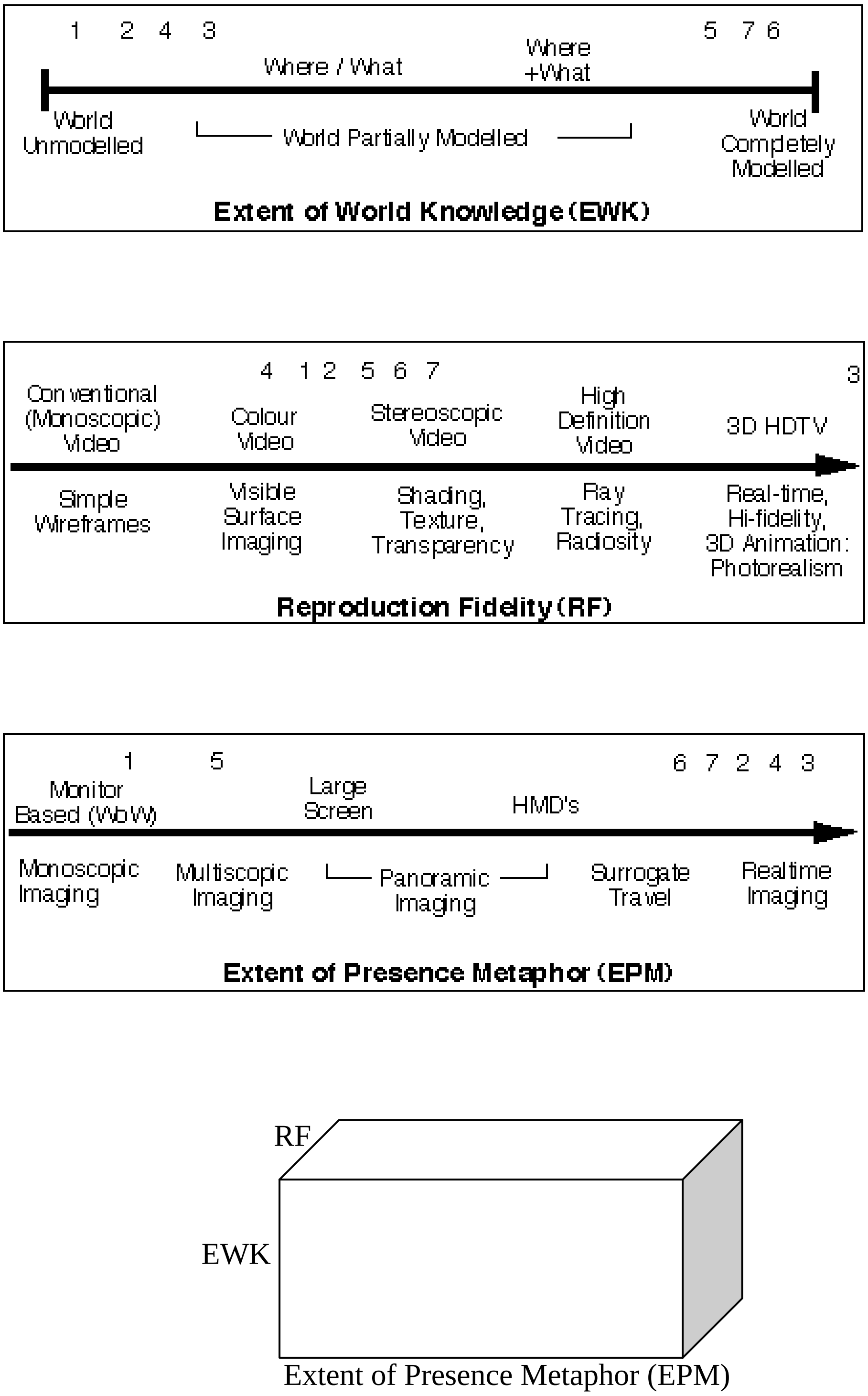


Figure 1. Pierre Levy's ontological *quadrivium* of the virtual, potential, real and the actual.



Figures 2- 5. Milgram et al. use a combination of three factors, namely, Reproduction Fidelity (RF), Extent of World Knowledge (EWK) and Extent of Presence Metaphor (EPM), in defining the reality- virtuality continuum which applies to augmented reality.

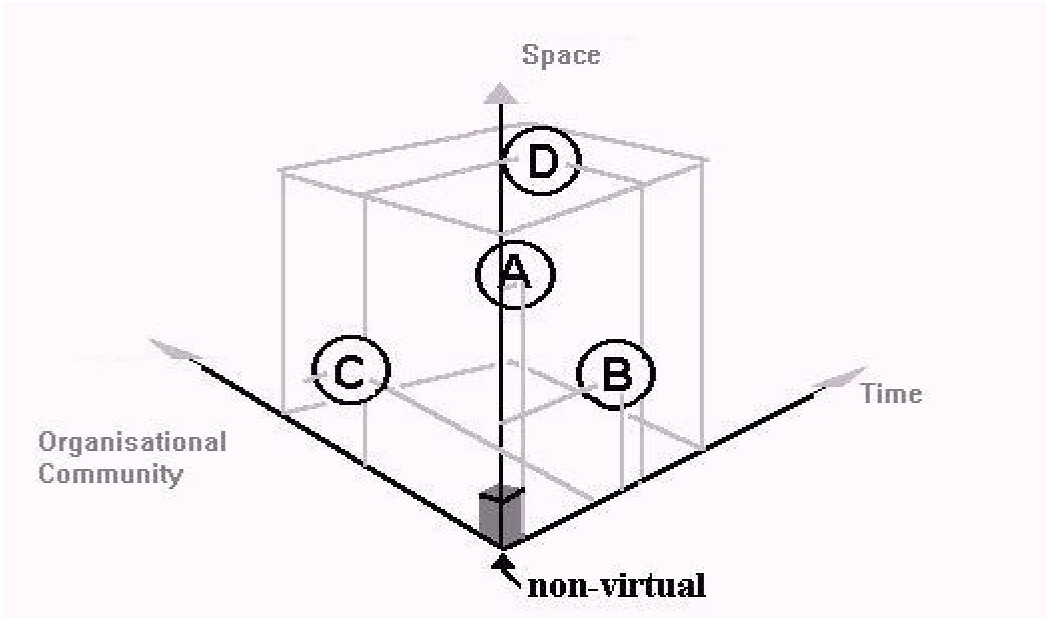


Figure 6. Visualisation of the non-virtual with respect to space, time and organisational community according to Gristock (1998).

Further study reveals that there is a wide range of meanings of virtuality. Some simply refer to their presence on the web as their virtuality.[8] The Cultural Studies section of the University of Vienna opposes models (virtuality) and ongoing activity (reality).[9] A project in Helsinki links virtuality and digital nomadism.[10] The difference between virtuality and cyberspace has been explored by Wooley.[11] A number of scholars have explored the implications of virtuality for public space, the concern being that public space will be commercialized;[12] its potentials for virtual space expression via interfaces with direct links to the senses[13] and its connections to a number of disciplines including: biosciences,[14] literary theory,[15] political theory[16] and political economy,[17]

We shall show how virtuality entails new extensions of the senses. To understand better its significance we examine how virtuality relates to scientific visualisation: how it is expanding the horizons of the visibile, invisible, possible and creative worlds. We show that virtuality is affecting a wide range of fields including astronomy, military planning, industrial design, nano-technology, film, video, crime reconstruction, stock market analysis and weather prediction. Next, the relation of virtuality to virtual and augmented reality is considered. Here we claim that virtuality is introducing a new simulation-reality feedback loop, which has profound implications. Connected with this are new methods of work through virtual laboratories and collaboratories. In the short term these methods are leading to global networks of knowledge in individual fields and new interplays among different fields. In the long-term, virtuality promises to be much more than a new gateway to reality.

2. Extension of Senses

Sigmund Freud is best known for having made us more aware of the interior workings of the human mind and soul. Ironically, it was also he who noted: "With every tool man is perfecting his own organs, whether motor or sensory, or is removing limits to their functioning."[18]

This idea was taken much further by the late Marshall McLuhan, who spoke of technologies as extensions of man.[19] In the past those technologies were invariably extensions of physical aspects of the human condition. Through a mechanical “extension” of our arms, bulldozers allowed us to push more than we could ever do with our bare hands. Similarly cranes allowed us to lift more. Telephones are extensions of our voice, televisions of our eyes.

The Internet began as an extension of our writing capacities: asynchronously through e-mail and synchronously through chat-rooms MOOs, MUDs and the like. Through web-telephone and web-TV we have digital extensions of our ears and eyes. Through web cameras on the Internet we can see news half way around the world without having to go there, and in some cases can actively control the camera to see what we choose. Computers and the Internet are gradually extending to all of the senses.

Sight

Sight is the most developed of these digital senses. Stereoscopic displays in cockpits were introduced at Wright Patterson Airforce Base by Tom Furness III as early as 1966. Work on this theme continues around the world at centres such as the University of Hull.

One of the most important developments of the past decades has been to extend the realm of the visible beyond the limits of everyday vision. This was one of the underlying incentives for Sutherland's original work on virtual reality in his 1967 paper and it is no co-incidence that scientific visualization is an enormous emerging field. The Massachusetts Institute of Technology (MIT), for instance, has a project on Aero/Astro Scientific Visualization.[20] MIT is also working on a Virtual Environment Technologies for Training Testbed (VETT), a Video Streamer,[21] and a Dynamic Personal Enhanced Reality System (DyPERS),[22] all of which will offer new modalities for digital vision.

The Graphics and Visualization Center[23]at Brown University has work on Magnetic Resonance Imaging (MRI), as well as Geometric Model Extraction for MRI Data, Ultrasound Image Data Use, Image Guided Streamline Placement, and Vector Field Visualization. There are now hundreds of such projects on scientific visualization around the world. New developments with respect to the computer/ human interface at the biological level suggest that direct neural implants allowing the blind to see will be available in the near future.[24]

A series of new display methods are emerging in this context. These range from the small screens in portable cell phones such as Nokia or Kyocera; to responsive workbenches by the GMD,[25] to auto-stereoscopic devices,[26] to 360 degree panels such as that used by NASA at Mountainview.[27]

Sound

Speakers were one of the earliest characteristics of early multimedia computers. This was typically a passive functionality limited to playing music or a short voice clip. In the past decade there have been enormous developments in the field of speech recognition which have led both to new voice activated navigation systems and direct dictation through products by firms such as Lernhout and Hauspie, Dragon Technologies and IBM. One of the latest developments in the audio field is SpeechBot which: "listens to Web-resident audio programming, converts the sound into a textual transcript, and then indexes those words so that you can type in queries and receive "hits" -- not to pages of text -- but to the very section of audio that interests you within a long program."[28]

The University of Bath's Media Technology Research Centre[29] is working on a Platform for Animation and Virtual Reality (PAVR),[30] which includes sound and music, speech, vision and image processing. Companies such as IMAX are working on 3D sound to complement their Omnimax and 3-D IMAX films. The Thorn EMI, Creative Research Laboratories (CRL, Hayes) are also working on a combination of a High Definition Video Display (HDVD) image and Sensaura artificial head for 3D sound recording.

Meanwhile, at the global level there are still debates about basic standards. The President of the World Digital Audio Broadcasting Forum (WorldDAB) favours Europe's Eureka 147 system which is competing with a series of other solutions by In Band On Channel (IBOC); Worldspace, the European Space Agency (ESA cf. DASA) and Inmarsat.

With respect to content there is an International Association of Sound and Audiovisual Archives (IASA)[31] and in Russia there is a fascinating Encyclopaedia of Sound.[32] As part of the Distance Education and Learning [33](DELTA) programme there is an interactive learning platform on the Internet about the history of music.

Music

In 1998 the Internet accounted for .4% of all music sales. By 2005 this is predicted to increase to 11% of sales valued at $5 billion.[34] These predictions are complicated by an underground scene which is against copyright and which champions MP3 through companies such as Liquid Audio,[35] and non-official sites such as MP3.com. Companies such as Diamond Multimedia and Samsung are producing MP3 recorders such as the Rio and the Yepp. This scene includes the Internet Undergound Music Archive (IUMA) and Napster, which has recently been sued by the Recording Industry Association of America. (RIAA).[36] To counter these developments, Leonardo Chiariglione, of CSELT (the research arm of Telecom Italia), has been developing the FIPA, MPEG 4 and 7 standards:

> (a) content providers must be given mechanisms to track the evolution of their content through the delivery chain; (b) service providers must be given the possibility to push content targeted to users' needs; (c) delivery systems providers must be given the possibility to charge the usage of their infrastructure depending on the quality of service requested by the service

provider or consumer; (d) consumers must be given the possibility to pull content targeted to their needs.

In early 1999 he was also invited to lead a new Secure Digital Music Initiative (SDMI). This began as a group of fifty leading companies in the recording and technology industries and has since grown to 120 firms and is working on two tracks: "The first has already produced a standard, or specification, for portable devices. The longer-term effort is working toward completion of an overall architecture for delivery of digital music in all forms.[37] Meanwhile, the International Music Joint Venture (IMJV),[38] was founded by three music copyright organizations: ASCAP (USA), Buma/Stemra (the Netherlands) and the MCPS-PRS Alliance (UK) in order to: "to eliminate duplication in, and improve the accuracy of, common databases; reduce costs and improve efficiency, upgrade systems and embrace new technology."[39]

A project of the European Commission (EC ESPRIT 22226[40]) is working with the International Federation of the Phonograph Industry (IFPI) at Developing Digital Media Management, Signalling and Encryption Systems for the European Music Industry (MUSE). Another EC project (IMPACT project 4050) is working on Music on Demand- A European Interactive Music Information and Delivery Service (MODE).[41]

At the same time major corporations are seeking independent solutions. IBM, for instance has launched the Madison Project which includes a partnership of the “big five” in the sound industry, Universal, Sony, Time-Warner, EMI and Bertelsmann; as well as British Telecom and Deutsche Telekom. Three of the big five (namely, Warner Music, Sony and EMI) have also joined with BSkyB to create Music Choice Europe. Meanwhile, AT&T is working with Universal (owned by Seagram) to create A2B.

Touch

Tactile Force Feedback has been developed in the context of virtual reality. At the non-military level the Teletact (1991)[42]project of Jim Helicon and Robert Stone was a pioneering effort.The University of North Carolina at Chapel Hill was one of the pioneers of force feedback at the microscopic level.[43] MIT has a Haptic Interfaces Lab,[44] work on Mechanics Control and Applications; and a Tangible Media Group[45] under Professor Hiroshi Ishii, which works on Tangible Bits,[46] and concepts such as the Meta-Desk. Northwestern University is working on a Haptic Display[47] in connection with the collaborative visualisation (CoVis) project. There is a Symposium for Haptic Interfaces for Virtual Environment and Teleoperator Systems[48] Companies such as General Electric have important research on haptic devices.[49]

In Europe, the Scuola Superiore Sant’Anna (Pisa) has a project on PERCeptual RObotics[50] (PERCRO) with haptic interfaces. Haptic feedback for surgical simulation is also being studied in the Virtual Environments Graphics and Applications (VEGA)[51] project at the University of Hull, which also has a Biomedical Model of Human Knee Joint, a Knee Arthroscopy Training System and Physically Based Modelling (PBM).

In Japan, Professor Michitaka Hirose at the Hirose Lab[52] of the Department of Mechano-Informatics is working on haptic displays. Professor Hiroo Iwata at the University of Tsukuba[53] is working on force display, on haptization, the haptic representation of scientific data; and a surgical simulator with force feedback as well as autonomous virtual objects and cooperative work.

Related to the above is the emerging field of gesture technology which could be seen as touch at a distance. MIT, for instance, is working on a Gesture and Narrative Language.[54] Mark Lucente, working with MIT and IBM has demonstrated how one can move virtual objects on a screen at a distance using only gestures.[55] This is another dimension of the wireless revolution.

Smell

In the autumn of 1999 Wired[56] reported on the new company Digiscent,[57] which is making smells available on line, although the notion of perfume on demand is not yet imminent. Behind the scenes are other developments which are potentially much more dramatic. The Pacific Northwestern Labs of the US department of energy have been developing an electronic, neural nose[58] the environmental applications of which include: identification of toxic wastes; analysis of fuel mixtures; detection of oil leaks; monitoring air quality; testing ground water for odors.

This means that robots could in future enter a room, a mine or some other uncertain place in order to determine whether there be poisonous gases present. It also means that a personal robot of the future might sniff their master and provide them with deodorant/perfume appropriate for the occasion.

Taste

As yet there is no official on-line software for taste. Developments at the microscopic level suggest that within two decades direct stimulation of the sensory cortex via neuronal implants will make it possible to evoke any or all of the senses at will. Meanwhile, there is work on sensory transducers, which increasingly allow us to translate experiences from one sense to another. Magnetic Resonance Imaging is an elementary example where sound scans are translated into visible images. A next stage would be a set of glasses, which translated such sounds into real-time images. These trends are summarized in figure 7.
The convergence of technologies is furthering this trend but at the same time is taking it inward. An almost anecdotal example in a recent newsletter gives an idea of the unlikely extensions of technology, which are occurring through these Internet developments:

Sight	Eyes	Cameras
Hearing	Ears	Microphone, Speaker
Touch	Fingers	Force Feedback Glove
Smell	Nose	Digiscent, Neural Nose
Taste	Tongue	---
Synaesthesia		Neural Implants

Figure 7. Five senses, their physical organs and their digital counterparts.

> Connecting your Singer to Cyberspace
> Was I shocked when I read this sentence in a sewing discussion board?
> "Husquavarna also has a new machine coming out in January which changes their software/hardware needs. The new machine will use a regular 3.5" floppy..." All my experiences with Husquavarnas were with chain saws, but beyond that - sewing machines with USBs, floppies, and their own file format debates? Bernina, Pfaff, and Singer all have developed product lines that connect to the Internet (via a PC) so you can download patterns and embroidery.[59]

3. Scientific Visualisation

Visible World

In 1878, Jules Marey, one of the pioneers in the development of motion pictures, published his classic book, *The Graphic Method in the Experimental Sciences*,[60] in which he argued that science faced two obstacles: the deficiences of the senses in discovering truths and the insufficiencies of language in expressing and transmitting those truths which have been acquired. His graphic method aimed to overcome these obstacles by rendering visible otherwise unseen aspects of the physical world.

Ninety years later, when Ivan Sutherland (1968) wrote one of the first articles on virtual reality, he was very articulate about the role of the new medium in visualizing things, which had not been seen before. In the past decades this theme has excited ever greater interest[61] and has led to the field of scientific visualization. Some examples have already been mentioned above. Here we shall outline how it is affecting almost all aspects of the visible and invisible world.

Visible World

In medicine, projects such as the Visible Embryo[62] and the Visible Human[63] project are providing us with new levels of visualization concerning the entire human body. A human body is frozen, cut into thousands of thin slices, each of which is then photographed and stored digitally. These photographs of real human can thus serve to correct proposed models. They also lead to new physical models.[64] Thus careful, detailed recording of the physical world, leads to more accurate bases for simulations thereof, which in turn lead to new discoveries about the physical world. A project at the Chihara Lab is exploring a virtual piano player in real time.[65] Virtuality leads to a discovery or rather a re-discovery of reality.

In engineering, CAD models, which were initially applied to individual objects in the workplace, are now being applied to entire factories. A project at the University of Manchester entails a factory with over 40 person years to create a virtual reality version.[66] There is a Global Engineering Network (GEN)[67] linking engineering elements all over the world. The Virtual Environments for Training (VET) project involves a reconstruction of the complete interior of a ship where the function of every dial is represented as a working java applet.[68]

In architecture, companies such as Infobyte have made a virtual reality reconstruction of the church of San Francesco in Assisi, which is being used to repair the original subsequent to its being damaged by an earthquake.[69] In Japan, another of Infobyte's reconstructions of Saint Peter's Basilica is being projected in a former planetarium called a Virtuarium.[70] CAD models, which were once limited to individual buildings are now being extended to entire cities. Bentley Systems, for instance, is creating a virtual Philadelphia[71] which, in fact, only covers a central portion of the city. Canal Plus is creating a reconstruction of Paris which is presently still limited to portions of the city such as the Eiffel Tower, the Louvre, and the Place des Vosges, but is so detailed that one can see the numbers on individual houses along a street. France Telecom, has a similar reconstruction which allows one to enter shops and do tele-shopping. Slightly less detailed, but at least as interesting conceptually is Virtual Helsinki, which will allow one not just to roam virtual streets but also to listen to sermons of ministers, lectures of professors and debates of politicians on-line.

The past decades have seen hundreds of virtual versions of historical sites and cities, the topic of a fascinating book by Maurizio Forte.[72] Cities such as Rome are perhaps the best known in this context. Some of these are also being put on line as in the case of La Rochelle where one can walk through the central part of the old town.[73]

More recently there is a quest to add a dynamic dimension to such reconstructions. Here, the Nuovo Museo Elettronico (NUME) project of the University of Bologna in conjunction with CINECA is perhaps the most important project to date. It provides a dynamic version of the central section of the city of Bologna from the year 1000 to the present. The three-dimensional reconstruction is linked with evidence from manuscripts, and other historical documents. Objects, which were originally part of monuments in the city and which are now dispersed in museums are linked to each other. CINECA is also engaged in another project concerning the reconstruction of Pompeii, Herculaneum and other Roman settlements near Naples. In this case, archaeological evidence is linked with detailed topographical and geological maps and a range of historical evidence. The quest is much more than a simple reconstruction of buildings as they once were.[74] The enormously detailed models are intended to serve as simulations of life in Antiquity against which historical and economic theories can be seriously studied: Sim City goes historical.

Invisible World: Natural Processes

Institutes such as the National Center for Atmospheric Research (NCAR)[75] use virtual reconstructions to study possible developments of heat in air and water (the El Nino effect), gases in the air, clouds, wind currents, storms, tornadoes and other extreme weather conditions. While some aspects of these phenomena may be visible to the human eye, the simulations allow us to see the processes in a much more comprehensive manner. In the case of storms, for instance, NCAR uses satellite images of real storms and compares these with model reconstructions of such a storm. Once again the evidence of physical relaity is being used to modify virtual models in order that they have greater predictive qualities in the future (cf. the simulation-feedback loop below). The Chesapeake Bay project explored environmental issues pertaining to underwater polution normally invisible to the human eye.

ISO Layer	Hardware	Software
Network	Gate Block	Gate Task
Transport		
Technical Service	Chip Card Appliance	Chip Card Process

Figure 8. Parallels between International Standards Organization layers, functions and Brad Cox's different layers of granularity in hardware and software.

Invisible World: Outer Space

Ever since the invention of the telescope, instruments have been opening up the horizons of planets, stars and galaxies beyond the sight of the unaided eye. The Hubble telescope has greatly expanded the range of images now available to us.[76] New methods of visualization are also being developed to make available the results of such visual explorations of the sun, the solar system, and outer space. For instance, a project at the Haydn Planetarium, called Digital Galaxy, uses Silicon Graphics machines (with seven pipes) to project images such as those from the Hubble Spacecraft onto the ceiling of a planetarium.

Invisible World: Concepts

In order to distinguish different functionalities in the tele-communications world, the International Standards Organisation, established three kinds of layers (entailing seven network layers). More recently, Brad Cox has made a plea for visualizing five different layers of computer hardware and software (figure 8), demonstrating how the major programming languages (Lisp, Smalltalk, C, C++ and Objective C) can be understood better using this approach.[77] In short, virtuality is being used to render visible dimensions of code which were hitherto invisible. The efforts of Dr. Steven Eick at Bell Labs to visualize patterns in software code mark another step in this direction.[78]

Invisible World: Economic Processes

The use of graphs is a well-known practice in economics. In the 1960's economists began exploring the potentials of three-dimensional graphs to visualize economic trends. With respect to investments, firms such as Visible Decisions[79] rendered such trends visible first in three-dimensional graphs and then with an added real time dimension. Asymptote's three dimensional real-time rendering of the New York Stock Exchange is one of the most dramatic developments in this context:

> The Exchange has chosen the world's most powerful visualization supercomputers to generate a completely interactive virtual representation of its trading floor. By consolidating the data streams from the various floor trading systems into one three-dimensional system, a visual display is created that allows users to intuitively understand complex business transactions instantaneously, as well as see system problems at a glance.[80]

Invisible World: Nano-Level

In the past decades, new links between electron microscopes, force feedback haptic devices or nano-manipulators, and visualization have led to an enormous new field of imagery. The opening slide of this lecture from the Hitachi Viewseum[81]is but one example. IBM, which was a pioneer by being the first to write IBM in molecules, has a small on-line gallery of such images.[82] Nano-photography is essential for the evolution of nano-simulation as a field. Again the visualization of hitherto invisible aspects is leading to the discovery of nano-reality and development of nano-technology.

Possible Worlds

The virtual reconstruction of entire landscapes has become of ever greater interest to the military who now use such images of the real world in order to develop realistic battle and other emergency scenarios.[83] In this context, war games are deadly serious. In a first stage, such simulations involved a demonstration at a local site, not very different from the way generals traditionally had models or at least maps of battlefields at their disposal. At a second stage, these simulated models became networked such that players in different centres could play the same game: like playing networked *Doom* with real scenarios. A third stage is integrating such networked scenarios with physical locations. For instance, the Terravision project at SRI,[84] linked with the Army's supercomputer in Minneapolis, provides persons on the battlefield access to satellite and other aerial images of the situation. This real time information can be used to modify scenarios on the home front. Virtuality thus leads to the discovery of reality and reality leads to corrections in the reality of the moment.

In design, the software of companies such as Alias Wavefront is being used for a whole gamut of products ranging from simple cosmetics and furniture to interiors of airplanes, the design of automobiles, trucks and boats. The design of cars, tractors, and aircraft, once the domain of secretive teams within a single company, is now increasingly the domain of collaborative teams linked with global databases of engineering and design elements.

In film, visualization in the form of special effects, has become a commonplace.[85] *True Lies* introduced a virtual Harrier jet into a cityscape. *Disclosure* created virtual information spaces, which bore an uncanny resemblance to St. Peter's Basilica. As *Dreams May Come* offered a visualization of the protagonist's heaven and hell and a library reminiscent of Robert's architectural phantasies.[86] *Toy Story* is an entirely virtual world. In Manchester, virtual reality was used to reconstruct the scene of a crime: said to be the first time such a reconstruction was used as evidence in a court of law.[87]

Creative Worlds

While many see virtuality as a means of making new scientific links with the physical world, some interpret virtuality as a blurring between the real and virtual.[88] The artist, Michel Moers, goes further and links virtuality with playful, creative, illusion:

> These simplified shapes often become archetypes that are more than true-to-nature, more colourful, more joyful and, more especially, easier to live with - all they have to do is to appear on the scene and pretend! This era of top models and virtuality has something comfortable about it. Doesn't it? All the rest is so confusing and turbulent.[89]

The musicians Martin Kornberger and Volker Kuhn, who created the music CD, *Virtuality*, in 1992 are more explicit in linking this blurring function with the creative process. Kornberger, for instance, notes that: "Virtuality - signifies the crossing of the borderlines between man, machine and nature. By means of computertechnology it is possible now to scan reality and form new virtual ones - at least in music." His colleague Kuhn puts it slightly differently: "Virtuality - this expresses in some way a longing for illusionary worlds of beauty and power beyond human restrictions. But the closer one gets to them, the more unreal and empty they seem. At last nothing remains but the lonelyness of our inner space."[90]

One of the prolific areas of development in this context is the realm of virtual reality worlds being created by artists.[91] In the literary field novelists such as John Barth have reflected on the meaning of virtuality with respect to culture.[92] One of the most complex experiments in this context is a project on Electronic Arenas for Culture, Performance, Art and Entertainment (eERENA),[93] which includes a vision system, visual content, audio content, user representation, content/story, physical space, virtual storybook of an electronic arena and a mixed reality theatre. Information from all of these layers interacts with live players on a stage.

At Manchester University, Professor Adrian West, one of the pioneers of large scale virtual reality programmes, has become fascinated with the potentials of virtual worlds to convey alternative worlds:

> Cages is a demonstration of the deva world hierarchy, and the idea of environments that impose behaviours on their contents. This is akin to specifing the properties of time, space and physical laws for a particular universe. The complexities of such laws are limited by the computational resources available to impose them. Any object placed within such an environment has these laws and behaviours imposed upon it. We believe this approach will make it significantly easier to create a range of complex virtual environments.[94]

Computer software such as Windows showed the world from one particular viewpoint within a single frame of reference. Professor West's software allows one to change perceptual world's: e.g. to look as an individual in a room at a fish in a fishtank; then look as a fish in the fish tank at an individual in a room beyond the tank and then as an individual standing outside the room looking at the individual and the fish. Not only are the viewpoints different, but each of these spaces can have their own laws of physics. For instance, the first individual can be in a room subject to the normal laws of gravity; the fish in virtual water can be subject to different rules and the person outside could be in a space not subject to ordinary gravity.

4. Virtual Reality

The idea of Virtual Reality (VR) goes back to the pioneering work of Sutherland (1967), Furness and Krueger (1983)[95], but did not gain popularity until a team at NASA including Warren Robinett and Scott Ellis, linked the 3-D glasses and the data glove for the first time (1986). One of the earliest goals of virtual reality was to help visualize things, which cannot be seen in everyday life, such as seeing the bonding structures of molecules. It soon became associated with the notion of tele-presence, which initially meant handling of objects at a distance. Here the concern was using robots to enter places, which might be unfit for human beings. For instance, it was imagined that one might in future have a robot enter a nuclear reactor such as Chernobyl, before it reached a breakdown stage and perform key operations at a distance.

In places such as Toronto the notion of tele-presence became linked with advanced forms of teleconferencing in the form of collaborative work-spaces. Such notions of tele-operation and tele-collaboration, led to the idea that one could also do experiments at a distance. Hence a scientist in one city without high-powered devices, could use the Internet to link with a centre which had the appropriate high level computers and other instruments. Tele-operation also brought with it the possibility of remote monitoring of a process.

In a second stage, virtual reality became linked with simulations. One could use it to visualize, for instance, the development of a major storm or tornado in order better to predict the consequences of these natural disasters. One could also use it to simulate all the operations of a complex machine or a combination of machines as in the case of a ship. In the Virtual Environments for Training, for example, this is used to teach persons the workings of a ship's many instrument panels -- each of which functions as an independent device through Java programming. Alan Dix has listed at least four major application areas of virtual reality: 1.simulate dangerous/expensive situations (including command and control; virtual tourism; practicing medical procedures; treatment of phobia); 2. see hidden real world features such as the virtual wind tunnel; 3. visualise complex information and 4. fun.[96]

As in the business world, the manufacturing world has seen important developments towards globalization. There is, for instance a Global Engineering Network (GEN),[97] initiated by companies such as Siemens, which seeks to co-ordinate all the basic laws and processes of engineering. Parallel with this Autodesk has led a consortium called the International Alliance for Interoperability (IAI), concerned with establishing Industry Foundation Classes[98]

5) Simulation - Reality Feedback Loop

More recently a third stage has begun combining the above developments. Hence one can now use virtual reality to simulate the workings of a complex set of operations such as those in a nuclear reactor. This simulation establishes the workings of a reactor under ideal conditions. Various discrete processes in this simulation can then be linked with devices, which monitor an actual reactor and check for anomalies. If such anomalies are found the simulation can be used as a basis for correction. For instance, the Industrial Computing Society's Web estimates that $20 billion is lost annually with respect to Abnormal Situation Management (ASM) and they:

> believe that we must move the control system design from a reactive mode to a predictive mode and a long time before an alarm is initiated the AEGIS system must predict the event using the latest State Estimation tools. AEGIS is currently evaluating two such tools Advanced Process Analysis & Control System (APACS) which is a Canadian PRECARN initiative and FORMENTOR which is a French EUREKA program.[99]

APACS is a tool which uses the ideal conditions in a simulation as the basis for monitoring real conditions, processes in the physical world, anomalies in which are used to adjust the simulation and lead in turn to preventative action. This approach is also implicit in the Visible Human project:

> The Visible Human Dataset (VHD) is playing a capital role in the validation of virtual endoscopy (VE). Next to mathematical simulations and phantom studies, both in vitro and in vivo research is required. The main difficulty consists in the provision of a "ground truth" measure. The VHD cryosection data precisely offers the standard against which the image processing effects can be calibrated and judged whereas the very same VHD data forms the basis to produce realistic simulations for testing procedures. The VHD models serve as a relevant framework for medical education, anaesthesiology training, surgery rehearsal and endoscopic simulation.[100]

This approach is explicit as well in a recent European project entitled Bridging Reality and Virtuality with a Graspable User Interface (BREVIE):

> A radical new kind of learning environment will be promoted. Based on the combination of real world phenomena and virtual world simulations through a Graspable User Interface it will be possible to freely change between operations on real physical objects and their virtual counterparts. These Twin-Objects, real and corresponding virtual components, will compose a new kind of complex construction kit which prepares a new era of simulation technology: Real and Virtual Reality. An era in which real physical parts have an adequate functional, structural and behavioural description, to build from these components a composite system which again shows the correspondence between the physical and the virtual system. The aim of this project is to demonstrate the feasibility as well as the advantages of this concept by providing a construction kit of TWIN-Mechatronic-Objects suitable for vocational training in production automation.[101]

The problems of relating an ideal model with the real world have a long history. They were a central concern of Plato who opposed objects in an ideal world of ideas with those in the physical world. In Plato's approach the ideal world was the perfect, "real" world and the physical world represented a copy, often an imperfect, deceptive world of (mere) appearances. In the centuries that followed, philosophers such as Plotinus, tried to bridge the Platonic world of ideas with the physical world through a hierarchy of being whereby one moved from the perfection of the ideal to the imperfection of the physical world. It took centuries before the Christian belief in the creation of the

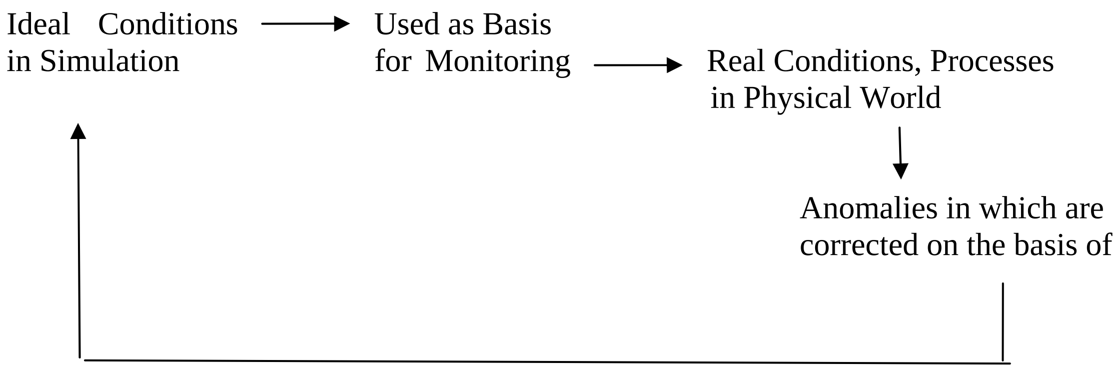


Figure. 9. Schematic view of how a simulation can be used to monitor real conditions in the physical world, anomalies in which are then corrected on the basis of the ideal conditions in the simulation.

world by God brought the physical world to a plain where it could vie with the reality of the ideal. Even so the manner of linking the two remained more a domain of theoretical debate between philosophers than something which could be addressed in practical terms.

The profound breakthrough of the new technologies outlined above is that there is now a complete loop between an "ideal" simulation and an actual process in the real world. Instead of being an abstract ideal, it serves as a model for the actual situation and then monitors this actual situation to register discrepancies, which can then be adjusted using the ideal conditions of the simulation as a control. As a result human intervention is theoretically no longer necessary.

6. Augmented Reality

Related to virtual reality are important developments in augmented or enhanced reality. In its simplest form augmented reality superimposes virtual information onto the physical world and the environment. For instance a project by Steve Feiner[102] at Columbia University called architectural anatomy uses glasses to superimpose on buildings and streets information about electricity wires, drainage pipes, heating ducts and other things behind walls, under the ground or otherwise invisible to the human eye.

Augmented reality is defined by Wendy MacKay[103] as having three dimensions, namely, augmenting the user, environment or the object. This represents a whole range of applications linked with virtuality. Some preliminary projects are listed in figure 10. Detailed discussion of these is beyond the scope of the present paper but deserves much more study. This will become all the more important as machine-to-machine communication and agent technologies mature which permit new interplays among environments, objects, and users. Of particular interest for our purposes is how these developments entail a range of new links between real objects and virtual information usually via databanks. In the case of augmented reality with respect to the user, if linked with personal profiles, new feedback loops are created. Meanwhile, virtual and augmented reality at a distance are leading to virtual laboratories.

Augment	
User	Charade[104] Karma[105]
Environment	Digital Desk[106] Smart Desk[107] Ubiquitous Computing[108] Active Badges[109]
Object	Lego Logo [110] Digital Ink[111]

Figure 10. Three forms of augmented reality according to Wendy Mackay (Xerox, Paris).

7. Virtual Laboratories

These virtual laboratories range considerably in their scope. For instance, the pressure chamber at the University of Oregon[112] to demonstrate the ideal gas law, is simply a simulation of a physical environment as a Java applet. The Microscape Virtual Microscope Lab[113] shows on the web examples of images seen by using a microscope. The Lawrence Livermore Laboratory Virtual Frog project represents a next level of interactivity. Here, students can manipulate reconstructions of a frog, various parts and layers of which are linked with film clips and other materials of a physical frog.

Meanwhile, another level is concerned with so-called remote instrumentation in real time, as is the case with the World-Wide Laboratory (WWL), a joint venture of the Beckman Institute, the Biomedical Magnetic Resonance Lab and the National Center for Supercomputer Applications (NCSA). WWL has two important educational projects: Chickscope,[114] whereby students can watch the embryo of a chicken through a microscope on-line in real time and Bugscope,[115] whereby classrooms can control an Environmental Scanning Electron Microscope in the Chicago lab from their schools via the Internet. A recent report describes clearly how at least three instrument access modes are supported:

> Single User: Allows dedicated access to an imaging system by a single user.
> Multiple non-cooperating users: Allows several users to access the system simultaneously. The users are not aware of each other. Commands from the users are queued and the data is returned to the requesting user. This mode is useful in education projects like Chickscope where several classrooms may be accessing the instrumentation simultaneously.
> Multiple cooperating users: Allows several users to use an instrument collaboratively by using mechanisms for passing instrument control among the users.[116]

The Beckman Institute has, moreover, three basic goals with respect to these experiments, namely, to provide: "a set of specifications for developing instrument control servers,…initial implementations of those servers, [and]…image processing tools which can be accessed over the internet through a variety of user interfaces." The experiments presently entail four kinds of instruments: Transmission Electron

Microscopes (TEM); Magnetic Resonance Imaging (MRI) Systems; Scanning Tunneling Microscopes (STM), and Laser Scanning Confocal Microscopes.[117] Related work, which has been operational since 1997, is being done in the Microsystems Technical Laboratories at MIT:

> The Remote Microscope is part of a project to aid in the remote fabrication of integrated circuits. It allows one or more users to remotely view and control a microscope connected to a local or wide area network. The control takes place through a client application written entirely in Java, allowing it to run on almost any computer platform and even from an ordinary Web browser. The client boasts a user friendly interface with advanced features, such as the ability to use a VLSI layout as a navigation tool. This project makes it possible to share a microscope facility among multiple research designers. It also increases the amount of collaboration that can take place during the inspection of a wafer. These uses and features make the Remote Microscope a valuable tool in distributed design.[118]

Such remote experiments can be seen as a subset of a more comprehensive quest for operation at a distance which began in the military as the goal of tele-presence. There are striking parallels between this quest and developments in virtual libraries qua traditional libraries. In the past, access to great libraries was limited to those who were privileged to be in a city, which could afford a great collection. Similarly, major scientific experiments were only possible in places, which could afford the millions or even billions of dollars required to have the latest scientific equipment. Thanks to virtual libraries and virtual laboratories such centralized resources can now function in a distributed way and be accessible to a far greater range of users around the world. For example, TNO in the Netherlands has recently opened a virtuality laboratorium.[119] In the realm of restoration a Virtual Laboratory is due to open at the Foundation for Fundamental Research on Matter (FOM) in Amsterdam in the summer of 2000.[120]

What makes all this so enormously significant is that the principle can be applied to every kind of instrument. For instance, the Argonne Laboratories have a Futures Lab, which is exploring three kinds of virtual reality applications: visualization for atomic and molecular simulations, multiresolution fluid dynamics, and visualization of databases.[121] There is no reason why the results of such processes and even the processes themselves could not be made accessible on-line. The frontiers of this field are represented by organizations such as the Metropolitan Research and Education Network (MREN) which provides access to remote instrumentation in:

> high energy physics, for example, the key facilities at Fermilab (eg, collider detectors…, high energy physics computational processors, and astronomy facilities, such as those related to the Sloan Digital Sky Survey project).
> MREN also provides access to the Advanced Photon Source…, as well as to the massively parallel (128 node) high- performance computer….MREN is also working on projects to link advanced virtual reality environments among member institutions over high performance networks. These VR laboratories, a type of "holodeck," are based on CAVE technology….Other projects involve linking terabyte mass storage facilities to high performance networks. The CATS project (Chicago-Argonne Terabyte System) is configured for 35

Terabyte and is scaleable to 180 TB. One early project used a satellite to establish digital communications to the University of Illinois at Chicago's National Science Foundation[122] Center for Astrophysics Research in Antarctica (CARA) to create the first interactive digital video-conference to the South Pole.

8. Collaboratories

Closely related to the above trend towards remote instrumentation is a further development known as collaboratories. Here, distributed groups of experts work together using combinations of tele-conferencing, collaborative tools and common repositories of knowledge in the form of complex databases. Thomas Finholt and G. W. Olson (1996) listed collaboratories in atmospheric and space science, biology, chemistry, medicine and physics.[123] Since then at least ten other collaboratories have appeared[124] in the fields of microscopic digital anatomy, developmental biology, chemistry, crystallography[125], culture, research on electronic work, team engineering, environmental and molecular sciences, fusion, libraries,[126] management information systems, medicine, physics, space physics, upper atmosphere research and spectro-microscopy. While these collaboratories are primarily in the United States they are increasingly becoming an international phenomenon.[127]

While the earliest collaboratories were strictly in the scientific field, more recently there have been examples in with respect to libraries and culture. There is also research into the process through Thomas Finholt's[128] Collaboratory for Research on Electronic Work (CREW)[129] and the Collaborative Systems Research Group (CSRG).[130]

There are also an increasing number of collective action tools.[131] These tools accomplish something, which sounds simple and obvious. They give researchers new access to knowledge in different databases. The brain model interface is an excellent case in point. In the past, scientific literature was stored in libraries. Experiments and experimental data were in laboratories and models were often in other university departments. Through the new interfaces both scientific literature in libraries and experimental results in laboratories all over the world, can be accessible at one's own desk. Indeed, given the developments in virtual laboratories outlined earlier, a researcher can theoretically repeat experiments at a distance. An analogous project at San Diego State College (SDSC) is the Molecular Interactive Collaborative Environment (MICE).[132] Here the innovation lies in integrating information from descriptive and structural databases in order to generate three-dimensional scenes for discussion "on the fly."

The computational environment at the Stanford 5Plab is also fascinating in this context. It supports Internet Mediated Collaborative Team-Work through Computer Integrated Manufacturing (CIM) and Agent Computer Aided Design (CAD), which links in turn with a Task Network of Activities. This is leading to Computer Integrated Engineering, Architecture and Construction.[133]

An important result of these networks is that they are bringing new interplay among different disciplines. For instance, the nano-manipulator project at the University of North Carolina, Chapel Hill, is part of a consortium of institutions in North America and Europe involving a wide range of disciplines: chemistry, computer supported collaborative work, distributed systems, education, gene therapy, graphics, information and library science, physics and psychology. Similarly the STAR TAP consortium has projects in biology, computer and information sciences, education, engineering, geosciences, mathematics, physical sciences (astronomical sciences, chemistry, materials science, physics), polar research, social and behavioral sciences as well as crosscutting programs.[134]

9. Conclusions

This paper began with a survey of different definitions of virtuality. It was shown that virtuality is extending our senses in ways far beyond those considered by Freud and McLuhan. Links with emerging fields such as scientific visualization were outlined to show how virtuality is expanding greatly the range of visible, invisible, possible and creative worlds. While the lecture focussed on the visual richness of this theme, the paper has examined also some developments in virtual and augmented reality, virtual laboratories and collaboratories.

A more thoroughgoing study would have placed these developments within a larger historical framework. The idea of virtuality in the sense of making something which is a model or simulation for something to be constructed physically goes back to Antiquity. During the Renaissance, the building of physical scale models as a preparation for a full-scale, real building became standard practice among architects such as Brunelleschi, Leonardo and Michelangelo. Virtuality in the new sense replaces the physical scale model, with an electronic surrogate, which can be worked on by hundreds or even thousands of designers linked by a network. Moreover, this electronic, virtual model can be viewed by millions and potentially billions of persons all around the world. Given stereolithography such virtual models can be rendered physical at anytime, at anyplace (which has a sterolithographic printer).

Dynamic simulations such as flight simulators are said to go back to the 1930's Controlling objects at a distance is known to almost everyone in the developed world through the everyday use of remote ([s] control intruments) for television. The origins of such control systems are linked with the development of V1and V2 rockets in the 1940's. The advent of Sputnik in 1957 introduced a new meaning to remote control. Soon rockets, satellites and even space stations could be manoeuvred from thousands and even millions of miles away. Most of these early experiences entailed very simple operations, turning an engine or some other machine on or off, changing direction or adjusting basic inputs such as temperature, pressure etc.

The developments of the past decades are fundamentally different for a number of reasons. First, they entail much more complex tasks. Medical operations can now be performed at a distance. Using simulations the doctor can practice before the actual operation. Second, these tasks can draw on a series of different databases as in the MICE project where description and structure databases are combined to generate reconstruction scenes.

A third and in our view most fundamental change lies in the introduction of a simulation-reality feedback loop. The simulation is no longer a model that stands in isolation from the reality it imitates. It is connected to real machines or factories through a series of sensors, which can inform the model of anomalies as a result of which the model then adjusts inputs into the physical machine or process. Simulation and reality are thus linked in a new way.

Fourth, there is a question of scale. Models and simulators of the past entailed an artist's or architect's impression of an object or a building. Today's virtuality involves fully detailed simulations of all the parts of a ship as in the VET project, of all the fittings in a complex factory as in the Manchester University example cited earlier, or even whole cities such as virtual Chicago, Helsinki or Paris.

Fifth, there is a far greater range of scales. In the past physical scale models were primarily about future, full-scale, physical objects and constructions. The new simulations of virtuality extend from the nano-scale of billionths of a meter to macro scales of thousands of light years, from the smallest known particles to the most distant galaxies of outer space.

Sixth, and paradoxically, the ever greater ability to document physical reality from the smallest particle to the largest galaxies of outer space has brought with it an increasing fascination with the creative implications of these worlds. Bodyscapes, space, science fiction are becoming new categories of art. The quest for new patterns of science is thus pointing to new experiences in art. The discovery of reality through virtuality is leading to discoveries of new creative realities.

The enormous advances in virtuality are part of a larger revolution, which has only yet begun. We are told that within twenty years there will be computers 100 million times more powerful than a contemporary personal computer. It is estimated that one gramme of DNA used for DNA computing will have a storage capacity equal to one trillion of today's CD-ROMS. This means that the entire contents of the great memory institutions since the invention of writing, including the British Library, the Bibliothèque Nationale, the Library of Congress, the Vatican and the Lenin Library could be carried in one's shirt pocket. For the first time in history it will be technically possible for every human being to have access to all human knowledge which has been recorded.

Three kinds of knowledge are becoming intertwined: enduring, collaborative and personal knowledge. Through mobile, wireless networks this enduring or perennial knowledge of the great libraries, museums and archives can be linked with the collaborative knowledge of collaboratories and other computer supported collaborative work (CSCW) as well as with the emerging field of tacit and personal knowledge which will give a recorded voice to many whose voices were all too fleetingly oral in the past. Incredible challenges stand in the way of a new synthesis which will serve as the 21st century's version of Aquinas' Summas, and yet connected with that vision lies the virtually infinite potential of virtuality.

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This paper and a paper for INET 2000 are preliminary version of sections in an upcoming book on *Augmented Knowledge and Culture*, which will explore some of the larger consequences of computers, new media and the Internet.

Notes

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48 See: http://hrl.harvard.edu/events/haptics-symposium/index.html Further work on haptic force and tactile feedback is being done by Steven J. Jacobsen, at the University of Utah (Salt Lake City) in the context of the Sarcos artificial arm, see: http://www.sarcos.com/Jacobsen.html and Corde Lane and Jerry Smith[48] at the University of Maryland, see: http://www.cs.umd.edu/projects/hcil.eve.restore/eve-articles/I.C.ForceTactile.html.

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[80] See: http://www.sgi.com/newsroom/press_releases/1999/march/nyse.html

[81] See: http://www.viewseum.com

[82] See: http://www.almaden.ibm.com/vis/stm/hexagone.html

[83] Evans and Sutherland are among the leading producers for the visualisation software used by the military.
See: http://www.stricom.army.mil/cgi-bin/PhotoArchive/image_gallery.pl

[84] See: http://www.ai.sri.com/TerraVision/

[85] In February 2000 there is a major conference at Stanford on Special Effects.
See: http://prelectur.stanford.edu/.

[86] See: http://www.whatdreamsmay.com/vers3/whatdreams.htm

[87] See: http://aig.cs.man.ac.uk/systems/Maverik/gmp.html

[88] Brygg Ullmer, " Physicality, Virtuality, and the Switch that Lights,"
See: http://tangible.media.mit.edu/~ullmer/courses/tat/paper1.html

[89] See: http://www.damasquine.be/Pages/Photogra/Moers1.htm

[90] See: http://www.memi.com/musiker/changing_images/ci_p3_e.htm

[91] See: http://www.vrml-art.org/cgi/vmsprg?tplt=index

[92] See: http://www.jhu.edu/~jhumag/994web/culture1.html

[93] See: http://imk.gmd.de/images/mars/files/erena99_D6_2.pdf

[94] See: http://aig.cs.man.ac.uk/systems/Deva/gallery/cages.html

[95] Myron Krueger, *Artificial Reality*, New York: Addison Wesley, 1983. Second edition 1991.

[96] See: http://www.soc.staffs.ac.uk/~cmtajd/teaching/VAV/VR.html

[97] See: http://gen.net/index.htm

[98] See: http://cic.cstb.fr/ILC/html/iai.htm.

[99] See: http://www.ics.org/memOnly/conference/papers/95N152.html. Re: Advanced Process and Control Systems (APACS)
See: http://www.cs.toronto.edu/~kramer/paper.doc.html#84736.

[100] See: http://www.hoise.com/vmw/articles/LV-VM-04-98-6.html#go_to_top.

[101] See: http://www.brevie.uni-bremen.de/

[102] See: http://www.cs.columbia.edu/~feiner/

[103] Keynote at the Virtual Worlds conference Paris July 1998. Cf. Wendy Mackay, A-L. Fayard, L. Frobert, L. Médini, "Reinventing the Familiar: Exploring an

Augmented Reality Design Space for Air Traffic Control." In: *Proceedings of ACM CHI '98 Human Factors in Computing Systems*. Los Angeles, California: ACM/SIGCHI. Cf. http://www.daimi.au.dk/~mackay/publications.html. For another discussion of virtual reality see Didier Verna and A. Grumbach, "Can we Define Virtual Reality, The MRIC Model" in: *Virtual Worlds*, ed. Jean-Claude Heudin, Berlin: Springer, 1998, pp. 29-41.

[104] CHARADE: Remote Control of Objects using Free-Hand Gestures
Baudel, Thomas and Beaudouin-Lafon, Michel, in *Communications of the ACM*, vol. 36, no. 7, p. 28-35, July, 1993

[105] Steve Feiner, Columbia University.

[106] See Pierre Wellner (ATT and Europarc), "Interacting with Paper on the Digital Desk," *Communications of the ACM*, (July 1993), pp. 86-96.
See: http://www.rxrc.xerox.com/showroom/techno/lightworks.html
Cf. http://www.cc.gatech.edu/fce/seminar/Presentation/Vision/DigDesk.html

[107] MIT.
See: http://www-white.media.mit.edu/vismod/demos/smartdesk/

[108] Mark Weiser, Xerox.
See: http://cs.ru.ac.za/func/java/docs/wwwbtb/chap24/chp24-09.html

[109] Olivetti.
See: http://www.cam-orl.co.uk/ab.html

[110] MIT.
See: http://lcs.www.media.mit.edu/groups/el/projects/legologo/

[111] Carnegie Mellon University.
See: http://www.cs.cmu.edu/~wearable/ink.html.

[112] See: http://jersey.uoregon.edu/vlab/Piston/index.html

[113] See: http://www.msa.microscopy.com/MicroScape/MicroScapeNature.html

[114] See: http://chickscope.beckman.uiuc.edu/

[115] See: http://bugscope.beckman.uiuc.edu/

[116] Technical report 98-010. *Remote Instrumentation for Service, Collaboration and Education, Lessons Learned*.
See:http://www.itg.uiuc.edu/tech_reports/98-010/remote_instrumentation.htm

[117] See: http://wwl.itg.uiuc.edu/

[118] Manuel Perez, "Java Remote Microscope for Collaborative Inspection of Integrated Circuits, Thesis, MIT Microsystems Technology Laboratories, May 1997 (CAPAM Memo No. 97-5).
See: http://www-mtl.mit.edu/mtlhome/ under MTL and other related research links under Remote Microscope.

[119] See: http://www.tno.nl/instit/fel/vl/vl.html

[120] I am grateful to Dr. Gert Eijkel for providing me with this information re FTIR Imaging Microspectometry and Data Analysis in the ICES-KIS Virtual Lab.
Cf. http://www.fom.nl/uk/links.html

[121] See: http://www-fp.mcs.anl.gov/division/research/vr_summary.htm

[122] The original contain's UIC's NSF which I have written in full in the interests of comprehension.

[123] For basic Collaboratory Information
See: http://www.spcomm.uiuc.edu/projects/collabs/. Cf. also Thomas Finholt and G. M. Olson, “From Laboratories to Collaboratories: A New Organizational Form for Scientific Collaboration", *University of Michigan, Department of Psychology, Working Paper*, 1996 [Copies available from finholt@umich.edu]; Thomas Finholt,

"Internet –Based Collaboratories Help Scientists Work Together," *Chronicle of Higher Education*, March 12, 1999, pp.21-23.

124 See also: Jolene Galegher, Robert E. Kraut, Carmen Egido, ed., *Intellectual Teamwork. Social and Technological Foundations of Cooperative Work*, Mahwah, NJ: Erlbaum, 1990.

See: http://www.erlbaum.com/html/60.htm

125 Reciprocal Net-A Global Shared Database for Crystallography, Indiana University, USA.

See: http://www.startap.net/APPLICATIONS/math.html#Chemistry.

126 Binghampton University Bartle Library Collaboratory.

See: http://128.226.37.29/subjects/polsci/collab.html

127 See: http://128.226.37.29/subjects/polsci/collab.html

128 See http://www.crew.umich.edu/Investigators/tfinholt.htm

129 See: http://www.crew.umich.edu/

130 See: http://www.eecs.umich.edu/~aprakash/csrg_pub.html

131 See: http://www.ics.uci.edu/~ackerman/docs/97.darpa/darpa.final.html.

Regular commercial software includes: Novell GroupWise 5; Oracle Interoffice; Lotus Notes; Attachmate; ICL Teamware; Microsoft Exchange.

132 See: http://mice.sdsc.edu/introduction.html

133 See: http://www.stanford.edu/group/CIFE/ce222/aec_projects.htm. For a dsicussion of related themes in an English context on the Design of Virtual Environments with particular reference to VRML.

See: http://www.man.ac.uk/MVC/SIMA/vrml_design/toc.html.

134 See: http://www.startap.net/APPLICATIONS/