Welcome!

Hey to all of you awesome people who have decided to immerse yourselves in the wide and wild world of neural prosthetics!

In order to give you some grounding on what you should expect from me this summer, here is a brief textual self-portrait:

Academically speaking, I am intrigued by the relationship between the physical brain and the subjective mind—and how we can exploit science and engineering to mess with it. I am currently studying the biological architecture of the brain with the ultimate intention of researching ways to interface it with computers.

In terms of hobbies, my most fervent extracurricular love is 武术, which I began studying freshman year. It has served as a source of joy and sanity for what is sometimes a very intense and stifling academic career, and I intend to take a year off after I graduate college to expand my skills in its 少林功夫 roots before pursuing a graduate education in computational neuroscience.

My additional passions include violin, drawing and painting, playing video games (Final Fantasy, Zelda, Tomb Raider, Rise of Nations… as we gamers say, w00t!), and trekking through the beautiful outdoors.

Finally, a random fact about myself: My most intimate inanimate friends are a bamboo plant named 早上好 and a suit of armor named Ederick. Weird? Sure. Cool? Well… you decide.

Before I go, I'd like to bring the discussion back to the eminently more important topic of the seminar itself by highlighting the fact that some (but certainly not all) of the readings in this coursepack are fairly technical and advanced. I have tried to define terms when appropriate, but I leave it up to you to connect my hints to the larger context of what is being discussed. I encourage you to take these on as a challenge—don't despair if you must read them multiple times!! Strong motivation can only enhance your comprehension of these articles.

I taught a very similar seminar to this one last year and have therefore established a course Facebook group at http://www.facebook.com/profile.php?id=2038. There you can find extra learning materials (including cool videos!) and interact with former students of the class as well as me. People DO respond if you write something, so check it out!

If you have questions, concerns, or other comments, I *STRONGLY* encourage you to emailing me ANY TIME at swanberg@fas.harvard.edu.

I look forward to a thrilling and eye-opening intellectual journey with you this summer!!!

THIS IS YOUR BRAIN ON COMPUTERS, V. 2.0:

PRESENT AND FUTURE POSSIBILITIES IN ELECTRONICALLY ENHANCING THE HUMAN MIND

Kelley Swanberg, HSYLC 2008

CLASS I: HARNESSING OUTPUT

Corvax and Isol. Robson, J. 2004. *Natural History*. New York, NY: Bantam Dell. 16-31, 35.
Interfacing the Brain and Machines. Kurzweil, R. 2005. *The Singularity is Near: When Humans Transcend Biology*. London: Penguin Books.
Brain Cells Fused with Computer Chip. Than, K. 27 March 2006. Brain cells fused with computer chip. *Live Science*. Available online at http://www.livescience.com/humanbiology/060327_neuro_chips.html.
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CLASS II: TWEAKING INPUT

Uluru. Robson, J. 2004. *Natural History*. New York, NY: Bantam Dell. 37-39.
Virtual Interrogation. Morgan, R.K. 2003. *Altered Carbon*. New York, NY: Del Rey. 225-228.
A Visual Overview of the Present State of Virtual Reality.
We Will All Become Virtual Humans. Kurzweil, R. 2003. Foreword to *Virtual Humans*. Boston: American Management Association.
Why It May Be Possible to Create Virtual Images by Electrically Stimulating the Brain. Fenandez, E., F. Pelayo, P. Ahnelt, J. Ammermüller, and R.A. Normann. 2004. Cortical visual neuroprostheses for the blind [in-press version]. *Restorative Neurology and Neuroscience*.
Caveats Associated with Creating Virtual Realities by Electrically Stimulating the Brain.
Fenandez, E., F. Pelayo, P. Ahnelt, J. Ammermüller, and R.A. Normann. 2004. Cortical visual neuroprostheses for the blind [in-press version]. *Restorative Neurology and Neuroscience*.

CLASS III: SHIFTING SUBSTRATE

The Cortical Stack. Morgan, R.K. 2003. Altered Carbon. New York, NY: Del Rey. 37-38, 74-75.
Jack's Transformation. Kurzweil, R. 1999. *The Age of Spiritual Machines: When Computers Exceed Human Intelligence*. London: Penguin Books.
Growing a Brain in Switzerland. Dworschak, M. 2007. Growing a brain in Switzerland. *Spiegel Online*. Available online at http://www.spiegel.de/international/spiegel/0,1518,466789,00.html
Works in Progress: An Artificial Hippocampus and an Artificial Olivocerebellar Region. Kurzweil, R. 2005. *The Singularity is Near: When Humans Transcend Biology*. London: Penguin Books.
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CLASS I: HARNESSING OUTPUT

Simple things should be simple; complex things should be possible.
—Alan Kay

CORVAX AND ISOL

Robson, J. 2004. *Natural History*. New York, NY: Bantam Dell. 16-31, 35.

This imaginative science fiction text describes a world in which computer technology and genetic engineering have allowed humans to expand their brains and bodies with new senses and physical attributes. Therefore, even though the main characters of this selection take on the appearances of birds and spaceships, they are, in fact, all human.

Corvax who was once a **Roc**, Handslicer Class, and who was now just Corvax with a body gone weak from misuse and the addition of layer on layer of **MekTek** experiments, was aware of the approach of the guests before his laboratory sensors informed him of their arrival. He felt a shiver along the roots of his feathers, where **tendrils** of the latest batch of semi-sentient Tek were triggered by the movement of shadows on the surface of his asteroid home. What **alchemy** he'd used to manufacture such sensitivity belonged to him alone, as far as he knew. He'd liked to have gone to see the respectable Earthbound technicians about his own programming and his developing skills, telling them that he dreamed his machines into shape, but they'd have had a hard time believing that. Then again, they didn't possess the imagination or the versions of **Uluru** that he was running. No **Forged** wanted to share their secrets with the **Unevolved** anymore, and MekTek was principally an Unevolved product—the brute cybernetics of machine and AI **spliced** into their feeble bodies and brains to enhance capacities too ecoprecious to have been butchered together like a Forged mind. And too small to cope with Forged consciousness.

Not that he was bitter about his lot, except for moments like this when he tried to hurry and found himself creaking along through the command gestures that summoned his holographic tool kits into life around him. He scanned the local geo-chaos and saw the silky amoeboid shape of the **Ironhorse** weaving nervously between spinning clumps of rock on its final approach. It hadn't picked up any tails. Probably he should be grateful for that, although there was an itching just under his skin that was nothing to do with MekTek and everything to do with this latest line of **mumbo-jumbo** the Ironhorse had been explaining to him for the last hour.

Ironhorse Timespan Tatresi had been made incarnate then years ago, after an Uluru-uprbringing of impassable standards within Corvax's own beloved mother-father, the **Forge Pangenesis Tupac**. Tatresi plied the lanes from Mercury to Pluto as a fairly impressive kind of bulk carrier who also **ferried** passengers and specialized in fragile cargo with strict environmental requirements. He was a member of the Independence Party and leader of the Solar Transport Workers Union…

Corvax exchanged approach protocols with Tatresi and let him try his skill at navigating the final descent by himself. Corvax had AIs that were capable of handling almost any complication caused by the spiraling **gigatonnes** of stone that sheltered the laboratory from unwanted attention. They could ease the passage of a terrified passenger lifter, or ensure that nosy busybodies were made into asteroid sandwiches, but he enjoyed the spectacle of seeing something as big and vain as the Timespan negotiating this potentially fatal dance.

With the dexterity of a much smaller vessel, the **leviathan** twitched himself aside from the path of a hurtling chunk, brushed a dump of debris away from his forward sensors and matched his direction and rotation to a fixed point above the docking bay. He was saying something about the Voyager, Isol, and her fabulous journey, which to Corvax sounded not unlike a drug-fuelled fantasy—in fact, he thought he remembered experiencing one of those about seven years or so ago when doing Uluru on a mix of uppers and blissers had seemed the ultimate in erotic heaven…

***

…"Do you believe her?" Corvax interrupted, trying to get the rich **tapestry** of the Timespan's vocabulary to ease up on its adjectives and superlatives so that he could clear his head.

"I don't believe Isol has an imagination capable of making it up," Tatresi replied, switching seamlessly from simple audio transmissions to full-band AI interface with Corvax's systems. His voice suddenly leaped out of Corvax's mind and began issuing from a point near his ear, where Tatresi's **avatar**—a hologram of a tall blue humanoid—appeared with equal speed. He took up a heroic stance on the observation deck.

Corvax ignored the blue man's self-appointed intrusion into his workspace and triggered the clamping procedure with a wave of one thick claw. Tatresi's avatar turned to watch through the viewing window as his physical body sank into the safety of the docking bay's oval **refuge**. Above and around the **skimpy** rigging of the bay the close-turning hills of other

Roc: a type of Forged (see below) (fictional term)

MekTek: a material that can be grafted onto biological tissue in order to connect human brains and bodies to computers (fictional term)

tendrils: strings or threads (e.g., the tendrils of an ivy plant; the tendrils of a jellyfish)

alchemy: a type of medieval chemistry that included such as turning lead into gold; here, used to mean technology so advanced it seems like magic

Uluru: a virtual reality program (fictional term)

Forged: a human born into a largely electronic body specially manufactured to perform hard labor (e.g., mining asteroids in deep space). Corvax, Tatresi, and Isol and are all Forged. (fictional term)

Unevolved: a human born into a natural and biological body that may or may not be enhanced with some MekTek (fictional term)

spliced: connected, grafted

Ironhorse: a type of Forged designed to perform work in deep space. Tatresi is an Ironhorse. (fictional term)

Forge Pangenesis Tupac: the giant spaceship that manufactures many of the Forged. Unlike a traditional factory, Tupac is herself a human individual inhabiting the body of a massive machine. (fictional term)

ferried: carried

gigatonne: a unit of mass: giga=10^9; tonne (metric ton)=1000 kilograms

leviathan: a giant sea demon of Judeo-Christian mythology; here, used as a reference to Tatresi to highlight his massive size

tapestry: an elaborate woven fabric; here, used to describe the complexity of Tatresi's speech

avatar: an image representing a person; online forums and chat programs often allow their users to select visual avatars that accompany all of their messages and posts

refuge: shelter, place of safety

skimpy: small, meager, sparse

asteroids bowled in all directions. Shadows within the dock leaped and darted at great and crazy speeds as they themselves also spun, dizzy as **gnats** in the weak sunlight.

The avatar glanced at Corvax with transparent admiration for his survival in this hellhole and informed him, "But Isol is an old form. They don't make them anymore. And they never made them with any inventiveness. A Voyager is nothing more than a desire to travel and meet new people fused onto a **psychopathic** preference for no company at all. That includes family ties, of which they have none whatsoever; no loyalty, no **philanthropy**. She has a strong mind, with single-tracked convictions based on ideals and theories, but no experience of a living social world."

He kept his attention apparently lodged on his holographic controls, while he watched both the avatar and the real Tatresi closely. Hugged in the cradle's **calipers**, the body of the Timespan—a kilometre in length—finally settled. Its shadow cut out most of the fierce rig-lighting from the bay, leaving them both in **sepulchral** darkness. Under instruction form Corvax's AIs, waldo arms extended their greetings to the cargo-man in the form of junctions, cables and unloader tubes, and Tatresi relaxed the irises of his **sphincters** to accept them, blink by blink.

"Why don't you let Isol speak for herself?" the blue man said. He smiled at Corvax, showing a white metal toothstrip. His **sapphire** eyes gleamed, partly as a result of the pleasure of ingesting some of Corvax's illegally upgraded biotrophins, of which he was currently **guzzling** fifty litres per second. "You can't tell me you wouldn't take up a chance to escape the stranglehold of Gaiasol and its attempt at democracy."

Corvax shrugged and gestured vaguely over his shoulder. "Watch that dial. You take more than fifty thousand litres and you start paying double."

Corvax bristled, his feathers rising with dusty irritation, and shuffled back onto his platform. With a flick of one wing-edge he ordered the Systems AI to present him with the tools needed to perform the minor repairs on the Timespan. As the array flashed into life in the air around him it ignored the presence of Tatresi's avatar entirely, intersecting it at the waist.

"And?" Corvax scanned the Timespan's internal systems, one of his fine manipulating arms plunged to the shoulder in a sensor sleeve that allowed him to taste, smell and touch the various layers via interface with his external machines. He **palpated** the Timepsan's digestive tracts and the avatar made a face. There was a flavour he recognized—more than one, in fact.

"Carrying cheapskate tourists? Your holds stink of garlic."

The Timespan ignored him. "And you could change my engines to enable me to take them to this other world—to take the Forged out of the rule of petty Gaiasol economics. You may keep my current main drive." He tried to make eye contact with Corvax and added, unnecessarily, "It is a Draconis 500, mark 3, installed only last year, full service history."

Corvax stopped listening and stared through the transparent shield of the direct-view window at the colossal body in the bay. It was roughly teardrop-shaped at the moment, studded with blunt, **barnacle**-like protrusions where colonies of **symbiont** cleaners attached to its skin. Here and there metal gleamed where ports and casings protruded from its surface. The skin was scaled, fishlike, with tough crystal plates of **homologue** diamond that reflected or absorbed light depending on Tatresi's mood. They veiled the Timespan's natural blue-grey hide in a dully glimmering net, a guarded and unforthcoming `presentation.

Tatresi winced and then giggled as Corvax pulse-checked his nervous system. His body strained and **bucked** briefly against the calipers holding it in place, and the asteroid's **torsion** controls had to break briefly from their avoidance of major collisions to compensate for the displacement caused by the huge impulse.

Corvax withdrew with a snap of rubber hosing. "There's nothing wrong with you—just some housekeeping. You want that? Or you going to get it free and legal back at Arrecife Base? Keep your service history."

"I brought someone to see you."

Corvax leant back, braced on the tips of his tough **Solarine** wings, and stared at the smug, smooth head, the hands pressed together in prayer position like a big blue Buddha, smiling at him.

"Where is she?" Corvax stuck his arm back into the sleeve and the Timespan's body.

"Hold Nine."

"Oh yes." There was nothing there out of the ordinary that he could smell.

He was smooth, Tatresi, a real diplomat, Corvax thought, extracting himself for the second time, and envying the power he could feel humming in that gigantic frame. Compared to a Timespan's capacities a Roc was far down the glamour list—barely a flea.

"I'll meet her in there." Corvax grunted and stabbed his finger into a bottle in his work-belt, taking a quick suck of **hi-ox** to perk himself up for the walk. He hooked his hands out around the protrusions of old **haematite** that formed his lintel and propelled himself out with as

gnats: small flying insects

psychopathic: emotionally and/or socially abnormal in a distressing or otherwise unhealthy way

philanthropy: doing good deeds for others

caliper: a pair of hinged metal bars, usually used for measuring things; here, used to dock a spaceship.

sepulchral: dark and gloomy like a tomb

sphincters: special muscles that extend to form an opening

sapphire: a type of deep blue gem; here, used figuratively to highlight the vivid color of Tatresi's eyes

guzzling: drinking large amounts very quickly

palpated: felt, examined closely using the sense of touch

barnacle: a type of crustacean that clings to the sides of boats and other structures in the ocean

symbiont: an organism that acts in a mutually beneficial relationship with another (e.g., some species of cleaner fish eat parasites off the backs of whales. The whales thus help the cleaner fish obtain food, and the cleaner fish help the whales stay healthy.)

bucked: leaped forcefully, like a horse trying to throw off a rider

torsion: the act of twisting; here, "torsion controls" act to steer Corvax's dwelling through deep space

Solarine: a type of building material (fictional term)

hi-ox: gas containing a high concentration of oxygen (fictional term)

haematite: a black mineral made of iron and oxygen much speed as he could manage. With as much dignity as he could muster, Corvax leapt into the stadium of light that was Hold Nine.

The tiny shape of the Voyager was almost lost in the middle of this hangar, suspended freely on fine lines of **Arachifibre** from the vast ribs that supported its dome. Corvax bowled himself towards her, rolling and enjoying a stretch, although his knuckles hurt from the jolting. He opened his wings, steadied into a straight vector with a few flicks, and brought himself to a halt just outside the reach of her insectile arms.

Isol was not pretty but Corvax could see, even from where he now rested, that she was in superb condition. Her Ti-bone exoskeleton, which had taken such a beating, was newly whole. Pieces of the old one lay scattered around her in grey and white flakes, where they'd peeled off most recently. From the tips of her antennae to the delicate vanes of her solar sails, she gleamed like a freshly **moulted** scorpion—and looked as dangerous.

Corvax made as if to tidy some of his gravity-sensitive **primaries** with his beak, not taking his eyes off her idly flexing arms, and watching her with MekTek sight. There was something new about her—and it wasn't just this meeting of strangers and her unfamiliarity to him that made him think so. She didn't fit the blueprint of her **Clade** anymore, he reflected. There were organs and implants he didn't recognize at all: things that he was sure no Forge **schematic** for any species would detail either in the official design labs, or even in the daydreams of Tupac and Mougiddo, the mother-fathers of them all. His interest sharpened to an acuity that made his muscles shiver.

"On my journey," Isol spoke slowly, choosing her words with care, "I have come across some ***detritus*** that I wish you to analyse. I believe it to be of alien origin."

Corvax shifted, feeling uncomfortable because he couldn't tell how closely she was watching him. Her visual sensors were a complex knot of radar, photo and radio, capable of 360-degree awareness. There was nowhere to hide his unease. In truth he would have liked to hear much more of this story, but what he didn't know would hurt less, he'd found—especially when the Gaiasol Police came calling.

He took the thing from her cautiously, avoiding the hair-fine tips of her many feelers and sensors, and tasted the firm **unalloyed** portion of the apple's perfected surface **fullerenes**. Frosty-assed and **autistic**, she was; he didn't want to touch her. "One scary move…" he warned her.

"**Ka-blooey**," she said softly, and in his mind's eye Corvax saw a strange little ballerina girl smile, fish-cold, her dark hair like waterweed floating in odd currents; the vision made the feathers on his back try to stand on end. Belatedly he realized it was Isol's personal mental **ident**, and that she'd chosen to broadcast to him on full Sympathetic Mode for a rare instant, filling his awareness with a comprehensive emotional understanding. It was a signals protocol used only between friends, and the sudden intimacy—an interior touch—was hard to resist. He knew when he was being played.

She giggled, soundlessly, in his head, "I heard you," and was gone.

Back in the confines of his laboratories Corvax felt instantly better, and that wasn't just due to the light atmosphere and a new rush of hi-ox hitting his system after the hard work of holding his breath and cycling on full **anaerobic** processes to survive in the true vacuum of the bay. He took the grey sphere and put it into his Skyroscope tray where small items could be examined right down to their atomic structures. As he thrust home the Analysis AI softjacks into his MekTek intake ports, he shivered with the memory of Isol's sudden presence: a curious mix of **voluptuous**, desiring neediness, and the cold teeth of emotional absolute zero.

Some Forged were sufficiently alien to the fundamental human base-template that even to their own kind they were so incomprehensible as to be a distinct species. Voyagers had one of the strangest psychologies. In the instant of Corvax's exposure to Isol he'd felt something he didn't know the name of, but it was savage and insistent—a kind of hunger that was as primal in its passion as any animal compulsion he'd ever known. Yet it wasn't linked to anything he'd ever wanted.

The sensor feeds were primed. He took a look at the two samples. As his first MekTek self-adaptation, many years ago now, he'd given himself the sensory appreciation of a master physician, one for whom smell, taste, touch, sight and sound provided data to the most precise of scales, with a brain function and a basic knowledge to match it. Corvax had seen stars die and could casually observe the deterioration of a single cell through every molecular transformation, every vibration, every split second. He knew bog-standard **silicon dioxide** when he saw it, and this was it; but subtly engineered in its crystal formations to be a storage object for data…

Arachifibre: an artificial material like spider's silk (fictional term)

moulted: having just shed an old layer of skin or exoskeleton

primaries: the largest and most visible feathers on a bird's wing

clade: a term used by geneticists to mean a group or type

schematic: blueprint, design

detritus: inanimate waste from a living creature (e.g., dog hairs, snail shells)

unalloyed: pure, not mixed with anything else

fullerenes: substances composed of cagelike structures of atoms, especially carbon

autistic: referring to a mental disorder marked by, among other things, antisocial behavior and communication deficits

ka-blooey: a spoken sound effect (onomatopoeia) meant to simulate the noise of an explosion

ident: avatar (fictional term)

anaerobic: not dependent on oxygen for proper function (as opposed to aerobic processes, which are dependent on oxygen)

voluptuous: pleasing, desirable, sensuous

silicon dioxide: SiO_2; one of the most abundant molecules in the earth's crust

INTERFACING THE BRAIN AND MACHINES

Kurzweil, R. 2005. *The Singularity is Near: When Humans Transcend Biology*. London: Penguin Books.

The following book excerpt summarizes some recent research on how to extend human brain capacity by connecting our neurons directly to computers. Descriptions of many of the studies to which the text refers appear elsewhere in this coursepack.

Understanding the methods of the human brain will help us to design similar biologically inspired machines. Another important application will be to actually **interface** our brains with computers, which I believe will become an increasingly intimate **merger** in the decades ahead.

Already the Defense Advanced Research Projects Agency is spending $24 million per year on investigating direct interfaces between brain and computer. Tomaso Poggio and James DiCarlo at MIT, along with Christof Koch at the California Institute of Technology (Caltech), are attempting to develop models of the recognition of visual objects and how this information is encoded. These could eventually be used to **transmit** images directly into our brains.

Miguel Nicolelis and his colleagues at Duke University implanted sensors in the brains of monkeys, enabling the animals to control a robot through thought alone. The first step in the experiment involved teaching the monkeys to control a cursor on a screen with a **joystick**. The scientists collected a pattern of signals from EEGs (brain sensors) and subsequently caused the cursor to respond to the appropriate patterns rather than physical movements of the joystick. The monkeys quickly learned that the joystick was no longer operative and that they could control the cursor just by thinking. This "thought detection" system was then hooked up to a robot, and the monkeys were able to learn how to control the robot's movements with their thoughts alone. By getting visual feedback on the robot's performance, the monkeys were able to perfect their thought control over the robot. The goal of this research is to provide a similar system for paralyzed humans that will enable to control their limbs and environment.

A key challenge in connecting neural implants to biological neurons is that the neurons generate glial cells, which surround a "foreign" object in an attempt to protect the brain. Ted Berger and his colleagues are developing special coatings that will appear to be biological and therefore attract rather than repel nearby neurons.

Another approach being pursued by the Max Planck Institute for Human Cognitive and Brain Sciences in Munich is directly interfacing nerves and electronic devices. A chip created by Infineon allows neurons to grow on a special **substrate** that provides direct contact between nerves and electronic sensors and stimulators. Similar work on a "neurochip" at Caltech has demonstrated two-way, noninvasive communication between neurons and electronics.

We have already learned how to interface surgically installed neural implants. In cochlear (inner-ear) implants it has been found that the **auditory** nerve reorganizes itself to correctly interpret the multichannel signal from the implant. A similar process appears to take place with the **deep-brain stimulation** implant used for Parkinson's patients. The biological neurons in the vicinity of this FDA-approved brain implant receive signals from the biological neurons that were once functional. Recent versions of the Parkinson's-disease implant provide the ability to download **upgraded software** directly to the implant from outside the patient.

interface: to bring together; connect

merger: combination, fusion

transmit: send

joystick: a computerized stick, often with buttons, that controls a computer's processes. Joysticks were often used in old video game systems instead of a handheld controller.

substrate: material, substance

auditory: relating to sound and the sense of hearing

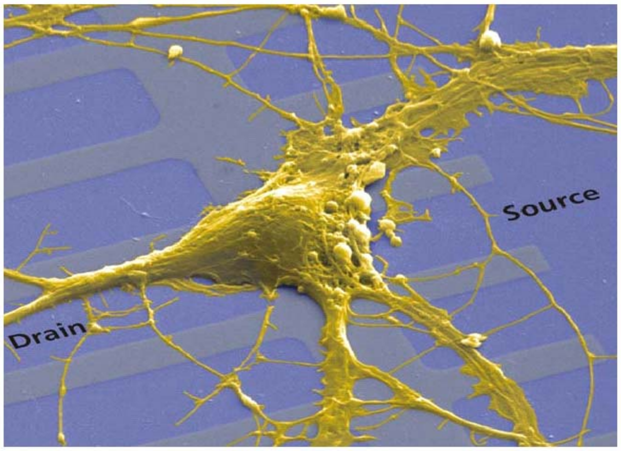
deep-brain stimulation: a therapy used for people suffering from neurological disorders (e.g., Parkinson's, Tourette syndrome, depression) that involves implanting deep inside the brain an electronic device that generates electrical impulses to interfere with abnormal neuronal activity

upgraded: improved

software: computer programs (as opposed to hardware, which refers to the physical components of the computer itself)

BRAIN CELLS FUSED WITH COMPUTER CHIP

Than, K. 27 March 2006. Brain cells fused with computer chip. *Live Science*. Available online at http://www.livescience.com/humanbiology/060327_neuro_chips.html.



Neuron from rat brain on a linear array of transistors. The ionic current in the cell interacts with the electronic current in the silicon. Credit: Max Planck Institute for Biochemistry; NACHIP; P.Fromherz

The line between living organisms and machines has just become a whole lot blurrier. European researchers have developed "neuro-chips" in which living **neurons** and **silicon** circuits are coupled together.

The achievement could one day enable the creation of sophisticated neural prostheses to treat neurological disorders or the development of organic computers that **crunch numbers** using living neurons.

To create the neuro-chip, researchers squeezed more than 16,000 electronic **transistors** and hundreds of **capacitors** onto a silicon chip just 1 millimeter square in size.

They used special proteins found in the brain to glue neurons onto the chip. However, the proteins acted as more than just a simple adhesive.

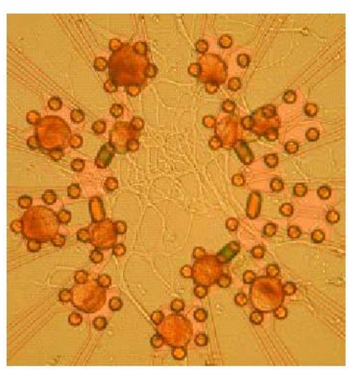
"They also provided the link between ionic channels of the neurons and **semiconductor** material in a way that neural electrical signals could be passed to the silicon chip," said study team member Stefano Vassanelli from the University of Padua in Italy.

The proteins allowed the neuro-chip's electronic components and its living cells to communicate with each other. Electrical signals from neurons were recorded using the chip's transistors, while the chip's capacitors were used to stimulate the neurons.

It could still be decades before the technology is advanced enough to treat neurological disorders or create living computers, the researchers say, but in the nearer term, the chips could provide an advanced method of screening drugs for the **pharmaceutical** industry.

"Pharmaceutical companies could use the chip to test the effect of drugs on neurons, to quickly discover promising avenues of research," Vassanelli said.

The researchers are now working on ways to avoid damaging the neurons during stimulation. The team is also exploring the possibility of using a neuron's genetic instructions to control the neuro-chip.



Network of snail neurons on a silicon chip. Credit: Max Planck Institute for Biochemistry; NACHIP; P.Fromherz

neuron: a brain cell that communicates with others of its kind using a combination of chemical and electrical signaling

silicon: element 14; used to construct computer transistors

crunch numbers: a slang term meaning "compute" or "calculate"

transistor: a semiconducting device that forms the basis of modern computers. Transistors can amplify, regulate the voltage of, switch the direction of, or otherwise modify an electrical current. These alterations allow the circuits of a computer to change based on their electrical input, thereby storing information.

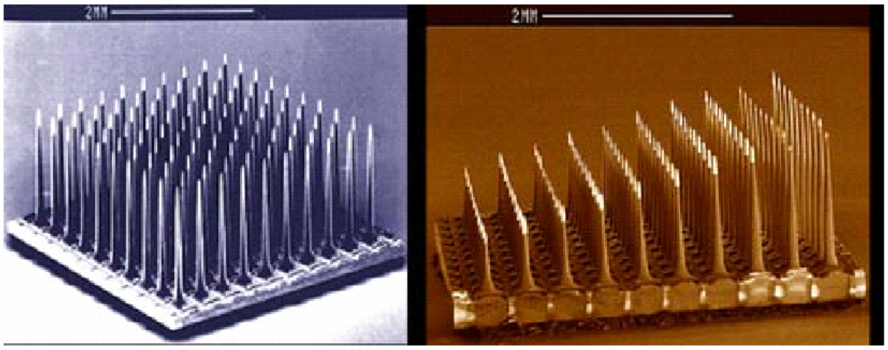
capacitor: a device used to store electrical energy by arranging electrons to build an electrical charge

semiconductor: a material whose tendency to let charge pass through it can be altered drastically

pharmaceutical: related to the development and sale of medicine and other drugs

WIRELESS BIONIC ARM WOULD FEEL REAL

Britt, R.R. 2006. Wireless bionic arm would feel real. *Live Science*. Available at http://www.livescience.com/humanbiology/060424_bionic_arm.html.



Two embodiments of the Utah Electrode Array. The standard array contains 100 equi-length electrodes and was designed for implantation in the **cerebral cortex** while the slanted array was designed for implantation into **peripheral nerve**. Credit: University of Utah

cerebral cortex: the outer nine layers of neurons in most of the top and front of the brain; responsible for integrating input from other parts of the brain as well as planning and executing behaviors based on that input

peripheral nerve: a nerve located outside the brain and spinal cord, such as the radial nerve in the arm

Work on artificial arms that would be controlled by the human mind is **ramping up** thanks to a helping financial hand from the Defense Advanced Research Projects Agency.

ramping up: increasing in intensity

DARPA announced in February that it would pour $55 million into a prosthetic arm research project to be led by Johns Hopkins University's Applied Physics Laboratory. The work will be spread among more than two dozen institutions.

Today, the University of Utah announced a $10 million contract, as part of the overall project, to develop a "peripheral nerve interface." The implanted device would relay nerve impulses wirelessly from what's left of a limb to a computer worn on the person's belt. From there, the signals would be routed to a bionic arm and back to the remainder of the **amputated** arm, where they would then flow naturally back to the brain.

amputated: cut off, removed

Researchers at the university have already developed a pill-sized array with 100 tiny electrodes. Now they'll seek to improve on the arrays so they can be implanted in up to four of the major nerves in a patient's **residual** arm. Each electrode would communicate with a small number of fibers within a nerve.

residual: remaining; here, referring to the nerve endings that are left from an amputated limb

"Imagine an artificial arm that moves naturally in response to your thoughts, that allows you to feel both the outside world and your own movements, and that is as strong and graceful as an intact, biological limb," said bioengineer Greg Clark, the University of Utah's principal investigator on the project. "That's what our researchers, teaming with others around the world, are setting out to achieve."

Over the next four years, other scientists will build a next-generation mechanical arm designed to work like the real thing.

Existing prosthetic limbs can typically manage just one movement at a time.

"The new arm will take the signals that go to all the different arm muscles at once, and all the person has to do is think about natural movement and the arm will respond in a natural way," Clark said. "We're basically listening in on what the nervous system would be telling the natural arm, and translating that into signals that will move the artificial arm in the same way.

WORKING TOWARD THE BIONIC HUMAN: RECENT DEVELOPMENTS IN MOTOR PROSTHESIS

This selection of scientific ***abstracts*** *overviews current research in interfacing the human brain with a variety of computerized devices, from mobile* ***prosthetic*** *arms to Internet browsers. The studies outlined below represent exciting steps toward a seamless and* ***ubiquitous*** *future* ***integration*** *of human with computer.*

Chapin, J.K., K.A. Moxon, R.S. Markowitz, and M.A. Nicolelis. 1999. Real-time control of a robot arm using simultaneously recorded neurons in the motor cortex. *Nature Neuroscience* 2(7):664-670.

To determine whether **simultaneously** recorded motor cortex neurons can be used for real-time device control, rats were trained to position a robot arm to obtain water by pressing a lever. Mathematical transformations, including neural networks, converted multineuron signals into 'neuronal population functions' that accurately predicted lever trajectory. Next, these functions were electronically converted into real-time signals for robot arm control. After switching to this 'neurorobotic' mode, 4 of 6 animals (those with > 25 task-related neurons) routinely used these brain-derived signals to position the robot arm and obtain water. With continued training in neurorobotic mode, the animals' lever movement **diminished** or stopped. These results suggest a possible means for movement restoration in paralysis patients.

Warwick, K., M. Gasson, B. Hutt, L. Goodhew, P. Kyberd, B. Andrews, et al. 2003. The application of implant technology for cybernetic systems. *Archives of Neurology* 6(10): 1369-1373.

OBJECTIVE: To assess the usefulness, compatibility, and long-term operability of a **microelectrode array** into the **median** nerve of the left arm of a healthy volunteer, including perception of feedback stimulation and operation of an instrumented prosthetic hand. SETTING: The study was carried out from March 14 through June 18, 2002, in England and the United States. RESULTS: The blindfolded subject received **feedback** information, obtained from force and slip sensors on the prosthetic hand, and subsequently used the implanted device to control the hand by applying an appropriate force to grip an unseen object. Operability was also demonstrated **remotely** via the Internet, with the subject in New York, NY, and the prosthetic hand in Reading, England. Finally, the subject was able to control an electric wheelchair, via decoded signals from the implant device, to select the direction of travel by opening and closing his hand. The implantation did not result in infection or any perceivable loss of hand sensation or motion control. The implant was finally extracted because of mechanical fatigue of the **percutaneous** connection. Further testing after extraction has not indicated any measurable long-term defects in the subject. CONCLUSIONS: This implant may allow recipients to have abilities they would otherwise not possess. The response to stimulation improved considerably during the trial, suggesting that the subject learned to process the incoming information more effectively.

Leuthardt. E.C., G. Schalk, J.R. Wolpaw, J.G. Ojemann, and D.W. Moran. 2004. A brain-computer interface using electrocorticographic signals in humans. *Journal of Neural Engineering* 1(2): 63-71.

Brain-computer interfaces (BCIs) enable users to control devices with **electroencephalographic** (EEG) activity from the scalp or with single-neuron activity from within the brain. Both methods have disadvantages: EEG has limited **resolution** and requires extensive training, while single-neuron recording entails significant clinical risks and has limited stability. We demonstrate here for the first time that **electrocorticographic** (ECoG) activity recorded from the surface of the brain can enable users to control a one-dimensional computer cursor rapidly and accurately. We first identified ECoG signals that were associated with different types of motor and speech imagery. Over brief training periods of 3-24 min, four patients then used these signals to master **closed-loop control** and to achieve success rates of 74-100% in a

abstract: a short paragraph presented at the beginning of a research article (usually in science) summarizing its contents

prosthetic: any nonbiological device used either to replace an old body part (e.g., an artificial eye for a blind person) or create an entirely new body part (e.g., a computerized sensory organ that detects the concentration of oxygen in someone's surroundings)

ubiquitous: very common; appearing everywhere

integration: connection; combination

simultaneously: at the same time

diminished: decreased

microelectrode array: a set of wires that allows researchers to simultaneously measure and stimulate action potentials in the neurons to which they are attached

median: a scientific term for "middle"; as opposed to lateral, a scientific term for "side"

feedback: a signal forming part of a behavioral loop that regulates itself. For example, feeling a full stomach is a feedback signal that regulates the cycle of hunger and eating that caused the full feeling in the first place.

remotely: from a faraway location

percutaneous: inserted just under the skin

electroencephalographic: coming from a device that measures electrical activity on the surface of the brain using electrodes implanted on the scalp

resolution: the amount of detail in which an image is presented; in higher resolution images, smaller details can be perceived

electrocorticographic: coming from a device that measures electrical activity on the surface of the brain using electrodes implanted on the brain itself

closed-loop control: referring to systems in which output is controlled by strategic changes in input. If one tries to ride a bike at constant speed (output) by using energy at a rate that counteracts environmental factors that change it (input) (pedaling more quickly when moving uphill, pedaling more slowly when moving downhill), one is subjecting her or his bicycle to closed-loop control. Opposite of open-loop control (see below).

one-dimensional **binary** task. In additional **open-loop** experiments, we found that ECoG signals at frequencies up to 180 **Hz** encoded substantial information about the direction of two-dimensional joystick movements. Our results suggest that an ECoG-based BCI could provide for people with severe motor disabilities a non-muscular communication and control option that is more powerful than EEG-based BCIs and is potentially more stable and less traumatic than BCIs that use electrodes penetrating the brain.

Schwartz, A.B., X.T. Cui, D.J. Weber, and D.W. Moran. 2006. Brain-controlled interfaces: movement restoration with neural prosthetics. *Neuron* 52(1):205-220.

Brain-controlled interfaces are devices that capture brain transmissions involved in a subject's intention to act, with the potential to restore communication and movement to those who are immobilized. Current devices record electrical activity from the scalp, on the surface of the brain, and within the cerebral cortex. These signals are being translated to command signals driving prosthetic limbs and computer displays. **Somatosensory** feedback is being added to this control as generated behaviors become more complex. New technology to engineer the tissue-electrode interface, electrode design, and extraction **algorithms** to transform the recorded signal to movement will help translate exciting laboratory demonstrations to patient practice in the near future.

Karim, A.A., T. Hinterberger, J. Richter, J. Mellinger, N. Neumann, H. Flor, et al. Neural internet: Web surfing with brain potentials for the completely paralyzed. *Neurorehabilitiation and Neural Repair* 20(4):508-515.

Neural Internet is a new technological advancement in brain-computer interface research, which enables **locked-in** patients to operate a Web browser directly with their brain potentials. Neural Internet was successfully tested with a locked-in patient diagnosed with **amyotrophic lateral sclerosis** rendering him the first paralyzed person to surf the Internet solely by regulating his electrical brain activity. The functioning of Neural Internet and its clinical implications for **motor-impaired** patients are highlighted.

Donogue, J.P., A. Nurmikko, M. Black, and L.R. Hochberg. 2007. Assistive technology and robotic control using motor cortex ensemble-based neural interface systems in humans with tetraplegia. *Journal of Physiology* 579(3): 603-611.

This review describes the rationale, early stage development, and initial human application of neural interface systems (NISs) for humans with paralysis. NISs are emerging medical devices designed to allow persons with paralysis to operate assistive technologies or to reanimate muscles based upon a command signal that is obtained directly from the brain. Such systems require the development of sensors to detect brain signals, decoders to transform neural activity signals into a useful command, and an interface for the user. We review initial pilot trial results of an NIS that is based on an **intracortical microelectrode sensor** that derives control signals from the **motor cortex**. We review recent findings showing, first, that neurons engaged by movement intentions persist in motor cortex years after injury or disease to the motor system, and second, that signals derived from motor cortex can be used by persons with paralysis to operate a range of devices. We suggest that, with further development, this form of NIS holds promise as a useful new neurotechnology for those with limited motor function or communication. We also discuss the additional potential for neural sensors to be used in the diagnosis and management of various neurological conditions and as a new way to learn about human brain function.

binary: referring to systems that exist in one of two mutually exclusive states. For example, a light is a binary system that can either be off or on—but not both.

open-loop (control): referring to systems in which output is not controlled by strategic changes in input. If one tries to ride a bike at constant speed (output) by using energy at a constant rate (input) regardless of what environmental factors are encountered (so riding up a hill slows you down and riding down a hill speeds you up), one is subjecting her or his bicycle to open-loop control. Opposite of closed-loop control (see above).

Hz (Hertz): a scientific Système Internationale (S.I.) unit of measure for the frequency of a wave (e.g., of light, of water, of sound). A frequency value in Hertz represents number of times a wave cycles in one second.

somatosensory: related to the various senses of touch, including pain, heat, and pressure reception

algorithm: a procedure (often mathematical) used to solve a problem; e.g., a computer program

locked-in: referring to a disease in which the patient is completely paralyzed (often able to move only their eyes) but still intelligent, aware, and fully awake

amyotrophic lateral sclerosis: a disease marked by progressive weakness and eventual loss of voluntary motion as a result of the degeneration of neurons responsible for muscle activity

motor-impaired: referring to those who have difficulty moving, either because of disease/injury or age

intracortical microelectrode sensor: a collection of stiff wires implanted into the brain to record the organ's electrical activity

motor cortex: the region of the brain responsible for complex motions of the body

CLASS II: TWEAKING INPUT

The computer programmer is a creator of universes for which he alone is the lawgiver… No playwright, no stage director, no emperor, however powerful, has ever exercised such absolute authority to arrange a stage or a field of battle and to command such unswervingly dutiful actors or troops.

—Joseph Weizenbaum

ULURU

Robson, J. 2004. *Natural History*. New York, NY: Bantam Dell. 37-39.

The following book excerpt gives one author's interpretation of a completely convincing, full-immersion virtual reality called Uluru–and how much more appealing it is than the physical world.

Virtua—variously named as the Dreamtime or Uluru, as Ghost-town or No-Space—had certain **protocols** for adult Forged. With regard to them, it didn't exist.

Conceived as a playground for the childhood and adolescence of the Forged, whose eventual bodies were constructed in a fully adult form only, it had later been developed illegally for recreational use. **Amenable** MekTek engineers put it together on stolen AI systems, in return for the promised benefits of free use of its arenas. Forged and MekTeks alone possessed the intricate cyborg structures that allowed them to partake of the pleasures on offer there.

Corvax had been a key developer of its later subsystems, a genius in his own youth, and he had introduced unlimited free-response within the grammar engines of the Dreamtime. He was now Uluru's primary host-keeper, and guardian of its gigantic servers now that the First Forged were mostly dead or pensioned off into milktoast assignments away from the action. He made his money renting time in it, and he maintained and continued to build upon it wherever he could.

His only personal guideline had been to let free will have its day. Everyone could be and do whatever the hell they wanted to inside Virtua and, so long as everyone signed up to the consent and the disclaimer, what did he care? The pay had been sufficient to buy him out of his standard Gaiasol government contract to Handslicer mining, and into his own laboratories. Most of his clients arriving on the asteroid came for adaptations to allow them to return to the experiences of Uluru that they'd enjoyed as children; like him they had old friends who were alive only in their imaginations, or other loves, or other worlds. He didn't ask and they didn't tell. Neither he nor they were much bothered by the constraints of reality or by the **hypothetical** moral censure of the Unevolved who couldn't **partake**, and who had **callously** stamped their own lack of options onto Forged workers when they decided that virtual environments were for fit only for those who possessed no physical forms and must be forbidden, on "mental health grounds," to those who had.

A single glance was all it took for one Forged to communicate with another the **acute** sense of loss that their adult physical Manifestation brought with it—so great they couldn't speak of it, so intense that no Unevolved would understand it. Manifest individuals had a social life, like any human, but without the Dreamtime they were **castrated** beings, haunted by the ghosts of imaginations that had once been all-powerful and were now forcibly limited to form attainable, mediocre longings within the bounds of their physical capacity to act. Some adapted better. Some claimed they were fine as they were. But some had a faraway look about them and a sadness that made Corvax turn away and hide his expressive forebody from them, in case they saw his sudden answering pain.

Someday I'll wish upon a star…

He vowed that he'd give them the bluebirds' wings. But it wasn't easy. Many Forged **immunologies** resented the overt MekTek intrusion that was necessary to bring them back into Uluru-consciousness. They became sick. They suffered. He had to fight to get the stolen **'ware** to adapt to them and give them the AI connection. Sometimes they died. But they still came.

protocols: rules

amenable: suggestible, submissive, easily manipulated or exploited

milktoast: an unusual and uncommon slang word meaning, here, unassuming and unimportant

hypothetical: theoretical, imaginary

partake: participate

callously: bitterly, spitefully

acute: strong, intense

castrated: lacking genitals; here, means incomplete and unfulfilled

immunology: immune system; the collection of biological processes that protects an organism against germ-borne illness

'ware: unusual and uncommon slang word for "software," or computer programs

Corvax got better at it and his reputation grew as he became known as the man who restored sex to the sexless, friends to the friendless, social contact to the isolated. Dreamtime was only the flicker of an eyelid away, once you were *changed*. And the police persistently hunted him, for the hours of time he lost the workforce, the broken contracts, the suicides and the crazies and all the problems the Forged were carefully engineered to be free of: perfect souls with no dissatisfaction, **as happy as Larry** in their world, **round pegs in round holes, bugs in rugs**, children born and brought up to live in bodies and in situations that didn't change, couldn't change, wouldn't change. Smother this instinct and take that one away in the test tube, **silence this gene** and slice out that hormone. What they don't feel they won't miss. Let them get used to it now and later they'll be glad. But Corvax knew from the start that he'd been made wrong, and others… they were botched as well: otters making their lives inside clamshells, wolves in lambs' clothing, horses driven to hang upside down and roost like bats.

Corvax had every physical add-on his badly treated Roc body could stand, but Dreamtime was where he did most of his living these days—his thinking, his recreation, his creation, everything but sleeping. His poor physical condition was a direct result of his addiction to its **siren call** but he was powerless to resist. There was no real life outside Dreamtime's spaceless span. As he still pondered Isol's problem he quietly activated his links and entered his own private ground…

as happy as Larry: a British slang expression meaning "extremely satisfied"

round pegs in round holes/bugs in rugs: slang expressions referring to someone who is in a situation in which he or she is perfectly comfortable. This is a play on the more usual expression "a square peg in a round hole," which refers to someone who is in a situation in which she or he does not belong (e.g., a very masculine football player who is asked to style someone's hair in a beauty salon)

gene silencing: preventing a segment of one's DNA (a "gene") from producing proteins or otherwise causing a change in an organism

siren call: extremely attractive temptation. Sirens are female sea deities of Greek legend who would sing to sailors at sea in order to lure them to their island so that they could eat them.

VIRTUAL INTERROGATION

Morgan, R.K. 2003. *Altered Carbon*. New York, NY: Del Rey. 225-228.

The following excerpt from a science fiction novel reflects one author's idea of a police interrogation conducted in a virtual world. In this short selection, the brains of the main characters are transitioning from physical to virtual reality—without moving a centimeter.

It was a rougher ride than I'd expected from a government department installation, but no worse than many **jury-rigged** virtuals I'd done on the World. First the **hypnos**, pulsing their **sonocodes** until the dull grey ceiling grew abruptly fascinating with fishtail swirls of light, and meaning drained out of the universe like dirty water from a sink. And then I was

Elsewhere.

It spread out around me, racing away from my viewpoint in all directions like nothing so much as a huge magnification of one of the spiral steps we had used to get down from the **gantry**. Steel gray, stippled every few meters with a nipple-like swelling, receding to infinity. The sky above was a paler shade of the same gray with shiftings that seemed vaguely to suggest bars and antique locks. Nice psychology, assuming any of the felons interrogated had anything but race memory of what an actual lock looked like.

In front of me softly shaped gray furniture was evolving from the floor like a sculpture from a pool of mercury. A plain metal table first, then two chairs this side, one opposite. Their edges and surfaces ran liquidy smooth for the final seconds of their emergence, then snapped solid and geometric as they took on an existence separate from the floor.

Ortega appeared beside me, at first a pale pencil sketch of a woman, all flickering lines and **diffident** shading. As I watched, pastel colors raced through her, and her movements grew more defined. She was turning to speak to me, one hand reaching into the pocket of her jacket. I waited and the final gloss of color popped out onto her surfaces.

I looked up at the geometric sky. "Is this standard?"

"Pretty much," Ortega squinted into the distance. "Resolution looks a bit higher than usual. Think Micky's showing off."

Kadmin scribbled into existence on the other side of the table. Before the virtual program had even colored him in properly, he became aware of us and folded his arms across his chest. If my appearance in the cell was putting him off balance as had hoped, it didn't show.

"Again, Lieutenant?" he said when the program had rendered him complete. "There is a U.N. ruling on maximum virtual time for one arrest, you know."

"That's right, and we're still a long way off it," Ortega said.

We took our seats, and I stared as Kadmin as we did it. It was the first time I'd seen anything quite like it.

He was the Patchwork Man.

Most virtual systems re-create you from self-images held in the memory, with a commonsense subroutine to prevent your delusions from **impinging** too much. I generally come out a little taller and thinner in the face than I usually am. In this case, the system seemed to have scrambled a **myriad** different perceptions from Kadmin's presumably long list of sleeves. I'd seen it done before, as a technique, but most of us grow rapidly attached to whatever sleeve we're living in, and that form blanks out previous **incarnations**. We are, after all, evolved to relate to the physical world.

The man in front of me was different. His frame was that of a Caucasian Nordic, topping mine by nearly thirty centimeters, but the face was at odds. It began African, broad and deep ebony, but the color ended like a mask under the eyes, and the lower half was divided along the line of the nose, pale copper on the left, corpse white on the right. The nose was both fleshy and **aquiline** and mediated well between the top and bottom halves of the face, but the mouth was a mismatch of left and right sides that left the lips peculiarly twisted. Long straight black hair was combed manelike back from the forehead, shot through one side with pure white. The hands, immobile on the metal table, were equipped with claws similar to the ones I'd seen on the giant Freak Fighter in Licktown, but the fingers were long and sensitive. He had breasts, impossibly full on a torso so overmuscled. The eyes, set in jet skin, were a startling pale green. Kadmin had freed himself from conventional perceptions of the physical. In an earlier age, he would have been a **shaman**; here, the centuries of technology had made him more. An electronic demon, a malignant spirit that dwelled in altered carbon and emerged only to possess flesh and wreak havoc.

jury-rigged: thrown together from a variety of poor-quality parts; makeshift

hypnos: devices designed to change one's focus from the real world to virtual reality (fictional term)

sonocodes: the software used by hypnos to transfer someone from actual to virtual reality (fictional term)

gantry: a framework for holding something (e.g., a sign) high in the air; a scaffold

diffident: quiet, shy; here, used to mean vague, barely visible

impinging: interfering

myriad: large amount

incarnation: body, manifestation

aquiline: hooked, like an eagle's beak

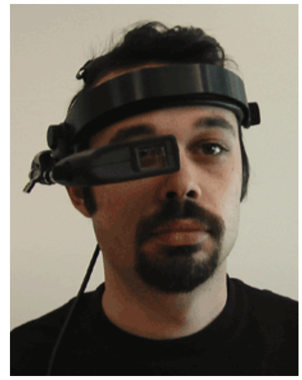
shaman: a person who guides communication between the physical and spiritual realms; an important figure in many tribal peoples

A Visual Overview of the Present State of Virtual Reality

The following images are taken from the website of the Virtual Reality Laboratory (VR Lab) at the Swiss Federal Institute of Technology in Lausanne, Switzerland. Try to figure out how each pictured device might work. How convincing of a virtual reality do you think they can produce?

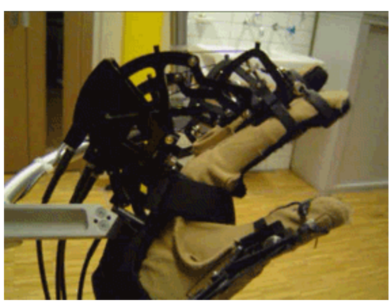
Creating Vision





Creativg Touch




Tracking Motion



WE WILL ALL BECOME VIRTUAL HUMANS

Kurzweil, R. 2003. Foreword to *Virtual Humans*. Boston: American Management Association.

The following excerpt makes predictions about the increasing prevalence of virtual realities in everyday life. As you read, evaluate the accuracy of the author's predictions. Do you agree with them?

By the end of this decade, we will have **full-immersion** visual-auditory environments, populated by realistic-looking virtual humans. These technologies are evolving today at an accelerating pace, as reflected in the book *Virtual Humans*. By the 2030s, virtual reality will be totally realistic and compelling, and we will spend most of our time in virtual environments. By the 2040s, even people of biological origin are likely to have the vast majority of their thinking processes taking place in nonbiological substrates. We will all become virtual humans.

full-immersion: encompassing every human sense (sight, sound, touch, smell, and taste)

If you ask what is unique about the human species, you're likely to get a variety of responses, including use of language, creation of technology, even the wearing of clothes. In my mind, the most salient distinguishing feature of the leadership **niche** we occupy in evolution is our ability to create mental models. We create models of everything we encounter from our experiences to our own thinking. The ancient arts of story telling were models of our experiences, which evolved into theater and the more modern art of cinema.

niche: area of specialization

Science represents our attempts to create precise mathematical models of the world around us. Our **inclination** to create models is **culminating** in our rapidly growing efforts to create virtual environments and to populate these artificial worlds with virtual humans.

inclination: tendency

culminating: arriving at a high point

We've had at least one form of virtual reality for over a century—it's called the telephone. To people in the late nineteenth century, it was remarkable that you could actually "be with" someone else without actually being in the same room, at least as far as talking was concerned. That had never happened before in human history. Today, we routinely engage in this form of auditory virtual reality at the same time that we inhabit "real" reality.

Virtual humans have also started to inhabit this virtual auditory world. If you call British Airways, you can have a reasonably satisfactory conversation with their virtual reservation agent. Through a combination of state-of-the-art, large-vocabulary, over-the-phone speech recognition and natural language processing, you can talk to their pleasant-mannered virtual human about anything you want, as long as it has to do with making reservations on British Airways flights.

On the Web, we've added at least a **crude** version of the visual sense to our virtual environments, albeit low-resolution and encompassing only a small portion of our visual field. We can enter virtual visual-auditory virtual environments (e.g., Internet-based videoconferencing) with other real people. We can also engage in interactions with an emerging **genre** of Web-based virtual personalities with a visual presence incorporating real-time animation. There are also a number of virtual worlds with animated avatars representing participants.

crude: rough, simple, unsophisticated

By the end of this decade, we will have full-immersion visual-auditory environments, with images written directly onto our retinas by our eyeglasses and contact lenses. All of the electronics for the computation, image reconstruction, and very- **high-bandwidth** wireless connection to the Internet will be embedded in our glasses and woven into our clothing, so computers as distinct objects will disappear. We will be able to enter virtual environments that are strikingly realistic recreations of earthly environments (or strikingly fantastic imaginary ones) either by ourselves or with other "real" people.

high-bandwidth: able to transfer a great deal of information at one time

Also populating these virtual environments will be realistic-looking virtual humans. Although these circa-2010 virtual humans won't yet pass the **Turing test** (i.e., we won't mistake them for biological humans), they will have reasonable facility with language. We'll interact with them as information assistants, virtual sales clerks, virtual teachers, entertainers, even lovers (although this application won't really be satisfactory until we achieve satisfactory emulation of the **tactile** sense).

Turing test: A hypothetical test postulated by mathematician Alan Turing that is designed to determine the limits of a particular artificial intelligence. If a computer is able to fool a human being into thinking that it is actually a human, it passes the Turing Test.

tactile: concerning the sense of touch

Virtual reality and virtual humans will become a profoundly transforming technology by 2030. By then, nanobots (robots the size of human blood cells or smaller, built with key features at the multi-nanometer—billionth of a meter—scale) will provide fully immersive, totally convincing virtual reality in the following way. The nanobots take up positions in close physical **proximity** to every **interneuronal** connection coming from all of our senses (e.g., eyes, ears, skin). We already have the technology for electronic devices to

proximity: here, spatial closeness

interneuronal: literally, "between neurons"; "inter"=between; "neuronal"=concerning brain cells communicate with neurons in both directions that requires no direct physical contact with the neurons.

For example, scientists at the Max Planck Institute have developed "neuron transistors" that can detect the firing of a nearby neuron, or alternatively, can cause a nearby neuron to fire, or **suppress** it from firing. This amounts to two-way communication between neurons and the electronic-based neuron transistors. The Institute scientists demonstrated their invention by controlling the movement of a living leech from their computer.

suppress: stop

Nanobot-based virtual reality is not yet feasible in size and cost, but we have made a good start in understanding the **encoding** of sensory signals. For example, Lloyd Watts and his colleagues have developed a detailed model of the sensory coding and transformations that take place in the auditory processing regions of the human brain. We are at an even earlier stage in understanding the complex feedback loops and neural pathways in the visual system.

encoding: the translation of disorganized phenomena into an information-carrying message

When we want to experience real reality, the nanobots just stay in position (in the **capillaries**) and do nothing. If we want to enter virtual reality, they suppress all of the inputs coming from the real senses, and replace them with the signals that would be appropriate for the virtual environment. You (i.e., your brain) could decide to cause your muscles and limbs to move as you normally would, but the nanobots again intercept these interneuronal signals, suppress your real limbs from moving, and instead cause your virtual limbs to move and provide the appropriate movement and reorientation in the virtual environment.

capillaries: smallest blood vessels in the body; act as the interface between the circulatory system and bodily tissues

The Web will provide a **panoply** of virtual environments to explore. Some will be recreations of real places, others will be fanciful environments that have no "real" counterpart. Some indeed would be impossible in the physical world (perhaps because they violate the laws of physics). We will be able to "go" to these virtual environments by ourselves, or we will meet other people there, both real people and virtual people.

panoply: wide variety

By 2030, going to a web site will mean entering a full-immersion virtual-reality environment. In addition to encompassing all of the senses, these shared environments could include emotional **overlays**, since the nanobots will be capable of triggering the neurological correlates of emotions, sexual pleasure, and other derivatives of our sensory experience and mental reactions.

overlay: covering; external layer

In the same way that people today beam their lives from Web cams in their bedrooms, "experience beamers" circa 2030 will beam their entire flow of sensory experiences, and if so desired, their emotions and other secondary reactions. We'll be able to plug in (by going to the appropriate Web site) and experience other people's lives as in the plot concept of "Being John Malkovich." Particularly interesting experiences could be **archived** and relived at any time.

archived: stored for later reference

By 2030, there won't be a clear distinction between real and virtual people. "Real people," i.e., people of a biological origin, will have the potential of enhancing their own thinking using the same nanobot technology. For example, the nanobots could create new virtual connections, so we will no longer be restricted to a mere hundred trillion interneuronal connections.

We will also develop intimate connections to new forms of nonbiological thinking. We will evolve thereby into a hybrid of biological and nonbiological thinking. Conversely, fully nonbiological "AI's" (artificial intelligent **entities**) will be based at least in part on the **reverse engineering** of the human brain and thus will have many human-like qualities.

entity: discrete unit

reverse engineering: studying an existing system to replicate it in another medium without knowing the precise design and function of every component

These technologies are evolving today at an accelerating pace. Like any other technology, virtual reality and virtual humans will not emerge in perfect form in a single generation of technology. By the 2030s, however, virtual reality will be totally realistic and compelling and we will spend most of our time in virtual environments. In these virtual environments, we won't be able to tell the difference between biological people who have projected themselves into the virtual environment and fully virtual (i.e., nonbiological) people.

Nonbiological intelligence has already secured a foothold in our brains. There are many people walking around whose brains are now a hybrid of biological thinking with computer implants (e.g., a neural implant for Parkinson's Disease that replaces the function of the biological cells destroyed by that disease).

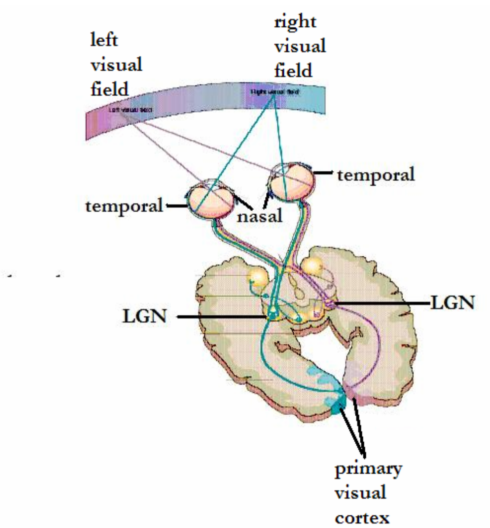
It is the nature of machine intelligence that its powers grow exponentially. Currently, machines are doubling their information processing capabilities every year and even that exponential rate is accelerating. As we get to the 2040s, even people of biological origin are likely to have the vast majority of their thinking processes taking place in nonbiological substrates.

We will all become virtual humans.

WHY IT MAY BE POSSIBLE TO CREATE VIRTUAL IMAGES BY ELECTRICALLY STIMULATING THE BRAIN

Fenandez, E., F. Pelayo, P. Ahnelt, J. Ammermüller, and R.A. Normann. 2004. Cortical visual neuroprostheses for the blind [in-press version]. ***Restorative Neurology and Neuroscience.***

The following excerpt from an article written in 2004 gives three reasons that it might be possible to make people perceive virtual realities by directly stimulating their brains with electricity. What are they?



"The visual pathways and primary visual cortex are organized in a relatively rational scheme."
(Credit: Nature Reviews: Neuroscience)

There is abundant and positive clinical experience with many neural prosthetic interfaces.

Microdevices for cell-electrode interfacing for both **cardiac** and neural cells have been available for ***in vitro*** and ***in vivo*** applications for many years. For example deep brain stimulators have been implanted in patients for pain management and control of **motor disorders** like **Parkinson's disease**, **cochlear** implants are used for restoring auditory function, and a variety of devices have been developed to control respiration, activate paralysed muscles, or stimulate bladder evacuation. The interest in neural interfaces has grown significantly, and today it is feasible to interface the nervous system with safe and effective devices.

The visual pathways and primary visual cortex are organized in a relatively rational scheme.

A greatly improved understanding of the organization of the visual pathways and the roles of its neural elements has gradually emerged from the early theories of Brodmann. Based upon **electrophysiological** experiments conducted in monkeys and other mammals, we know that **receptive field** centers of **primary visual cortex** neurons correspond in a moderately systematic fashion to locations from the **fovea** to the periphery. Points located in the right visual field are imaged on the **temporal** side of the left eye and the **nasal** side of the right eye. **Axons** from **ganglion cells** in these **retinal** cell regions make connections with separate layers in the **LGN** and these neurons send their outputs to cortical layers **4Ca** and **4Cb** respectively. Thus the overall spatial position of the retinal ganglion cells within the retina is preserved by the spatial organization of neurons within the LGN and visual cortex. This rational mapping of visual space onto the neurons of the visual cortex is one of the fundamental cornerstones upon which a cortical visual neuroprosthesis is based.

Electrical stimulation of neurons in the visual pathway evokes the perception of point of light

As Johannes Müller stated with his law of specific nerve energies, perceptions are determined by which nerve fibers are activated, not by how the nerve fibers are activated. For example, mechanical pressure to the eye produces a sensation of light, and electrical activation of axons in the auditory nerve give rise to a sensation of sound. In this sense, studies during neurosurgical procedures have revealed that localized direct electrical stimulation of the exposed human visual cortex can evoke **topographically mapped** visual percepts. These percepts are generally called "phosphenes" and are usually described as 'stars in the sky', 'clouds', 'pinwheels', and occasionally as complex **chromatic** or **kinetic** sensations. The induction of phosphenes by cortical stimulation establishes the visual nature of the stimulated cortex and provides the basis for the development of a cortical visual prosthesis.

cardiac: related to the heart

in vitro: a Latin term meaning "in glass"; refers to experiments that have been done in a controlled environment outside a living organism (e.g., in a test tube)

in vivo: a Latin term meaning "in the living"; refers to experiments that have been done inside a living organism (e.g., blood tests from transgenic mice)

motor disorder: a disease that affects one's ability to move appropriately

Parkinson's disease: a motor disorder in which the patient has trouble starting and stopping voluntary movements, resulting in tremors, slowed physical movement, and, in extreme cases, a complete loss of motion

cochlea: a fluid-filled, spiral-shaped region deep inside the ear that is responsible for transforming sound waves into electrical signals sent to the brain, resulting in the sensation of hearing

electrophysiological: related to the use of electricity by living systems (e.g., stimulating a neuron with an electrode to measure the number of action potentials it then fires)

receptive field: the region of the world to which a cell in the visual system (e.g., a photoreceptor, a ganglion, a primary visual cortex neuron) responds

primary visual cortex: the second major brain region to process visual information coming from the eye (the first is the LGN); located in the occipital lobe near the back of the head and arranged in layers (e.g., 4Ca, 4Cb, etc.)

fovea: part of the eye that sends the most visual information to the brain; corresponds to the center of one's visual field

temporal: closest to the ear

nasal: closest to the nose

axon: the part of a neuron that sends information to other neurons

ganglion cells: retinal cells that collect visual information from the photoreceptors to send to the brain

retina: a sheet of cells (photoreceptors, ganglion cells, etc.) on the back of the eye that sends visual information to the brain when it is hit by light in various conditions

LGN: A region of the thalamus that processes information coming from the eye

4Ca, 4Cb: two layers of neurons in the primary visual cortex

topographically mapped: here, referring to a direct correspondence between the location of electrical stimulation on the visual cortex and the location of the perceived "phosphenes"

chromatic: relating to color

kinetic: relating to motion

CAVEATS ASSOCIATED WITH CREATING VIRTUAL REALITIES BY ELECTRICALLY STIMULATING THE BRAIN

Fenandez, E., F. Pelayo, P. Ahnelt, J. Ammermüller, and R.A. Normann. 2004. Cortical visual neuroprostheses for the blind [in-press version]. *Restorative Neurology and Neuroscience.*

The following excerpt from a scientific research article talks about some problems that might occur as a result of directly stimulating the brain with computerized implants. While the technologies discussed in this text pertain to the restoration of sight to the blind with artificial retina, the principles it highlights are applicable to the implantation of electrical stimulation devices into the brain for any reason, including, for the purposes of this seminar, the creation of virtual realities.

A neuroprosthetic system must remain fully functional for many decades. Therefore, these devices must be highly **biocompatible** and able to resist the attack of biological fluids, proteases, macrophages or any substances of the metabolism. It is also necessary to take into account the possible damage of neural tissues by permanent charge injection using **multielectrode arrays**. These considerations place unique constraints on the architecture, material, and surgical techniques used in the implementation of neural interfaces. Once a particular type of electrode is selected, one must design a surgical procedure for electrode implantation. Although the individual microelectrodes of the **UEA** are extremely sharp, early attempts to implant an array of 10 x 10 electrodes into the animal visual cortex only deformed the cortical surface and resulted in incomplete implantation. A system that rapidly inserts the UEA into the cortex has been developed, allowing implantation in a manner that minimizes dimpling and compression of the subjacent structures. The implantation is so rapid that the cortex experiences only slight mechanical dimpling, and the insertion is generally complete. The most typical findings in acute experiments are occasional **microhemorrhages** emanating from the electrode tracks, probably due to the high probability of electrode tips encountering one or more blood vessels during implantation. This typically resolves itself, and aside from a few mechanically-distorted and somewhat **hyperchromic** neurons, the neurons near most tracks appear normal. **Single-unit recordings** of neural activity can often by made within hours after the implantation.

An important problem reported with all available microelectrodes to date is long-term viability and biocompatibility. Although silicon-based shafts, siliconoxide-based surfaces, and other glass-based products are reportedly highly biocompatible, there are **acute** and **chronic** inflammatory reactions that affect both the neural tissue and the surface of the microelectrodes. These reactions often result in damage to neurons and microelectrodes and lead to the proliferation of a **glial** scar around the implanted probes that prevents neurons from being recorded or stimulated. Our experiments with the UEA support this and show a thick capsule (2-5 microns thick) around each electrode track. The reasons for the inflammatory response lie in molecular and cellular reactions at foreign surfaces. These responses can be controlled, and one of our goals is to contribute to this field, both in terms of increasing the understanding of how at the **nanoscale** inflammatory events take place and in terms of creating new, more biocompatible surfaces for use in neurosurgery and brain implants.

Other possible problems are related to motion of the brain with respect to the skull. These devices should stay in place for years, but how to keep them biologically and electrically viable remains a difficult problem. We have described a new surgical technique to minimize the formation of **adhesions** between the **dura** and implanted electrode arrays using a 12 mm (0.5 mil) thick sheet of Teflon® film positioned between the matrix of microelectrodes and the dura. We are also collaborating with the Department of Medical Physics of the University of Vienna to develop a new *in vivo* technique for **optical coherence tomography** with unprecedented resolution (< 10 µm). In the future, this technique could help the development of a non-invasive diagnostic technique to obtain precise information about the cortical differentiation of blind persons. It could be also very valuable for determining the required advancement depth of multi-electrode tips to access the most appropriate cortical sublayer (4C). By implanting penetrating microelectrodes within the visual cortex, with exposed tip sizes the same order of magnitude as the neurons we want to stimulate, much selective stimulation can, in principle, be achieved. However, implantation of penetrating electrodes is intrinsically more invasive than application of surface electrodes, and studies regarding safety and preservation of neuronal tissues as well as **optimization** of stimulating parameters are needed preceding the actual clinical application. Experiments to determine the levels of current injections that are required to evoke **sensory percept** via **intracortical microstimulation** have shown that most of the microelectrodes had threshold currents below 25 mA. Nevertheless more data on the possible damage of neural tissues by permanent charge injection using multielectrode arrays and the most effective means of stimulating the cerebral cortex are still needed.

Another important issue for the design of a useful cortical visual neuroprosthesis is whether **retinotopic** organization changes from electrical stimulation. Repeated sensory stimulation of either primary visual cortex or other primary sensory cortices can lead to changes in the representation of the sensory input. Additionally, changes in the cortical representation can occur as a result of repeated electrical stimulation of auditory, **somatosensory,** motor and visual cortex. However, preliminary results are inconsistent and more work needs to be done.

biocompatible: able to connect to and function with biological materials

microelectrode array: a set of wires that allows researchers to simultaneously measure and stimulate action potentials in the neurons to which they are attached

UEA: Utah Electrode Array; a silicon chip containing 100 electrodes that is implanted on the surface of the brain to measure and stimulate action potentials

microhemorrhage: small attacks of internal bleeding

hyperchromic: containing too much hemoglobin (the protein in red blood cells that carries oxygen to other cells in the body)

single-unit recording: measuring the patterns of electrical activity of one neuron using an electrode

acute: occurring during or after a short period of time

chronic: occurring during or after a long period of time

glial: relating to the glia, a type of cell found in the nervous system that acts to support neuronal development and function

nanoscale: pertaining to objects that are on the nanometer (10^{-9} meters) scale

adhesions: attractions, connections

dura (dura mater): Latin for “tough mother”; the tough outermost layer of tissue wrapping the brain and spinal cord

optical coherence tomography: a brain-imaging technology that uses white light to view the brain in great detail

optimization: the process of setting a particular quality to its best possible values

sensory percept: the experience of a sense (e.g., seeing a flash of light; hearing a brief tone)

intracortical microstimulation: electrically stimulating the brain using microelectrodes implanted within the cortex

retinotopic: relating to the idea that cells in the retina, lateral geniculate nucleus, and visual cortex are all organized similarly to the visual field they represent. In other words, there exists a one-to-one correspondence among regions of the visual world and each of the cell types that help us see these regions. For example, the distance between two retinal cells responding to two points of light in the retinal visual field depends on the distance between those two points of light.

somatosensory: relating to the sense of touch

Class III: Shifting Substrate

Everyone takes the limits of his own vision for the limits of the world.
—Arthur Schopenhauer

THE CORTICAL STACK

Morgan, R.K. 2003. *Altered Carbon*. New York, NY: Del Rey. 37-38, 74-75.

Imagine a technology that could upload the human brain—its memories, emotions, personality: essentially the person comprising it—into a computer as though it were a movie or music file. Now imagine that this is a technology used by the greater part of the human race to switch bodies and extend the average lifespan. These ideas are referenced in this author's description of the futuristic "Envoy Corps," an elite military unit that relies on brain-computerizing—or "cortical stack"—technology to transport their minds great distances into bodies designed for special combat assignments. They also underlie his description of "Meths," or humans who use cortical stacks to live for hundreds of years in several different bodies.

cortical stack: a small computerized device implanted at the base of one's skull that continually records its wearer's brain state for eventual transfer to another body (or "sleeve"; see below) in the case of death or a need to travel great distances (fictional term)

"Envoy training was developed for the U.N. colonial **commando** units. That doesn't mean…"

Doesn't mean every Envoy is a commando. No, not exactly, but then what is a soldier anyway? How much of special-forces training is engraved on the physical body and how much in the mind? And what happens when the two are separated?

Space, to use a cliché, is big. The closest of the Settled Worlds is fifty light-years out from Earth. The most far-flung are four times that distance, and some of the colony transports are still going. If some maniac starts rattling **tactical** nukes, or some other biosphere-threatening toys, what are you going to do? You can transmit the information, via **hyperspatial needlecast**, so close to instantaneously that scientists are still arguing about the terminology, but that, to quote Quellcrist Falconer, deploys no bloody divisions. Even if you launched a troop carrier the moment the shit hit the fan, the marines would be arriving just in time to quiz the grandchildren of whoever won.

That's no way to run a **protectorate**.

Okay, you can digitize and freight the minds of a crack combat team. It's been a long time since the weight of numbers counted for much in a war, and most of the military victories of the last half millennium have been won by small, mobile guerrilla forces. You can even **decant** your crack D.H.F. soldiers directly into **sleeves** with combat conditioning, **jacked-up** nervous systems, and **steroid**-built bodies. Then what do you do?

They're in bodies they don't know, on a world they don't know, fighting for one bunch of total strangers against another bunch of total strangers over causes they've probably never heard of and certainly don't understand. The climate is different, the language and culture are different, the wildlife and vegetation are different, the atmosphere is different, shit, even the *gravity* is different. They know nothing, and even if you download them with implanted local knowledge, it's a massive amount of information to assimilate at a time when they're likely to be fighting for their lives within hours of sleeving.

That's where you get the Envoy Corps.

Neurachem conditioning, **cyborg** interfaces, augmentation—all this stuff is *physical*. Most of it doesn't even touch the pure mind, and it's the pure mind that gets **freighted**. That's where the corps started. They took psychospiritual techniques that Oriental cultures on Earth had known about for millennia and distilled them into a training system so complete that on most worlds graduates of it were instantly forbidden by law to hold any political or military office.

Not soldiers, no. Not exactly.

"I work by absorption," I finished. "Whenever I come into contact with, I soak up, and I use that to get by."

***

"Bancroft's not people, like you and me. He's a Meth."

"A Meth?"

commando: an elite soldier

tactical: used for a strategic purpose

hyperspatial needlecast: a technology that allows extremely fast communication between galaxies (fictional term)

protectorate: a powerful state that is politically responsible for a weaker state

decant: pour

sleeves: human bodies built to house cortical stacks (fictional term)

jacked-up: a slang term meaning "enhanced"

steroid: a class of biological molecules containing four carbon rings; here, refers to anabolic steroids, a subclass of steroids that promotes the construction of muscle

neurachem: A class of drugs that enhance brain function (fictional term)

cyborg: an organism that contains both biological and computerized parts

freighted: downloaded into a cortical stack for transfer to another sleeve (fictional term)

"Yeah. A Meth. You know, and all the days of Methusulah were nine hundred sixty and nine years. He's old. I mean, really old."

"Is that a crime, Lieutenant?"

"It should be," Ortega said grimly. "You live that long, things start happening to you. You get too impressed with yourself. Ends up, you think you're God. Suddenly the little people, thirty, maybe forty years old, well, they don't really matter anymore. You've seen whole societies rise and fall, and you start to feel you're standing outside it all, and none of it really matters to you. And maybe you'll start snuffing those little people, just like picking daisies, if they get under your feet."

I looked seriously at her. "You pin anything like that on Bancroft? Ever?"

"I'm not talking about Bancroft." She waved the objection aside impatiently. "I'm talking about his *kind*. They're like the A.I.s. They're a breed apart. They're not human. They deal with humanity the way you and I deal with insect life. Well, when you're dealing with the Bay City Police Department, having that kind of attitude can sometimes back up on you."

I thought briefly of Reileen Kawahara's excesses and wondered how far off the mark Ortega really was. On Harlan's World, most people could afford to be resleeved at least once, but the point was that unless you were very rich, you had to live out your full span each each time and old age, even with the **antisen** treatment, was a wearying business. Second time around was worse because you knew what to expect. Not many had the **stamina** to do it more than twice. Most people went into voluntary storage after that, with occasional temporary resleevings for family matters, and of course, even these resleevings thinned out as time passed and new generations bustled in without the old ties.

It took a certain kind of person to keep going, to want to keep going, life after life, sleeve after sleeve. You had to start out different, never mind what you might become as the centuries piled up.

antisen: short for "antisenility," or guarding against the loss of mental function in old age (fictional term)

stamina: endurance, ability to expend energy and effort for a long time

JACK'S TRANSFORMATION

Kurzweil, R. 1999. *The Age of Spiritual Machines: When Computers Exceed Human Intelligence*. London: Penguin Books.

The following excerpt discusses the inadequacy of traditional Western notions of identity to describe the possible effect of shifting the substrate of our brains from neurons to computer chips. In doing so, the discussion brings to mind the Greek riddle of Theseus' ship, which replaced its boards one by one as they broke down and, after fifty years, did not contain a single piece of its original material. Was it still the same ship at the end of these fifty years? What if, like Theseus' ship, a human could replace each of her brain regions as they broke down? Would she stay the same person?

Our friend Jack (**circa** some time in the twenty-first century) has been complaining of difficulty with his hearing. A diagnostic test indicates he needs more than conventional hearing aid, so he gets a **cochlear** implant. Once used only by people with severe hearing impairments, these implants are now common to correct the ability of people to hear across the entire **sonic** spectrum. The surgery is successful; Jack is pleased with his new hearing.

Is he still the same person? Well, sure he is. People have cochlear implants circa 1999. We still regard them as the same person.

Now (back to circa sometime in the twenty-first century), Jack is so impressed with the success of his cochlear implants that he elects to switch on the built-in **phonic** cognition circuits, which improve overall auditory perception. These circuits are already built in so that he does not require another insertion procedure should he subsequently decide to enable them. By activating these neural-replacement circuits, the phonics-detection **nets** built into the implant bypass his own aging neural-phonics regions. His cash account is also **debited** for the use of this additional neural software. Again, Jack is pleased with his improved ability to understand what people are saying.

Do we still have the same Jack? Of course; no one gives it a second thought.

Jack is now sold on the benefits of the emerging neural-implant technology. His **retinas** are still working well, so he keeps them intact (although he does have permanently implanted retinal imaging displays in his corneas to view virtual reality), but he decides to try out the newly introduced image-processing implants, and is amazed how much more vivid and rapid his visual perception has become.

Still Jack? Why, sure.

Jack notices that his memory is not what it was, as he struggles to recall names, the details of earlier events, and so on. So he's back for memory implants. These are amazing—memories that had grown fuzzy with time are now as clear as if they had just happened. He also struggles with some unintended consequences as he encounters unpleasant memories that he would have preferred to remain dim.

Still the same Jack? Clearly he had changed in some ways and his friends are impressed with his improved faculties. But the same self-deprecating humor, the same silly grin—yes, it's still the same guy.

So why stop here? Ultimately Jack will have the option of scanning his entire brain and neural system (which is not entirely located in the skull) and replacing it with electronic circuits of far greater capacity, speed, and reliability. There's also the benefit of keeping a backup copy in case anything happened to the physical Jack.

Certainly this specter is unnerving, perhaps more frightening than appealing. And undoubtedly it will be controversial for a long time (although according to the Law of Accelerating Returns, a "long time" is not as long as it used to be). Ultimately, the overwhelming benefits of replacing unreliable neural circuits with improved ones will be too compelling to ignore.

Have we lost Jack somewhere along the line? Jack's friends think not. Jack also claims that he's the same old guy, just newer. His hearing, vision, memory, and reasoning ability have all improved, but it's still the same Jack.

However, let's examine the process a little more carefully. Suppose rather than implementing this change a step at a time as in the above scenario, Jack does it all at once. He goes in for a computer brain scan and has the information from the scan instantiated (installed) in an electronic neural computer. Not one to do things **piecemeal**, he upgrades his body as well. Does making the transition at one time change anything? Well, what's the difference between changing from neural circuits to electronic/**photonic** ones all at once, as opposed to doing it gradually? Even if he makes the change in one quick step, the new Jack is still the same old Jack, right?

circa: Latin for "about"; around

cochlear: relating to a spiral-shaped tunnel in the inner ear responsible for transforming sound waves into electrical impulses to be sent to the brain

sonic: relating to sound

phonic: relating to the sounds of speech

nets: neural nets, or computerized representations of the dynamic, pattern-seeking networks of cells that compose the human brain

debited: charged money

retina: a sheet of cells (photoreceptors, ganglion cells, etc.) on the back of the eye that sends visual information to the brain when it is hit by light in various conditions

piecemeal: in a series of steps instead of all at once

photonic: functioning as a result of the motion of photons, the elementary particles from which light is composed (as opposed to electronic, which functions as a result of the motion of electrons)

But what about Jack's old brain and body? Assuming a noninvasive scan, these still exist. This is Jack! Whether the scanned information is subsequently used to instantiate a copy of Jack does not change the fact that the original Jack still exists and is relatively unchanged. Jack may not even be aware of whether a not a new Jack is ever created. And for that matter, we can create more than one new Jack. If the procedure involves destroying the old Jack once we have conducted some quality-assurance steps to make sure the new Jack is fully functional, does that not constitute the murder (or suicide) of Jack?

Suppose the original scan of Jack is not noninvasive, that it is a "destructive" scan. Note that technologically speaking, a destructive scan is much easier—in fact we have the technology today (1999) to destructively scan frozen neural sections, ascertain the interneuronal wiring, and reverse engineer the neurons' parallel digital-analog algorithms. We don't yet have the bandwidth to do this quickly enough to scan anything but a very small portion of the brain. But the same speed issue existed for another scanning project—the human **genome** scan—when that project began. At the speed that researchers were able to scan and sequence the human genetic code in 1991, it would have taken thousands of years to complete the project. Yet a fourteen-year schedule was set, which it now appears will be successfully realized. The Human Genome Project deadline obviously made the (correct) assumption that the speed of our methods for sequencing DNA codes would greatly accelerate over time. The same phenomenon will hold true for our human-brain-scanning projects. We can do it now—very slowly—but that speed, like most everything else governed by the **Law of Accelerating Returns**, will get **exponentially** faster in the years ahead.

Now suppose as we destructively scan Jack, we simultaneously install this information into the new Jack. We can consider this a process of "transferring" Jack to his new brain and body. So one might say that Jack is not destroyed, just transferred to a more suitable embodiment. But is this not equivalent to scanning Jack noninvasively, subsequently instantiating the new Jack and then destroying the old Jack? If that sequence of steps basically amounts to killing the old Jack, then this process of transferring the Jack in a single step must amount to the same thing. Thus we can argue that any process of transferring Jack amounts to the old Jack committing suicide, and that the new Jack is not the same person.

The concept of scanning and reinstantiation of the information is familiar to us from the fictional "beam me up" teleportation technology of *Star Trek*. In this fictional show, the scan and reconstitution is presumably on a nanoengineering scale, that is, particle by particle, rather than just reconstituting the **salient** algorithms of neural-information processing envisioned above. But the concept is very similar. Therefore, it can be argued that Star Trek characters are committing suicide each time they teleport, with new characters being created. These new characters, while essentially identical, are made up of entirely different particles, unless we imagine that it is the actual particles being beamed to the new destination. Probably it would be easier to beam just the information and use local particles to instantiate the new embodiments. Should it matter? Is consciousness **a function of** the actual particles or just of their pattern and organization?

We can argue that consciousness and identity are not a function of the specific particles at all, because our own particles are constantly changing. On a cellular basis, we change most of our cells (although not our brain cells) over a period of several years. On an atomic level, the change is much faster than that, and does include our brain cells. We are not at all permanent collections of particles. It is the patterns of matter and energy that are semipermanent (that is, changing only gradually), but our actual material content is changing constantly, and very quickly. We are rather like the patterns that water makes in a stream. The rushing water around a formation of rocks makes a particular, unique pattern. This pattern may remain relatively unchanged for hours, even years. Of course, the actual material constituting the pattern—the water—is totally replaced within milliseconds. This argues that we should not associate our fundamental identity with specific sets of particles, but rather the pattern of matter and energy that we represent. This, then, would argue that we should consider the new Jack to be the same as the old Jack because the pattern is the same. (One might **quibble** that while the new Jack has similar functionality to the old Jack, he is not identical. However, this just dodges the essential question, because we can reframe the scenario with a nanoengineering technology that copies Jack atom by atom rather than just copying the salient information-processing algorithms.)

Contemporary philosophers seem to **be partial to** the "identity from pattern" argument. And given that our pattern changes only slowly in comparison to our particles, there is some apparent merit to this view. But the counter to that argument is the "old Jack" waiting to be extinguished after his "pattern" has been scanned and installed in a new computing **medium**. Old Jack may suddenly realize that the "identity from pattern" argument is flawed.

genome: the set of DNA from which a whole organism is made

Law of Accelerating Returns: an extension of Moore's Law (which says that the information capacity of one computer chip is increasing exponentially with time due to transistors' increasingly small size and cheap price) that predicts exponential advancement in technology as time goes on (in part because the development of new technology itself increases the speed at which even newer technologies can be developed).

exponentially: increasing at a that is itself increasing

salient: important

a function of: dependent on

quibble: argue (usually used in reference to arguing about something unimportant)

be partial to: prefer, favor

medium: substrate, material

GROWING A BRAIN IN SWITZERLAND

Dworschak, M. 2007. Growing a brain in Switzerland. Spiegel Online. Available online at http://www.spiegel.de/international/spiegel/0,1518,466789,00.html

The following article discusses a recent endeavor in Switzerland to create a detailed simulation of certain brain regions with a supercomputer in order to ***facilitate*** *research on the biology of cognitive function. While the model is meant to be used as a visualization tool and not as a true representation of artificial intelligence, its construction may nonetheless provide insights into brain circuitry that aid in the eventual construction of computerized consciousness.*

A network of artificial nerves is growing in a Swiss supercomputer -- meant to simulate a natural brain, cell-for-cell. The researchers at work on "Blue Brain" promise new insights into the sources of human consciousness.

The machine is beautiful as it wakes up -- nerve cells flicker on the screen in soft pastel tones, electrical charges flash through a maze of **synapses**. The brain, just after being switched on, seems a little sleepy, but gentle bursts of current bring it fully to life.
This **unprecedented** piece of hardware consists of about 10,000 computer chips that act like real nerve cells. To simulate a natural brain, part of the **cerebral cortex** of young rats was painstakingly replicated in the computer, cell by cell, together with the branched tree-like structure of the synapses.

The simulation was created at the Technical University in Lausanne, Switzerland, where 35 researchers participate in maintaining this artificial brain. It runs on one of the world's most powerful supercomputers, but soon even that computer will be too small. The goal is to build a much bigger electronic thinking machine -- one that would ultimately replicate the human brain.

A project this ambitious would have been ridiculed a few years ago. "Today we have the computers we need," says biologist Henry Markram, 44, the project's director. "And we know enough to begin."

Markram knows about the problems his group can look forward to. "But if we don't build the brain," he says, "we'll never understand how it works." In fact, there have been tremendous advances in brain research for years; but answers to the big questions are as elusive as ever. How does consciousness develop within the electric orchestra of cells? How exactly does a spark of intellect ignite from the interplay among **genes**, **proteins** and messenger substances?

The Lausanne model, dubbed "Blue Brain," is the most radical attempt so far to investigate the mystery of consciousness. The idea is **seductively** simple: To determine how the mind emerges from biology, replicate the biology. It's a task that requires enormous patience and attention to detail, a process that ultimately means mimicking nature one molecule at a time.

Though the first artificial brain may seem simple, it will be a useful model. Brain researchers can use it to reproduce functions from the real organ and test their theories. As they build in new processes, the model grows ever more detailed -- a sort of wiki project of the mind. It also offers an important advantage over a natural brain, since it lets researchers monitor each and every (simulated) mental activity in the machine.

But -- has there been mental activity?

The newborn "Blue Brain" surprised the designers with its willfulness from the very first day. It had hardly been fed electrical impulses before strange patterns began to appear on the screen with the lightning-like flashes produced by cells that scientists recognize from actual thought processes. Groups of neurons started becoming attuned to one another until they were firing in rhythm. "It happened entirely on its own," says Markram. "Spontaneously."

Building the Electronic Rat Brain

Ten thousand artificial nerve cells have been interwoven in Lausanne, and the researchers aim to increase the number to one million within the next year. Which doesn't mean they're satisfied: The work is scheduled right now to last beyond 2015. By then, unless the project proves too ambitious, Markram and his team hope to be ready for their primary

facilitate: make easier

synapses: connections between neurons across which information is sent by neurotransmitters, or chemicals released by neurons to change the electrical potentials of other neurons with which they form synapses

unprecedented: never before seen

cerebral cortex: the outer nine layers of neurons covering most of the front and top of the brain in humans and some other animals; responsible for integrating information from a variety of other brain regions to plan and execute complex behaviors

gene: though scientists dispute over the exact meaning of this word, it most commonly refers to a piece of an organism's DNA that provides the information needed to build a single protein

protein: a type of large molecule mainly composed of carbon, nitrogen, oxygen that can play several roles in a cell, including providing structural support, aiding chemical reactions, acting as a signal to other cells

seductively: appealingly, attractively goal: a computer model of an entire human brain -- right now almost a sheer **flight of fancy**, given the 100 billion cells they would have to engineer.

flight of fancy: unattainable goal; whimsical dream

Skeptics wonder what the purpose is of **painstakingly** replicating things when scientists have so little understanding of their purpose and function. Indeed, no one will know, within the foreseeable future, what exactly happens in the circuits of the replicated brain -- except that whatever it is, it looks seductively authentic to an outside observer.

skeptic: someone who is reluctant to hold firm beliefs

painstakingly: very carefully; meticulously

Perhaps the only ones who could have known are the scores of rats that carry on a shadow-like existence in this supercomputer. Researchers opened thousands of rat skulls over the years, removed their brains, and cut them into thin slices, which they kept alive. Then they directed tiny sensors at the individual neurons. They listened to the cells firing neurons, and intercepted the responses coming from the adjacent cells.

The brain slices were exposed to a variety of electrical impulses. The impulses reflected the **stimuli** that may have been received by the laboratory rats' brains when the animals smelled cheese or were startled by a shape. The cells reacted -- just as they did when the rats were still alive -- by sending electrical charges through the **neuroplexus**. The researchers' measuring devices recorded all signals until the brain slices expired.

stimuli: events in the external world that cause a change in the electrical potential in a neuron (e.g., a sound, a taste, a smell)

neuroplexus: the network of neurons composing the brain

In the end, the researchers at Markram's lab collected the entire **repertoire** of behavior of hundreds of types of cells in every conceivable situation in a rat's life -- stored in endless tables. This vast stockpile of data let the researchers start building their digital **doppelgänger**.

repertoire: collection

doppelgänger: an evil twin

Henry Markram, a South African by birth, has spent the last 15 years studying the **interplay** among brain cells. He learned to use brain-impulse sensors in the Heidelberg laboratory of Dr. Bert Sakmann. Sakmann had developed a method of applying suction to individual gray cells using tiny glass tubes, prompting the cells to release their electric signals. In 1991 he was awarded the Nobel Prize in Physiology or Medicine for his research. His student, Markram, further developed the method until he was able to monitor several cells at the same time -- a number that he has now increased to twelve. "That was the breakthrough," says Markram. "We had **paved the way** to the artificial brain by the time we arrived at communication between the cells."

interplay: interaction, relationship

paved the way: made future progress easier by taking initial steps toward a goal

Researchers working on this puzzle, though, still expect to receive a few lessons in applied modesty, given the overwhelming complexity of the brain. It took months to complete a copy of the first brain cell to be transferred to the computer. The **digital** cell model is based on millions of formulas -- that much data is needed to achieve fairly natural behavior. The computing capacity the project requires is correspondingly high. A whole processor is currently needed to simulate the behavior of a single cell.

digital: referring to a system that can be in one of only two discrete states. For example, a light, which is either “off” or “on,” is a very simple digital system. This is the opposite of an analog system, which can be in any of a continuously variable range of states. For example, the two hands of a clock, which can be position such that they are separated by any angle between 0 and 360, is an extremely simple analog system.

But this is the price of **uncompromising** realism. A nerve cell's capacity to process electric signals is almost unfathomable. It reacts to incoming stimuli using tiny pores, known as ion channels, tens of thousands of which are distributed across its surface. Electrically charged particles slip in and out of the cell through these gateways. The cell takes part in the orchestra of thought by opening or closing its ion channels. This is how it prepares itself to fire; this is also how it sends signals to neighboring cells, through thin **protrusions** known as axons.

uncompromising: unwilling to negotiate; inflexible

protrusions: bulges; projections; extensions

The computer model also includes ion channels, and their distribution almost mirrors the original. "However, at this level of precision it would be impossible for us to produce millions of cells **manually**," says Markram. The solution required a stroke of boldness: "We had to **industrialize** it."

manually: by hand

industrialize: place a certain process under the guide of machines

Technology ***Recapitulates*** *Biology*

recapitulates: recreates in a simpler form; summarizes

Today the Blue Brain project essentially has its own factory to produce artificial brain matter, so the computer can **clone** nerve cells almost automatically. The system's production line can produce whole series of neurons, one after another. Its memory contains close to 400 types, differentiated by shape. The stored neurons could be used to construct thinking tools of any size, in principle. Before they can be approved for use, though, the individual cells are randomly provided with individual characteristics -- because in the actual brain, no two cells are identical.

clone: create a organism containing the same DNA as another; copy

While none of this is especially challenging for a supercomputer, the real work starts when the time comes to link 10,000 non-identical cells to one another in a way that mirrors nature. The result is a particularly tricky 3-D puzzle, because each cell has about 10,000 protrusions with which it attempts to connect to other cells. The computer, in other words, must rotate and twist all cells in the space until their conductors are connected -- correctly -- at a total of 100 million points of contact.

The first phase of the project, which is currently underway, simulates a tiny part of a rat's cerebral cortex known as a cortical column, a dense tangle of interconnected cells about two millimeters long and half a millimeter in diameter. The cerebral cortex of all mammals, including man, consists of such cortical columns. Once evolution had hit upon a successful model, it apparently saw no reason to modify it significantly.

Cortical columns are all-purpose tools, equally suited to provide sharp vision, acute hearing and complex reasoning. "We see it as a sort of miniature brain," says Markram. "With only one of these columns, we would certainly be capable of processing environmental stimuli, though only in a very blurred way."

The cells in the Lausanne brain model still lack their chemical insides. They simulate the abundance of electric signals being exchanged, but not the molecular machines that produce them. The artificial cells do not contain proteins, which, in real cells, combine to form **ion** grids, for example. More important, the genes that are switched on to produce these proteins are also absent.

"We will **incorporate** the molecules later," says project manager Felix Schürmann. "In the next few months we'll focus on fine-tuning the model we already have." The researchers repeatedly test their circuits, comparing their behavior with the results from the rat experiments. Only when there are no longer any significant differences is the simulation ready for the next phase.

The team expects to begin replicating a whole rat brain by early next year. For that purpose, however, the current computer will no longer be sufficient and the researchers will need a new supercomputer, the world's fastest. But even that level of computing speed won't be enough for long, as the team scrambles up the ladder of life forms. "We'll model a cat brain, a primate brain and finally a human brain," says Markram confidently, as if there's no reason to doubt the feasibility of such a goal. Each step along the way will likely need the latest generation of supercomputer.

Is it even possible?

Computer giant IBM has provided the machinery for Blue Brain from the beginning. The company has positioned itself for some time as a supplier of supercomputers for the scientific community, lured by a rapidly growing market. The Lausanne brain simulation is therefore also a chance for IBM to gather experience in new and **daunting** challenges.

The researchers in the Blue Brain group are already working with IBM experts on the plans for a computer that would operate at nearly inconceivable speeds -- the kind of machine needed to simulate the human brain. It would be an absurd undertaking if it were based on current technology. A computer capable of running such a simulation would be a colossus the size of several soccer fields. "And we'd have an electric bill of $3 billion a year," says Markram. But the outlook changes considerably when Markram accounts for the rapid growth in performance in chip technology. "By 2015 we will have arrived at a level of energy consumption that we could certainly afford."

But the question is, is all the cost and effort worth it? "Half the research community will say our project is nonsense," says Markram. "In their view, the brain is far too complex to allow for successful replication." In fact, there are an almost infinite number of possibilities to connect only a few million brain cells. How could it ever be possible to decide which of those combinations will produce consciousness? "That's a fundamental misconception," says Markram. "We aren't interested in the theoretical number. After all, evolution found a biological solution."

The researchers in Lausanne believe they can reach this solution one step at a time. The more detailed information about brain biology they incorporate into the simulation, the easier their remaining work becomes. This is because many theoretically possible but meaningless brain combinations will be eliminated. What will remain, the researchers believe, are valid combinations that could give rise to thought.

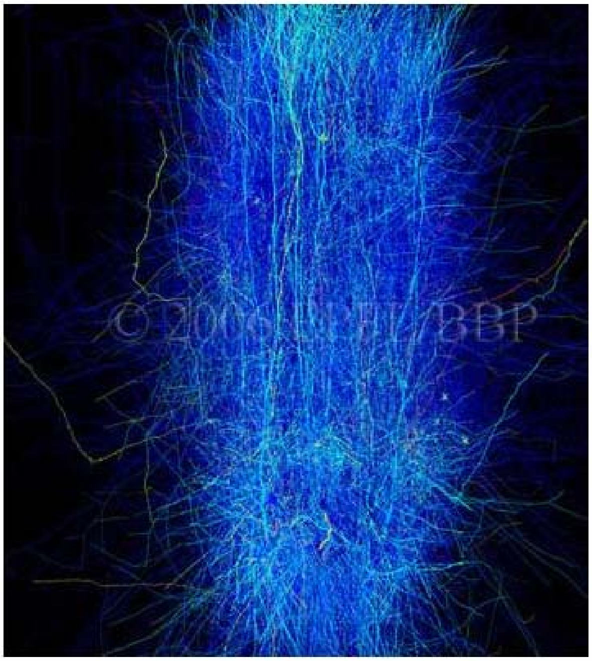
It's a daring bet on the future. The Blue Brain group lacks neither funds nor pioneering spirit. Its researchers do not hesitate to place it on par with the human genome project. They are convinced that just as the genome project has decoded man's genetic makeup, their project in Lausanne will decipher the fundamental biological tools of his capacity for thought.

ion: an atom that has an electric charge because the number of its protons does not equal the number of its electrons. For example, O^{2-} is an ion because it is an oxygen atom with two extra electons.

incorporate: to include or integrate into a system

daunting: intimidating to the point of discouraging one from trying

If all goes well, the results of research in Lausanne will not be the only data incorporated into the brain model. The Brain Mind Institute alone, which Markram co-directs, employs up to 125 researchers, but it could theoretically draw on the collective research of the global scientific community. "We now have about 35,000 publications a year in neuroscience," says Markram. "No single researcher knows even one percent of that. We won't get anywhere without a model that integrates all of this fragmented knowledge."



A glimpse from a computer monitor into Blue Brain's neural network simulation
Credit: http://mediatheque.epfl

Once Blue Brain operates reliably, fellow scientists from the around the world will be invited to use it to try out their new discoveries and theories. The project laboratory also includes a screening room where simulations can be viewed in real time. Researchers watching the simulation can distinguish individual cell groups and watch as cascades of excitation patterns not unlike toppling dominoes surge through the tissue. They can simulate flying around in the cerebral cortex or watch in slow motion as millions of ion channels systematically open and close.

But the main purpose of the artificial brain, say its creators, is to make new types of experiments possible. For example, what happens when damage is inflicted on certain types of cells whose function still isn't determined? How many cells can be switched off until the behavior of the surviving cells around them becomes **erratic**, or the entire circuit breaks down? Scientists know that a similar process occurs in the brains of **epileptics** and **Alzheimer's** patients. Armed with current methods, which by their very nature are based on external observation, medical science has gained only a **schematic** picture of the processes in these patients' brains. Using Blue Brain, researchers would simply fly to the **crisis** zones inside a virtual skull.

Such studies are conceivable, though, only in a model that mirrors biology. The so-called neural networks that other researchers have developed for years are very different. A neural network is also meant to behave like a brain, somehow, but how the likeness is achieved -- the circuitry underneath -- is more or less irrelevant. Someone building a cow using this principle would be content with any milk machine that moos and produces the occasional **cowpat**.

"That doesn't help us to understand the biology," says Markram. The researchers in Lausanne are interested in the real cow: "Our first priority is that we never use tricks to achieve the correct result," says project manager Schürmann. "If something goes wrong in the simulation, our only option to improve it is by incorporating new biological knowledge."

One day the research could even open a door to real life for their artificial brain. This wouldn't present much of a technological challenge. "We could simply connect a robot to the brain model," says Markram. "Then we could see how it reacts to real environments." But Blue Brain will be given a taste of real life only after it has performed flawlessly in the laboratory. Until then its environment won't be very exciting -- nothing but an air-conditioned **mainframe** room, and standard stimuli derived from textbook data.

erratic: chaotic and disorganized

epileptics: people with a disease that causes them to have periodic seizures, or attacks of abnormal brain activity often accompanied by spasms and convulsions

Alzheimer's: a disease marked by the death and/or dysfunction of neurons, which causes extreme memory loss, confusion, and emotional imbalances; usually occurs in old age

schematic: a model that represents a system with simple symbols, ignoring much of the system's true complexity

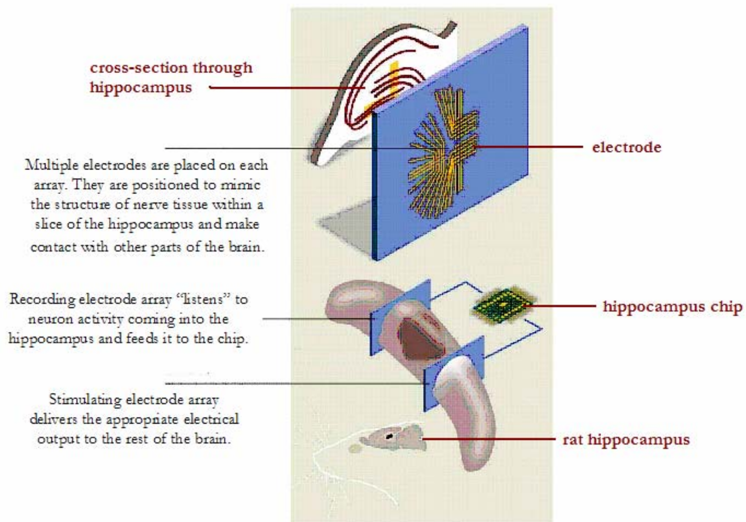
crisis: big problem; disaster

cowpat: a slang term for the fecal matter of a cow

mainframe: a large, often room-sized collection of processors used for performing several simultaneous tasks and storing a lot of data

WORKS IN PROGRESS: AN ARTIFICIAL HIPPOCAMPUS AND AN ARTIFICIAL OLIVOCEREBELLAR REGION

Kurzweil, R. 2005. *The Singularity is Near: When Humans Transcend Biology.* London: Penguin Books.



The artificial hippocampus currently in development at the University of Southern California uses silicon chips that communicate with the brain through electrodes to augment the function of biological neurons.
Credit: www.techpsychnet.net

The hippocampus is **vital** for learning new information and long-term storage of memories. Ted Berger and his colleagues at the University of Southern California mapped the signal patterns of this region by stimulating slices of rat **hippocampus** with electrical signals millions of times to determine which input produced a corresponding output. They then developed a real-time mathematical model of the **transformations** performed by layers of the hippocampus and programmed the model onto a chip. Their plan is to test the chip in animals by first disabling the corresponding hippocampus region, noting the resulting memory failure, and then determining whether that mental function can be restored by installing their hippocampal chip in place of the disabled region.

vital: very important; necessary

hippocampus: a region of the brain involved in the formation of new memories

transformation: the act of mathematically changing a particular input to an output. For example, rotating a triangle (input) by 90° and then reflecting it over the y-axis is an example of a transformation.

Ultimately, this approach could be used to replace the hippocampus in patients affected by strokes, epilepsy, or Alzheimer's disease. The chip would be located on a patient's skull, rather than inside the brain, and would communicate with the brain via two arrays of electrodes, placed on either side of the damaged hippocampal section. One would record the electrical activity coming from the rest of the brain, while the other would send the necessary instructions back to the brain.

Another brain region being modeled and **simulated** is the olivocerebellar region, which is responsible for balance and coordinating the movement of limbs. The goal of the international research group involved in this effort is to apply their artificial olivocerebellar circuit to military robots as well as to robots that could assist the disabled. One of their reasons for selecting this particular brain region was that "it's present in all **vertebrates**—it's very much the same from the most simple to the most complex brains," explains Rodolfo Llinas, one of the researchers and a neuroscientist at New York University Medical School. "The assumption is that it is conserved [in evolution] because it embodies a very intelligent solution. As the system is involved in motor coordination—and we want to have a machine that has sophisticated motor control—then the choice [of the circuit to mimic] was easy."

simulated: copied, mimicked

vertebrates: organisms with a backbone

One of the unique aspects of their simulator is that it uses **analog** circuits. Similar to Mead's pioneering work on analog emulation of brain regions, the researchers found substantially greater performance with far fewer components by using transistors in their native analog mode.

One of the team's researchers, Ferdinando Mussa-Ivaldi, a neuroscientist at Northwestern University, commented on the application of an artificial olivocerebellar circuit for the disabled: "Think of a paralyzed patient. It is possible to imagine that many ordinary tasks—such as getting a glass of water, dressing, undressing, transferring to a wheelchair—could be carried out by robotic assistants, thus providing the patient with more independence."

analog: referring to a system that can be in any of a continuously variable range of states. For example, the two hands of a clock, which can be position such that they are separated by any angle between 0 and 360, is an extremely simple analog system. This is the opposite of a digital system, which can be in one of only two discrete states. For example, a light, which is either "off" or "on," is a very simple digital system.

HIPPOCAMPAL-CORTICAL NEURAL PROSTHESES

Berger, T.W., A. Ahuja, S.H. Courellis, S.A. Deadwyler, G. Erinjippurath, G.A. Gerhardt, et al. 2005. ***IEEE Engineering in Medicine and Biology Magazine*** **24(5): 30-44.**

The following excerpt from a scientific review discusses methods used by Theodore Berger's research group at the University of Southern California to develop a computerized model of layer CA3 of the rat hippocampus that could interact with a network of living hippocampal neurons much like its biological counterpart. While, at the time of this article's publication, the device the authors describe had only been tested **in vitro***, versions developed for use in living organisms followed soon after.*

One of the frontiers in the biomedical sciences is the development of prostheses for the **central nervous system (CNS)** to replace higher thought processes that have been lost due to damage or disease. Prosthetic systems that interact with the CNS are currently being developed by several groups, though virtually all other CNS prostheses focus on sensory or motor system dysfunction and not on restoring cognitive loss resulting from damage to central brain regions. Systems designed to compensate for the loss of sensory input attempt to replace the **transduction** of physical energy from the environment into electrical stimulation of sensory nerve fibers (e.g., a cochlear implant or artificial retina) or the sensory cortex. Systems designed to compensate for the loss of motor control do so through functional electrical stimulation (FES), in which preprogrammed stimulation protocols are used to activate muscular movement, or by **decoding** premotor/motor cortical commands for the control of robotic systems. The type of neural prosthesis that performs or assists a cognitive function is qualitatively different from the cochlear implant, artificial retina, or FES. We consider here a prosthetic device that functions in a **biomimetic** manner to replace information transmission between cortical brain regions. In such a prosthesis, damaged CNS neurons would be replaced with a biomimetic system comprised of silicon neurons. The replacement silicon neurons would have functional properties specific to those of the damaged neurons and would both receive as inputs and send as outputs electrical activity to regions of the brain with which the damaged region previously communicated. Thus, the class of prosthesis being proposed is one that would replace the computational function of the damaged brain and restore the transmission of that computational result to other regions of the nervous system. Such a new generation of neural prostheses would have a profound impact on the quality of life throughout society; it would offer a biomedical remedy for the cognitive and memory loss accompanying Alzheimer's disease, the speech and language deficits resulting from stroke, and the impaired ability to execute skilled movements following **trauma** to brain regions responsible for motor control.

The Hippocampal System: Basis for Long-Term Declarative Memory

We are in the process of developing such a cognitive prosthesis for the hippocampus, a region of the brain involved in the formation of new long-term memories. The hippocampus is responsible for what have been termed long-term declarative or recognition memories: the formation of **mnemonic** labels that identify a unifying collection of features (e.g., those comprising a person's face) and form relations between multiple collections of features (e.g., associating the visual features of a face with the auditory features of the name for that face). It is the degeneration and malformation of hippocampal neurons that is the underlying cause of the memory disorders associated with Alzheimer's disease. Similarly, hippocampal **pyramidal cells**, particularly those in region CA1, are highly susceptible to even brief periods of **anoxia**, such as those that accompany **stroke**. Even blunt head trauma has been shown to be associated with a preferential loss of hippocampal neurons in the **hilus of the dentate gyrus**. Finally, there is a long history of association between hippocampal dysfunction (particularly in region CA3)

in vitro: a Latin term meaning "in glass"; refers to experiments that have been done in a controlled environment outside a living organism (e.g., in a test tube)

central nervous system (CNS): the brain and spinal cord; as opposed to the peripheral nervous system, or the network of neurons found in limbs and organs outside the brain and spinal cord

transduction: the translation of one type of signal into another. For example, sound waves undergo transduction into electrical impulses when they hit the cochlea of the ear.

decoding: unscrambling, extracting meaning from

biomimetic: mimicking or copying biological systems

trauma: injury from a forceful blow

mnemonic: assisting the memory

pyramidal cell: a type of neuron found in the cerebral cortex whose pattern of dendrites (cellular protrusions that receive input from other neurons) give it a pyramidal shape

anoxia: oxygen deprivation, often resulting in cell damage and death

stroke: a loss of blood supply to the brain that causes temporary loss of consciousness and/or localized brain damage

hilus of the dentate gyrus: also called region CA4; the brain region that sends information to the hippocampus from the entorhinal cortex and **epileptiform activity**. Thus, there is a wide array of neural damage and neurodegenerative disease conditions for which a hippocampal prosthesis would be clinically relevant. The hippocampus comprises several different subsystems that form a **closed feedback loop**; input from the neocortex enters via the **entorhinal cortex,** propagates through the intrinsic subregions of hippocampus, and then returns to the **neocortex**. The intrinsic pathways consist of a cascade of excitatory connections organized roughly **transverse** to the **longitudinal axis** of the hippocampus. As such, the hippocampus can be conceived of as a set of interconnected, parallel circuits. The significance of this organizational feature is that, after removing the hippocampus from the brain, transverse slices (400 μm thick) of the structure may be maintained in vitro that preserve a substantial portion of the intrinsic circuitry.

Proof-of-Concept: Replacement of the CA3 Region of the Hippocampal Slice with a Biomimetic Device

We have developed a multistage plan for achieving a neural prosthesis for the hippocampus. The first stage involves a proof of concept in which we develop a replacement biomimetic model of the CA3 subregion of hippocampal in vitro slice. We have chosen to realize our first-generation prosthesis in the context of a hippocampal slice for several reasons. Among these is that the 400-**μm** thickness of the slice allows us, essentially, to reduce the problems of modeling the three-dimensional (3-D) function of the hippocampus and of interfacing with its complex, 3-D structure to a more tractable two-dimensions. This allows us to develop the initial stages of experimental strategies, modeling methodologies, hardware designs, and interfacing technologies within the context of a more simplified and controlled set of conditions.

Experimental Characterization and Mathematical Modeling of the Nonlinear Dynamic Properties of the Hippocampal CA3 Region

Our strategy for achieving a hippocampal neural prosthesis is based on several system requirements for replacing any CNS region with a biomimetic device that interacts bidirectionally with the rest of the undamaged brain (i.e., sensing and communicating input to the biomimetic device from **afferents** of the damaged region and communicating and electrically stimulating outputs from the biomimetic device to **efferents** of the damaged region). The most important component is the nature of the biomimetic model that constitutes the core of the prosthetic system. Information in the hippocampus and all other parts of the brain is coded in terms of variation in the sequence of **all-or-none**, **point-process** (spike) events, or **temporal pattern** (for multiple neurons, variation in the **spatio-temporal pattern**). The essential signal processing capability of a neuron is derived from its capacity to change an input sequence of **interspike intervals** into a different output sequence of interspike intervals. In all brain areas, the resulting input/output transformations are strongly **nonlinear** because of the nonlinear dynamics inherent in the cellular/molecular mechanisms comprising neurons and their **synaptic** connections. Consequently, the output of virtually all neurons in the brain is highly dependent on temporal properties of the input. Thus, identifying the nonlinear input/output (I/O) properties of hippocampal neurons and the composite I/O transformations of hippocampal circuitry is the fundamental functionality that must be captured by any mathematical model designed to replace damaged hippocampal tissue. Attempting to accomplish this modeling goal with compartmental neuron models based on **cable theory** is simply not feasible.

The number of parameters required to represent complex **dendritic** structures and the number and variety of **ligand-** and voltage-dependent conductances common to hippocampal neurons is simply too large to include in a multineuron network model that is sufficiently compact for a microchip or even a multichip module. Although simplifications of compartmental neuron models are an

epileptiform activity: uncontrolled electrical activity in the brain; often associated with seizures

closed feedback loop: a system that operates under closed-loop control, in which output is controlled by strategic changes in input. If one tries to ride a bike at constant speed (output) by using energy at a rate that counteracts environmental factors that change it (input) (pedaling more quickly when moving uphill, pedaling more slowly when moving downhill), one is subjecting her or his bicycle to closed-loop control.

entorhinal cortex: a part of the cerebral cortex that provides a great deal of input to the hippocampus

neocortex: the upper- and frontal-most region of the cerebral cortex; responsible for higher-order cognition like planning complex behaviors

transverse: perpendicular to

longitudinal axis: an imaginary line drawn along the longest side of a structure

μm: micrometer; one 10^{-6} of a meter

afferents: connections that run from the environment into the system

efferents: connections that run from the system out to the environment

all-or-none: if input reaches a threshold value, an output is yielded; if not, no output is yielded (no in-between)

point-process: a phenomenon that can be modeled as discrete events occuring at particular points in time

temporal pattern: patterns in time (when neurons fire)

spatio-temporal pattern: patterns in space (what neurons fire) and time (when neurons fire)

interspike intervals: the time between neural firing events

nonlinear: unable to be modeled by an equation of a form Ax+By=C (or any of its higher-dimensional variants)

synaptic: relating to the connections between neurons across which information is sent by neurotransmitters, or chemicals released by neurons to change the electrical potentials of other neurons with which they form synapses

cable theory: a model that treats neurons as a system in which charge passively diffuses through and out of the neural membrane according to Ohm's Law and its derivatives

dendritic: relating to dendrites, or protrusions on one end of a neuron that receive input from other neurons

ligand-: a molecule that attaches to another molecule, usually a receptor in the membrane of a neuron option, the trade-offs between the complexity of the model and representation of neuron and network dynamics are not yet fully understood. For this reason, we are using a nonlinear systems analytic approach to modeling hippocampal neurons. In this approach, neurons and circuits or networks to be modeled are first characterized experimentally using a broad-band stimulus, e.g., a series of impulses (typically 1,000–2,000 total) in which the interimpulse intervals vary according to a random (**Poisson**) process. Because the distribution of interimpulse intervals is exponential, the mean frequency can remain relatively low (2 Hz), and thus be **physiological**, yet the range of intervals can be wide (10–5,000 ms). Such a stimulation protocol ensures that the majority, if not all, of synaptic and cellular mechanisms are activated, and as a consequence, contribute to neuron, circuit, or network output which is measured (e.g., electrophysiologically). The modeling effort, identified as the Volterra-Poisson modeling approach, then becomes focused on estimating linear and nonlinear components of the mapping of the known input to the experimentally measured output. The Volterra modeling approach is a mathematically rigorous, **scalable** method that can be applied to biological systems. The nonlinear dynamic I/O characteristics of the modeled system are quantitatively captured by the Volterra kernels. Volterra kernels are system descriptors that remain invariant with respect to the type or the power of the stimulus. Given accurate estimation methods, the result is a compact (many fewer terms than a compartmental neuron network model) and predictive (for virtually any temporal pattern) model that incorporates at least the majority of known and unknown biological mechanisms (thus, not requiring modification and optimization for each new discovery in the future).

Poisson: a statistical model used to predict the probability that a certain numbers of discrete events will occur at the same time

physiological: here, possible in a living system

scalable: able to be applied to increasingly large systems

Extension to the Hippocampus of the Behaving Animal

The research described here represents the first step in developing a neural prosthesis for the hippocampus of a behaving animal, and ultimately of the human, to restore memory function after damage. In animals (and humans) performing learned behaviors, memory-related information is coded in a distributed manner among a population (or ensemble) of neurons, each subpopulation firing at different times and with different patterns in relation to environmental and behavioral cues. Thus, extending the approach described here to the behaving animal will require

- multiple input-multiple output models to represent the nonlinear dynamics of each of the different subpopulations of the ensemble
- a more complex **VLSI** device design (perhaps involving a multichip module) to implement the multiple input-multiple output model
- vertically oriented, **conformal,** multisite electrode arrays capable of penetrating into the hippocampus from the surface of the brain to record/stimulate target regions
- development and application of packaging technologies to integrate VLSI and electrode sensing/actuating functions
- surface patterning of novel chemistries to increase biocompatibility of microfabricated materials/ devices.

VLSI: "Very Large-Scale Integration"; refers to the process of making computing devices by integrating many transistors on a single chip

conformal: pertaining to a map in which the relative angles and sizes among the various components are preserved

Progress on these critical fronts is currently proceeding. Extending the biomimetic cortical prosthesis approach demonstrated here to the behaving animal/human also will require dealing with issues that we have yet to address, namely, **context-dependence** of hippocampal nonlinearities, i.e., the influence of stress, **diurnal cycles**, and learning-related alterations of hippocampal nonlinearities. An additional challenge will be accounting for the well-established reactivity of the hippocampal circuitry to damage and injury. Incorporating these physiological factors will require significant elaborations of the current model, the means for alteration of model parameters as a function of environmental setting and experience as well as the possibility of dynamic reconfiguration of the spatial distribution of multisite electrode array elements.

context-dependence: referring to the changes that occur in a system as a result of its environment

diurnal cycles: any number of cyclical hormonal and/or behavioral changes that occur with a period of roughly 24 hours