

A Comparison of Human and Computer Information Processing¹

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Abstract

Like a computer, the human brain inputs, processes, stores and outputs information. Yet the brain has evolved along different design principles from those behind the Von Neumann computer architecture which most computers still follow today. A comparison of human and computer information processing suggests basic differences in: Control (Central vs. Distributed), Input (Sequential vs. Parallel), Output (Exclusive vs. Overlaid), Storage (by Address vs. by Connection), Initiation (Input driven vs. Process driven) and Self Processing (Low vs. High). Implications of these differences for computer and computer-human interaction CHI design are discussed.

Introduction

Over thirty years ago, TV shows from *The Jetsons* to *Star Trek* suggested that by the millennium's end computers would read, talk, recognize, walk, converse, think and maybe even feel. People do these things easily, so how hard could it be? However in general we still don't talk to our computers, cars or houses, and they still don't talk to us. The Roomba, a successful household robot, is a functional flat round machine that neither talks to nor recognizes its owner. Its "smart" programming tries mainly to stop it getting "stuck", which it still frequently does, either by getting jammed somewhere or tangling in things like carpet tassels. The idea that computers are incredibly clever is changing, as when computers enter human specialties like conversation, many people find them more stupid than smart, as any "conversation" with a computer help can illustrate.

Computers do easily calculation tasks that people find hard, but the opposite also applies, e.g. people quickly recognize familiar faces but computers still cannot recognize known terrorist faces at airport check-ins. Apparently minor variations, like lighting, facial angle or expression, accessories like glasses or hat, upset them. Figure 1 shows a Letraset page, which any small child would easily recognize as letter "A"s, but computers find this extremely difficult. People find such visual tasks easy, so few in artificial intelligence (AI) appreciated the difficulties of computer-vision at first. Initial advances were rapid, but AI has struck a 99% barrier, e.g. computer voice recognition is 99% accurate but one error per 100 words is unacceptable. There are no computer controlled "auto-drive" cars because 99% accuracy means an accident every month or so, which is also unacceptable. In contrast, the "mean time between accidents" of competent human drivers is years not months, and good drivers go 10+ years without accidents. Other problems easy for most people but hard for computers are language translation, speech recognition, problem solving, social interaction and spatial coordination.

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Figure 1. Letraset page for letter ‘A’

Advanced computers struggle with skills most five-year olds have already mastered, like speaking, reading, conversing, and running:

“As yet, no computer-controlled robot could begin to compete with even a young child in performing some of the simplest of everyday activities: such as recognizing that a colored crayon lying on the floor at the other end of the room is what is needed to complete a drawing, walking across to collect that crayon, and then putting it to use. For that matter, even the capabilities of an ant, in performing its everyday activities, would far surpass what can be achieved by the most sophisticated of today’s computer control systems.” (Penrose, 1994, p45).

That computers cannot even today compete with an ant, with its minute sliver of a brain, is surprising. We suggest this is from processing design not processing incapacity. Computer pixel-by-pixel processing has not lead to face recognition because, as David Marr (Marr, 1982) observed, trying to understand perception by studying neuronal (pixel level) choices is *“like trying to understand bird flight by studying only feathers. It just cannot be done.”* Processing power alone is insufficient for real world problems (Copeland, 1993), e.g. processing power alone cannot deduce a three-dimensional world from two-dimensional retina data, as the brain does.

Enthusiastic claims that computers are overtaking people in processing power (Kurzweil, 1999) repeat the mistake AI made forty years ago, of underestimating life’s complexity. If computers still struggle with five year old skills, what about what children learn after five, while “growing up”? The Robot World Cup aims to transform current clumsy robot shuffles into soccer brilliance by 2050 (<http://www.robocup.org>). If computing is going in the wrong direction the question is not whether 50 years will suffice, but whether a thousand years will. In contrast we suggest that:

1. For computers to do what people do requires a different type processing.
2. Computers that work with people can combine the strengths of both.

Background

Brains can be compared to computers as information processors, since:

1. Neurons are on/off devices that can represent digital information.
2. The neuron threshold effect allows logic gates (McCulloch & Pitts, 1943)

3. The brain has input/output channels (the senses) as a computer does.
4. The brain works by electricity as computers do.
5. As a computer has many transistors so the brain has many neurons (about 10^{10} , more than there are people in the world)

We contrast how computers process with how the brain processes the senses to combine their strengths, not to decide which is “better”. This has implications for:

1. **Computer Design** - *to improve computer design*. While computer systems evolved over about 60 years, the brain has evolved over millions of years, and was rigorously beta tested over many lives. It probably embodies useful design principles.
2. **Computer-human interaction (CHI) Design** - *to improve interface design*. Computer success often depends on it human interaction, and knowing how people process information can improve this.

Computer vs. Human information processing

We use a systems theory approach (Bertalanffy, 1968) to contrast computer and human information processing. A processing system, whether computer or brain, is presumed composed of processors, whether computer or cognitive, that receive input from sensors or ports, and send output to effectors or peripherals. The following discussion applies whether the system is physical (hardware) or informational (software).

Von Neumann computers

While the brain’s design is relatively consistent between people due to genetics, a computer’s design is whatever its designers choose it to be. In the following, “the computer” refers to computers whose design derives directly from Von Neumann’s original architecture, which encompasses the vast majority of computers in use today. In his original design, Von Neumann made certain assumptions to ensure valid processing:

1. **Control: Centralized**. Processing is directed from a central processing unit (CPU).
2. **Input: Sequential**. Input channels are processed in sequence.
3. **Output: Exclusive**. Output resources are locked for single use.
4. **Storage: Location based**. Information is accessed by memory address.
5. **Initiation: Input driven**. Processing is initiated by input.
6. **Self-processing: Minimal**. System does not monitor or change itself.

Each of the above is not a yes/no dichotomy but a proposed continuum, with computer and brain at opposite ends, e.g. a computer’s “parallel port” has more bit lines than its “serial port”, but both are far removed from the massively parallel signals carried by millions of optic nerve fibers in the human brain. While modern computers have dual-core chips and multi-channel processing, this decentralization is relatively little compared to the brain. The above generic differences between human and computer processing are in degree, rather than black and white distinctions, but they are still major differences.

1. Control

Centralized control means all processing ultimately originates from and returns to a central processing unit (CPU), even if that unit delegates work to sub-processors. Computers have a CPU for *control* reasons, so the computer always knows exactly where, in processing terms, it is up to. However a disadvantage is that if the central unit fails, the whole system fails. On a hardware level, if the CPU stops so does the computer. On a software level, if the operating system enters an infinite processing loop, the whole system “hangs”. Asking a room of people if their computer hung this week usually gives a good show of hands, especially for Windows users, but asking people if their brain permanently “hung” in an infinite neural loop this week is almost a non-question. The repetitive rocking of autism may involve neural loops cycling endlessly in parts of the brain, but such cases are infrequent. While the brain’s “operating system” can work over seventy years, Windows gets “old” after 2-3 years and must be reinstalled.

The brain, unlike the computer, does not have a clear “CPU”. In its neural hierarchy lower sub-systems report to higher ones, but the hierarchy top, the cortex, is divided into two hemispheres. The highest level of brain processing is in two parts, that divide up the work between them, e.g. each hemisphere receives only half the visual field, with the left half from both eyes going only to the right hemisphere, which also mainly controls the left body side. Each hemisphere replicates its data to the other using the corpus callosum, a massive 800 million nerve fiber bridge, so both hemispheres “see” the entire visual field. Studies of “split-brain” patients, whose corpus callosum was surgically cut, suggest that each hemisphere can independently process input and create output, i.e. each hemisphere acts like an autonomous “brain” (Sperry & Gazzaniga, 1967). The sub-systems within a hemisphere seem also to have autonomy, as do other systems like the cerebellum (psychomotor control) and mid-brain (emotions). Unlike the computer, the brain has no single central control point, but *distributes control among autonomous sub-systems*.

A computer design implication is *to create systems that share control on demand among autonomous sub-systems*. Local area networks illustrate the trend, and CSMA/CD (Ethernet) “on-demand” networks have largely replaced centralized polling networks. Object orientated programming also illustrates shared control, as program sub-units exchange messages and take control as required, so there is no code “mainline”. The World Wide Web is a network without central control, something almost unthinkable twenty years ago.

A CHI implication is *to design computer-human interactions to manage the user attention flow*. If the brain is a loose collection of autonomous sub-systems, in this “Society of Mind” (Minsky, 1986) attention may operate like a market place, where attention’s focus goes to the sub-system with the strongest neural potentials. In *concentration* higher sub-systems exert top-down control to direct lower ones to some focus, while in *distraction* lower sub-systems exert bottom-up control to engage higher ones to attend to some peripheral input. Which is good or bad depends on the situation, e.g. a colorful “New” graphic at the start of a text sentence directs the user to begin reading it, but a flashing graphic at the end of a sentence makes it difficult to read, as one is continuously distracted to the flashing at the end.

2. Input

Sequential processing carries out many instructions one after another rather than processing them simultaneously (in parallel). While computers use pipelining and hyper-threading, computer

processing is mostly sequential due to cable and port bandwidth limits. While supercomputers use some parallel processing, each cell of the human retina has already begun to process boundary information before signals leave the eye.

The serial/parallel difference explains how people can recognize sentences in 1/10th second, faster than most computers, although a neuron event is a million-times slower than computer event. The 1/1,000 second neuron refractory period, a brain hardware property, allows for only 100 sequential steps in this time. No computer code can do human pattern recognition in 100 lines. The brain's slow components can give a fast response using parallel processing, e.g. suppose Ali Baba is hiding inside one of forty jars. The sequential way to find him is for a fast slave to check jar 1, jar 2, etc. The parallel way is for 40 slow slaves to each check their jar independently, when:

“It is odds on that a machine - or organ - with sluggishly functioning components and a parallel mode of operation would be able to thrash a computer with high speed components but a sequential mode of operation” (Copeland, 1993)

While the brain pre-processes visual input in parallel at the retinal level, computers scan screen pixels in sequence, and printers print pixels in sequence. *The alternative to sequential processing is parallel processing.*

One computer design implication is *to increase processing power by operating in parallel.* Parallel super-computer arrays illustrate the power of this approach, as does the SETI (Search for Extraterrestrial Intelligence) program where computers from around the world parallel process signals from space.

An CHI implication is *to design computer-human interactions to engage many input channels at once, i.e. multi-media interfaces.* Since people process senses in parallel, computers should provide the same. Multi-media web sites don't increase information overload, e.g. a web site without depth cues merely leaves human visual depth processors with nothing to do, which reduces the user experience. Adding a parchment background to a screen seems to need more processing, but users have dedicated visual processors for background textures. Adding depth, color, texture, sound or movement to web sites gives interface designers something for nothing, as these are “always on” human processing channels. Many prefer Netscape's big icons plus text buttons to Microsoft's icons only buttons because the brain processes graphics and text in parallel. Here “multi-media” means using both graphics and text, although both are channels within the same visual medium. Likewise color, shape, orientation, movement, texture and depth invoke different brain processes though all are the visual medium. The concept of *multi-media can be extended to mean multi-processor*, where a multi-media interface engages many neural processes.

3. Output

Exclusive output processing “locks” output for sole access, e.g. two documents sent from different computers to a network printer at the same time come out one after the other, not interleaved, as each gets exclusive access. Databases also use exclusive control to avoid the deadly embrace of a double lock. In the computer, one function works at a time, so a software update will overwrite the previous version.

However in the brain, new systems *overlay* rather than replace older ones, e.g. primitive brain stem responses still operate in adults as reflexes. Keeping older but simpler systems has two advantages:

- a. *Older systems are more reliable*, and can take over if higher systems fail, e.g. brain damage.
- b. *Older systems are faster*, and a fast-simple response can be better than a slow-complex one, e.g. touching a hot stove gives a reflex pull back.

The alternative to exclusive output control is overlaid output control (Figure 2), where newer sub-systems inhibit older ones, but older ones can act before the new ones can stop them.

An implication for computer design is *to overlay rather than replace when updating*. A Windows computer is somewhat layered like this, as a Word failure usually drops the user into Windows, and Windows can revert to DOS if one reboots via the recovery console. However Microsoft has tried to replace DOS, rather than seeing it as a useful fallback. If Word used this principle, a Word crash would drop users into a kernel like WordPad that would still let the user save the current document in rich text form.

An CHI implication is *to design for both primitive (fast) and sophisticated (slow) user responses*, occurring on a time gradient, e.g. users may decide to stay at a web site or not within a second based on its “feel”, but take longer to decide if an interface understandable. Designers must satisfy immediate demands like border contrast as well as more considered responses. An interface that fails the quick analysis may not even get to the considered assessment.

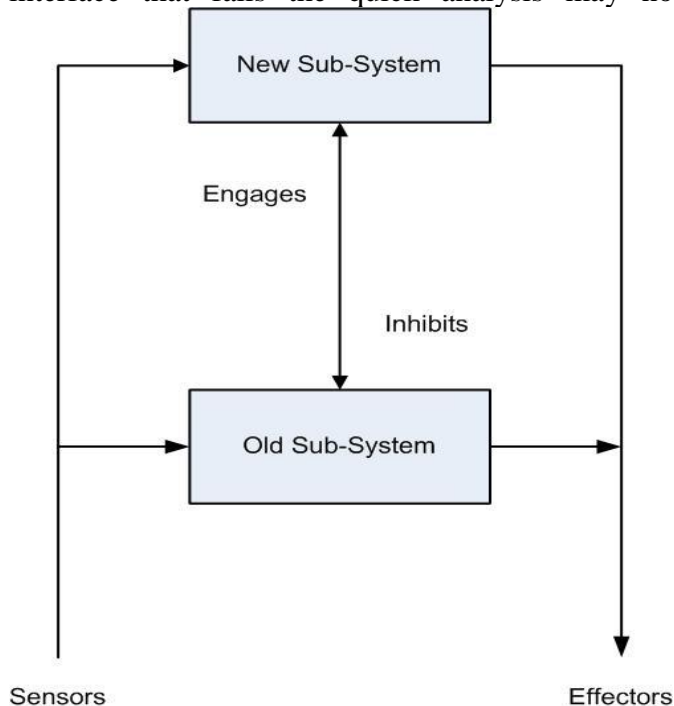


Figure 2. Overlaid sub-systems in the brain

4. Storage

Location based storage stores and recalls information by numbered memory locations, e.g. a disk's side, track and sector. While such systems can duplicate data by duplicating storage (e.g. RAID 0), this is costly, so one computer "fact" is usually stored in one place, giving the restriction that damaging that location destroys the data held there. Since storage capacity depends linearly on the number of locations, such systems can report "memory full".

In contrast the brain never seems to report a "memory full" error, even after a lifetime's experience. If human memory operated like an information data warehouse it should have a clear maximum capacity. Also, if the brain were like a filing cabinet specific brain damage should destroy specific information. Lashley explored this hypothesis in his well known "search for the engram." (Lashley, 1929). He taught rats to run a maze, then surgically removed different cortical areas in each rat, to find the part holding the maze running memory. He found that removing *any* 10% of cortex had almost no effect, and after that, maze running degraded gradually, i.e. the amount of brain removed was more important than its location. The conclusion of 33 years of ablation studies was that there are no particular brain cells for particular memories.

While modern studies show memory is not entirely equi-potential, it is clear that one memory is not stored in only one place, i.e. brains don't store memories as computers do. That electrodes stimulating certain brain cells evoke particular memories does not mean they are stored at that location, only that they can be activated from there. Studies suggest that one memory involves many neurons, with perhaps 1,000 to 1,000,000+ neurons per memory. Equally one neuron is involved many memories rather than just dedicated to one. Somehow memory is stored in the neural interconnections, which increase as the square of neuron number. As each neuron connects to 1,000 - 10,000 others, this gives over 100,000,000,000,000 interconnections, ample capacity to store a lifetime's data.

The alternative to storage by location is storing information in unit interconnections, e.g. the following "searches":

- What did you eat last night?
- When did you last have fish?
- Have you been to Northcote?
- Do you know John Davis?

and thousands of others, could all link to a single memory.

A computer design implication is *memory that stores data as unit interconnections* rather than as static unit values. Neural networks illustrate this approach, as their "memory" is in the network interaction weights, that can repeat an output from a linked input. One advantage is greater capacity, i.e. no "disk full" messages. Another is that every stored datum is in effect "indexed" on every data attribute, though such flexible access is less reliable. While "teaching" a neural network a fact takes longer than a memory "save", one trained neural network can train others, as people train each other.

A CHI *implication* is to design computer-human interactions to access information by associations, e.g. hypertext links let people recall things by connecting from one thing to the next, linking any word in a document to any other document, or to a part of the same document. Hypertext succeeds because it works as human memory works.

5. Initiation

Input driven processing means that input initiates the processing which generates the output, i.e. given a program, a computer system's output is determined by its input. Software analysis methods like Jackson Structured Programming use this property to derive program code from



Figure 3. Linear Input/Process/Output (IPO)

input and output specifications.

If people worked this way, the mind would turn sensory input into behaviour as a mill turns flour into wheat, i.e. mechanically. Just as without wheat there is no flour, so without sensations there should be no mental processing. Yet people start to hallucinate after a few days in sensory deprivation studies, i.e. the brain can create perceptions. Also while computers without input usually fall “idle”, people without input go looking for it. In the brain, while signals go from the retina to the visual cortex via the lateral geniculate body (LGB) relay station, even more nerves go *from* the visual cortex *to* the LGB, i.e. in the opposite direction. The brain is clearly not merely an input processor.

The linear relation in Figure 3's is actually an Input-Process-Output (IPO) feedback loop, modified by life, as a system's output affects its consequent input, e.g. turning one's head affects what one sees. This gives the circular feedback system of Figure 4, which while in theory still deterministic, is chaotic, i.e. tiny initial differences can produce vastly different end results (Lorenz, 1963).

Psychology theory has two approaches to human sensory input:

- a. *Objectivist*. Behaviorists like Watson, Hull, and Skinner claim an objective world creates sensations, which if analyzed correctly reflect a defined external reality.
- b. *Constructivist*. Others like Piaget and Chomsky suggest people construct rather than derive the “world”, and interpret sensations to see *a* world not *the* world (Maturana & Varela, 1998).

The objectivist view is represented by Figure 4, where the system's input stimulus contingencies define its response (Skinner, 1948). However Chomsky showed it was not mathematically possible for children to learn the profundity of language in a lifetime of stimulus-response chaining, let alone years (Chomsky, 2006). The alternative constructivist view is shown in Figure 5. Logically a circular interaction can be initiated from any point, so an input-process-output (IPO) loop (Figure 4) can be represented as a *process-output-input (POI)* loop (Figure 5). In such feed-forward cybernetic loops (Mayr, 1970) output acts before input, and it is interesting that in babies motor neurons develop before sensory ones, and embryos move before sensory cells are connected, i.e. output seems to precede input in phylogeny.

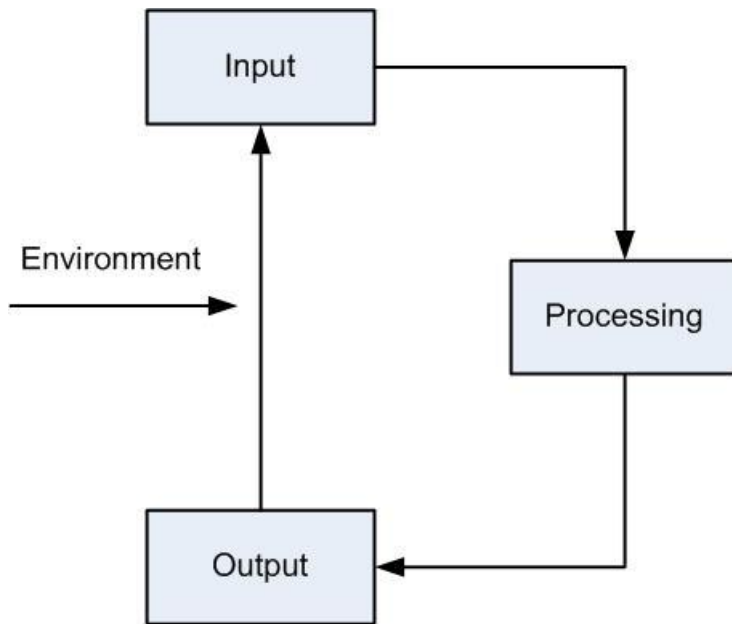


Figure 4. An Input/Process/Output (IPO) partial feedback loop

We know that simple cybernetic systems can achieve steady states similar to biology’s homeostasis, and a home heating system’s steady end state derives from the temperature its thermostat processing defines. Since in a process-driven (POI) system the temperature is defined first, processing can determine the system’s final end-state, i.e. act as a teleological “goal”. Purpose can arise when processing initiates interactions.

Feed-forward loops can also generate *expectation contexts* for future input. Context effects are common in language, as word meaning creates sentence meaning and sentence meaning alters word meaning. As Gestalt psychologists noted, the whole affects the parts that create it, e.g. “Hit me” in a Blackjack card game vs. “Hit me” in a boxing match. While people frequently define new contexts, computer systems are heavily context dependent, e.g. the fixed response categories of computer help (Press 1 for ...).

The general alternative to an input driven system is a *process-driven system* that actively initiates the interaction loop with expectations, hypotheses and goals.

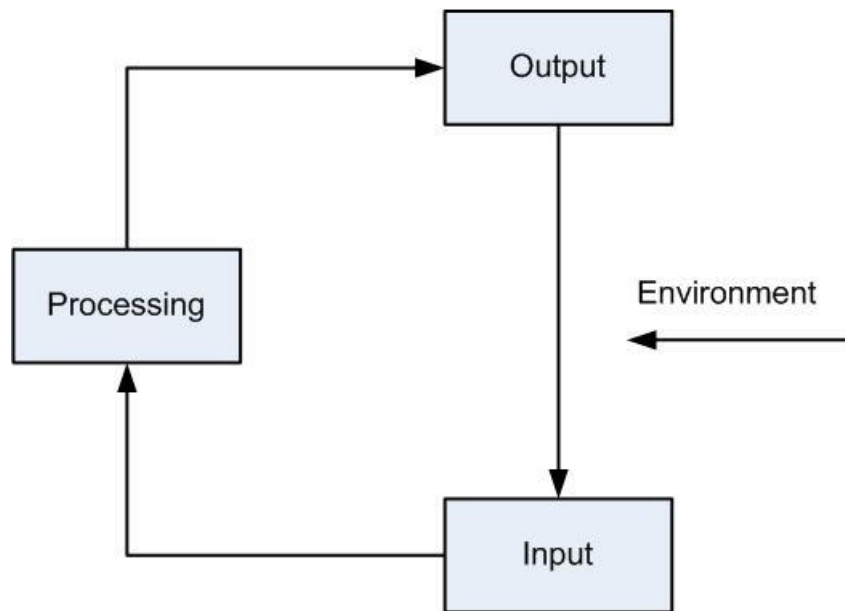


Figure 5. A Process/Output/Input (POI) partial feedback loop

A computer implication is *to develop active feed-forward loops that enable purposes and expectations*, e.g. web-bots that trawl the Internet with a purpose.

A CHI implication is *to design for user driven feedback loops*. Even given a multi-media visual feast, people become bored when passive. Interactive web sites are more interesting because we act on them and feel we are in charge (Langer, 1975). To some the Back button was the greatest software invention of the last decade, as it returned interaction control to the user. Students who struggle to spend an hour passively “inputting” textbook data, can easily spend 4 hours/night battling imaginary enemies i.e. playing a game. If actively driving a feedback loop is naturally rewarding, why not apply this principle to software other than computer games?

6. Self-processing

Self processing means a system can process its own processing, i.e. “itself”. This is not one part of a system processing as input another part’s output, which is common. If a system’s processing is a feedback loop, processing that processing means processing the entire loop. A system that cannot do this is unaware of its own interactions, although it may be “clever”, e.g. Mr. Clippy, Office ‘97’s assistant, was a paper clip figure who asked ‘Do you want to write a letter?’ any time you wrote the word ‘Dear’. Using advanced Bayesian logic, he was touted as the future of “smart help”, yet a PC Magazine survey found Mr. Clippy the third biggest software flop of the year (PCMagazine, 2001). While Mr. Clippy analyzed *your* document actions, he had no idea at all of *his* actions. Even if told a thousand times to go away, he happily popped up again offering to “help”. People expect “smart” software to be smart enough to recognize rejection. Mr. Clippy, like most “intelligent” software today, was unable to process itself.

In contrast people create an “ego”, or idea of themselves, which self-concept strongly affects their behavior. While computers do not have an “I”, or give themselves names, most people do. Yet is not a “self” processing itself, like a finger pointing to itself, impossible? Parts of the brain

like the frontal cortex, perhaps using autonomy and interconnections, seem able to observe the rest in action sufficiently to not only form a concept of self, but also use it in interpersonal relationships. Social Identity Theory goes further to suggest that groups only arise when individuals use a group's "identity" to form their self identity (Hogg, 1990). The group normative behavior that makes groups cohere can be linked to this concept of self (Whitworth, Gallupe, & McQueen, 2001), i.e. human social development may connect to our ability to self-process.

The alternative to processing external data is to process one's own processing, to allow levels of self-awareness, ideas like "self", and self-change. While computers rarely change their own code, and an operating system that overwrites itself is considered faulty, people have goals like: "To be less selfish" that imply changing their own neural "programming". Such learning is not just "inputting" knowledge as a database inputs data, but a system changing itself.

A computer design implication is *software that recognizes common good goals* as well as individual goals. Without this an Internet flooded by selfish web-crawlers could suffer the technology equivalent of the tragedy of the commons (Hardin, 1968).

A CHI implication is *to design applications to be polite*, rather than the rudeness illustrated by spam, pop-up windows and updates that change a user's home page and file associations without asking (Whitworth, 2005).

Summary

In general, the brain's design contrasts with that of most computers as follows:

1. *Control*: Decentralized at all levels, to maximize flexibility.
2. *Input*: Uses massively parallel processing, to maximize processing power.
3. *Output*: Overlays primitive and advanced sub-systems, giving the benefits of both.
4. *Storage*: Uses interconnectivity to store a lifetime's data.
5. *Initiation*: Allows process driven interaction, to hypothesize and predict life.
6. *Self-processing*: Has developed concepts of self and group, to allow social activity.

While the differences are not absolute and advanced computer designs change rapidly, the overall difference is marked.

Future trends

The above admittedly initial analysis suggests some possible areas where computers will work more like the brain in the future:

1. *Autonomous computing*: How simple rules can create emergent systems.
2. *Massively parallel computing*: How to use parallel processing effectively.
3. *Overlaid computing*: How to combine simple and complex systems.
4. *Neural net computing*: Systems that use the power of interconnections.
5. *Process-driven computing*: Systems with goals and expectations.
6. *Self-aware computing*: Systems that can reflect and learn.

As computers develop human information processing strengths, will they also gain their weaknesses, like Marvin the permanently depressed robot in the “Hitchhikers Guide to the Galaxy”?

If so, the future of computers may lie not in replacing people but in becoming more human compatible. This changes the research goal from making computers better than people to making the human-computer interaction (HCI) better than either people or computers alone. Interfaces that work how people work are better accepted, more effective and easier to learn. The runaway IT successes of the last decade (like cell-phones, the Internet, e-mail, chat, bulletin boards etc) all use computers to support rather than supplant human activity. The general principle is to base IS design on human design, i.e. to derive computer primitives from psychological ones. Multi-media systems illustrate the approach, as it works by matching the many human senses. In contrast, projects to develop clever stand-alone computer systems, like the Sony dog, have had limited success. Perhaps if the Sony dog was less smart but had cuddly fur and puppy dog eyes it would be more of a hit. Again, the above initial comparison of brain and computer design suggests possible areas for CHI advances:

1. *Attention flow management*: Where does the user look next?
2. *Multi-level user involvement*: What human neural processes are evoked?
3. *Immediate user engagement*: What are the “first impressions”?
4. *Link management*: How are the links interconnected?
5. *User feedback*: Does the system respond appropriately to user actions?
6. *Socially aware software*: Do application agents interact politely?

While traditional design has tools like entity-relationship diagrams, human-computer interaction currently lacks the equivalent tools to describe design.

Conclusions

Current computers by and large still represent their original deterministic design. They tend to centralize rather than distribute control, use faster sequential processing rather than parallel processing, use exclusive rather than overlaid functionality, minimize sub-system “coupling” rather than use interconnections, use input rather than process-driven loops, and to ignore self-processing of the “I”. However while avoiding recursive self-reference avoids dangerous infinite loops, it also misses opportunities. That recursive programs create fractal designs that look like snowflakes, plants and animals suggests that nature uses such dangerous information processing tactics. Perhaps it has already tried the “pure processing power” approach we now use in computing and found it wanting, e.g. autistic savants can deduce 20-digit prime numbers in their heads yet need continuous care to survive, as the movie “Rain Man” illustrates. Most computers today seem like this. Nature’s solution to the information processing problem is the brain, an electro-magnetic information processor which is unpredictable but not random, complex but not slow, adaptable but not unreliable, structured but not unchangeable, receptive but not input defined, and not only responds to potentially infinite variability in real time, but can also conceive of itself and form social groups.

To try to design computers to do everything that people do seems both unnecessary and undesirable, as computers are not responsible for their acts. In the human-computer relationship

people are, and must be, the senior partner. A readjustment seems needed in research and development, to move from technology centred computing to human centred computing. The future of computing lies in identifying significant human activities and designing computer systems to support them. We need not computer excellence, but human-computer excellence.

Terms

Autonomy: The degree to which a sub-system can act from within itself rather than react based on its input. For a system to advance, its parts must specialize, which means only they know what they do, and *when* to act. If a master control mechanism directs sub-system action, its specialty knowledge must be duplicated in the control mechanism, as it must know *when* to invoke the sub-system. This defeats the point of specialization. For specialization to succeed, each part needs autonomy to act from its own nature.

Process driven interaction: When a feedback loop is initiated by processing rather than input. This allows the system to develop expectations and goals.

Channel: A single, connected stream of signals of similar type, e.g. stereo sound has two channels. Different channels need not involve different media, just as a single communication wire can contain many channels, so can a single medium like vision. Different channels however have different processing destinations, i.e. different neural processors.

Neural Processor: Similar to Hebb's neural assembly, a set of neurons that act as a system with a defined input and output function, e.g. visual cortex processors that fire when presented with lines at specific orientations.

Polite computing: Any unrequired support for situating the locus of choice control of a social interaction with another party to it, given that control is desired, rightful and optional. (Whitworth, 2005, p355). Its opposite is selfish software that runs at every chance, usually loading at start-up, and slows down computer performance.

System: A system must exist within a world whose nature defines it, e.g. a physical world, a world of ideas, and a social world may contain physical systems, idea systems, and social systems, respectively. The point separating system from not system is the system boundary, and effects across it imply system input and system output.

System Levels: The term information system suggests physical systems are not the only possible systems. Philosophers propose idea systems, sociologists social systems, and psychologists mental models. While software requires hardware, the world of data is a different system level from hardware. An information system can be conceived of on four levels: hardware, software, personal and social, each emerging from the previous, e.g. the Internet is on one level hardware, on another software, on another level an interpersonal system, and finally an online social environment.

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