Selfridge's Milton: The Legacy of Pand(a)emonium in Cognitive Science and Artificial Intelligence

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John Milton was more forthcoming and meticulous about leaving a record of himself than were most other English authors of his own and previous eras. In this current age of social media and Big Data, many are following in Milton's footsteps while lacking his curatorial agenda. Increasingly, the task of building narratives from these records falls not to scholars in archives or employees at IT companies, but rather to Artificial Intelligence (AI) systems. Deep Learning is a new name for a 60-year-old practice of using algorithms conceived as artificial neural networks to identify patterns in data. According to a 2016 special report in *The Economist*, the discovery a few years ago that graphics processing units designed for gaming systems could dramatically accelerate Deep Learning networks, combined with increasingly massive datasets for them to process, led to an ongoing surge of development and investment in AI (Standage 4–5). But this technical explanation for the success of Deep Learning overlooks recent research in cognitive science finding that human brains and insect colonies self-organize without central or external control, much as the latest artificial neural networks do.

Some scholars trace the brain-computer analogy back to Thomas Hobbes, whom the philosopher John Haugeland credits with "prophetically launching Artificial Intelligence" (23). But Hobbes's famous equation *per ratiocinationem autem intelligo computationem* (translated as "by ratiocination I mean computation" in Hobbes 3) reduces thinking to the application of rules to symbols and does not account for how these rules and symbols are learned. Artificial neural networks offer insight into how brains acquire the equivalent of a computer's operators and operands from sensory experience. Ground-breaking programs of this type were designed in the 1950s by a British-born American computer scientist named Oliver Selfridge (1926-2008), the "father of machine perception" (Pieraccini 265) and a grandson of the founder of Selfridges, a chain of luxury department stores in England.

Selfridge was not inspired by Hobbes's analogy so much as by Milton's devils and their city of Pandæmonium. In an interview with science writer Steven Johnson, Selfridge recalls how, when first reading *Paradise Lost* at school in England, he had "been struck by the image of Pandemonium – it's Greek for 'all the demons.' Then after my second son, Peter, was born, I went over *Paradise Lost* again, and the shrieking of the demons awoke something in me" (Johnson 54). Although Selfridge is correct about the etymology of Milton's neologism (*Pan* "all" in Greek + *daemonium* "demon" in classical Latin), Milton does not refer to fallen angels as demons but rather as devils, which is how the King James and most other early modern English Bibles translate the Latin terms, their plurals, and/or their Greek or Hebrew equivalents. In the case of Pandæmonium, however, Milton was probably willing to sacrifice consistency for euphony, an analogy to the Pantheon, and homophony with the Panionium, an Ionian place of assembly mentioned by Herodotus (Bk. 1, Ch. 141-43, 148).

Selfridge's recollection notwithstanding, Milton's devils do not shriek – perhaps he interpolated the shrieks of his infant son. More likely, his misimpression

owes to a nineteenth-century shift in the usage of the word Pandæmonium from a proper noun denoting the capital of hell to a common noun denoting "a place or state of utter confusion and uproar" (*OED* 2a) or "wild and noisy disorder; a tumult; chaos" (*OED* 2b) while gradually dropping a vowel from the diphthong æ. Another Miltonic coinage, "all Hell broke loose" (*Paradise Lost* 4.918; quotations of Milton's poetry are from Fletcher's facsimile edition) is now used in roughly the same sense, and the two are sometimes conjoined, as in "pandemonium broke out." An inharmonious mixture of raucous voices is strongly implied; hence a flock of parrots is called a pandemonium (Woop Studios and Sacher 146-47).

Combining the Miltonic origin of the word with its modern senses, Selfridge envisioned a computer or brain as a space teeming with shrieking demons. Although this imaginative leap bespoke his own preoccupations more than Milton's, for a reader so primed, the parallels are evident: Pandæmonium, like a computer or brain, is a site for decision-making. Furthermore, as J. B. Broadbent observes, the narrator describes the landscape of hell in bodily (or corpselike) terms: scurf, womb, bowels, entrails, wound, ribs (*Some Graver Subject* 84). The devils construct the head(quarters).

Pandæmonium provided Selfridge with a conceptual foundation on which to build his own Pandemonium, a model for computer programs that could learn to recognize patterns. This article uses the amalgam Pand(a)emonium to acknowledge the underreported indebtedness of Selfridge's Pandemonium to Milton's Pandæmonium and assert their joint legacy in cognitive science and AI. The article will endeavour to reveal how this legacy is manifested in Deep Learning systems and the work of cognitive scientists studying insect colonies for insights into how the human brain operates. To this end, the article will situate Pandemonium in the larger context of cognitive science and AI and align it not only with Milton's government of devils but also with his depiction of human information processing and decision-making, both individual and collective.

Although there is little evidence that Selfridge was familiar with Milton's views on these matters, the two men faced similar problems and concocted similar solutions. Selfridge saw that whereas 1950s-era computers required predictable inputs to have reliable outputs, humans responded effectively to stimuli for which they had not been explicitly prepared. Human-like intelligence in computers, therefore, would require a process of human-like pattern recognition, which Selfridge defined as "the extraction of the significant features of data from a background of irrelevant detail" ("Pattern Recognition" 91). Selfridge's efforts to design a program that could determine significance in events beyond the foresight of a programmer are comparable to Milton's attempts to outline a government that could regulate England without the oversight of a king. Like Selfridge, Milton drew on the analogy of a mind distilling prompts from various sources, much as his commonwealth refines the ore of raw democracy. In his poetry, he figured the clamour of both public and internal voices as a swarm of insects, an association that has been vindicated by modern cognitive science.

Selfridge forged the connection to Milton at the 1958 National Physical Laboratory symposium in London, England. In his seminal paper, "Pandemonium: A Paradigm for Learning," he described a computer-program architecture consisting of four or more levels, each populated by a different type of "demon," his metaphor for a subroutine and, presupposing that a similar architecture exists in biological brains, a neural circuit: data or image demons store and display visual data; computation demons (later called feature demons) scan the data and shriek when they spot particular features; cognitive demons listen to the feature demons and shriek when

they find features of particular patterns; a decision demon listens to the cognitive demons and decides which of them is shrieking the loudest and therefore which pattern is the most likely match.

In a 1960 *Scientific American* article, Selfridge and the psychologist Ulric Neisser discussed two implementations of Pandemonium at MIT's Lincoln Laboratory, one for transliterating hand-sent Morse code and the other for identifying handwritten letters of the alphabet. To explain how the latter program works, they offered a simplified example assuming that the data demons can only display images of four block capital letters: A, H, V, or Y (65). Figure 1 shows the organization of the demonic network Selfridge and his collaborators configured to handle this pattern-matching task. Above the data demons are three feature demons, each representing a feature of one or more of these letters; four cognitive demons, each representing one of the letters; and one decision demon.
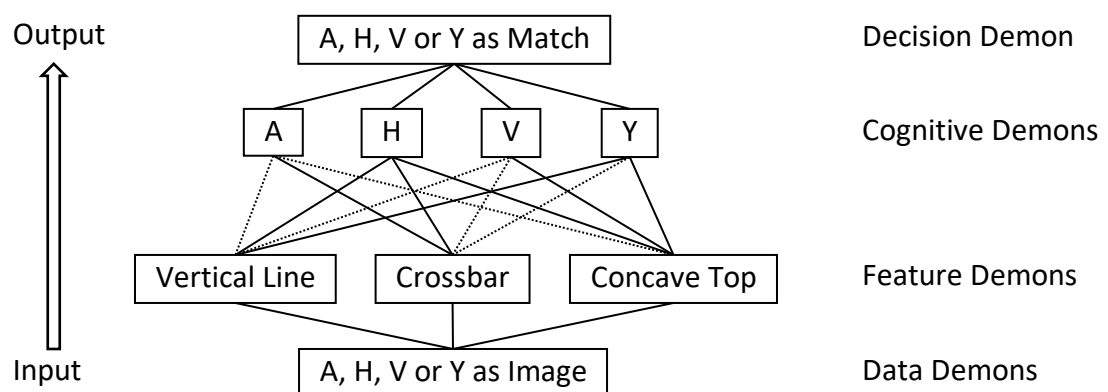

Fig. 1.
Example Pandemonium. Author's own image

The narcissistic feature demons shriek with delight when they recognize themselves in the image; otherwise they sulk in silence. The shrieking of each feature demon excites or inhibits a given cognitive demon. For example, suppose the data demons show an image of the letter A to the feature demons. The crossbar demon shrieks, and the A and H demons respond in kind. But since the concave top and vertical line demons remain silent, the H demon is not fully stimulated and does not shriek as loudly as the A demon does. The decision demon, therefore, sides correctly with the A demon. If an H is shown, all three feature demons shriek and are echoed by all four cognitive demons. However, the H demon shrieks loudest because it is excited by all three feature demons, whereas the Y demon is inhibited by one and the A and V demons by two. The decision demon, therefore, sides correctly with the H demon.

The Pandemonium projects were among the first AI computer programs to implement connectionism, a theory holding that intelligence arises from weighted connections between simple processing units communicating in parallel (Medler 63–65). The connectionist archetype is a biological neural network, in which neurons excite or inhibit other neurons by sending chemical or electrical signals across the synapses that connect them. The strength or weight of a synaptic connection is proportional to the frequency with which signals pass from one neuron to the other; augmentation and degradation of neural pathways correlate with remembering and forgetting respectively. In Pandemonium, the strength of the response of one demon

to another is adjusted based on probabilities derived from pattern-matching outcomes. Fittingly, the word demon is a slant rhyme with the word neuron.

Pandemonium proved superior to other contemporary pattern recognition schemes because it compared visual data against features rather than templates. Because no template of a given pattern closely matches all instances of that pattern, categorizing instances correctly required an impractical amount of pre-processing to normalize each instance. The fact that our brains categorize the vast majority of instances effortlessly, particularly in the case of written characters, was of little help to AI researchers because, even today, psycholinguists do not fully understand the mechanics of this process.

Another innovation of Pandemonium was that, unlike most computer-programming systems of the 1950s, it used parallel rather than sequential processing. In a sequential system, the outcome of one operation, such as a particular demon shrieking or remaining silent, determines how and/or if the next is conducted. If, on the other hand, multiple demons look for their features/patterns and shriek simultaneously, sequence has given way to pandemonium – Selfridge and Neisser's metaphor for parallel processing (66). Though parallel at each level, processing moves from lower demons to higher ones – hence the flow of information through the hierarchy is bottom-up – and demons only monitor a subset of the other demons (those one level below them).

Selfridge's eureka moment when rereading *Paradise Lost* was realizing that the word pandemonium fitted the model he was seeking both in Milton's sense of a structure filled with every member of a group (all demons or neurons) and in the contemporary sense of a seemingly chaotic situation in which multiple agents act or emit uncontrollably, without heeding peers or superiors. As long as decision makers were able to distinguish signal from noise, the hierarchy could function efficiently and expeditiously.

In *Paradise Lost*, the frequent recitation of angelic ranks and titles may have inspired Selfridge's multilevel architecture. But is the decision-making in Pandæmonium similarly parallel and bottom-up? It is parallel to the extent that Moloch, Belial, Mammon, and Beelzebub offer competing proposals, but these devils speak in turn, not all at once. Like Selfridge's demons, they each have a specialty, though not in a feature or pattern but rather in warfare, vice, wealth, and deceit respectively. A vote is then taken and Beelzebub, acting as a precursor of Selfridge's decision demon, announces the result.

For many Miltonists, this seemingly straightforward and democratic process is a sham. Two pieces of textual evidence are traditionally cited to support the charge that, as David Norbrook puts it, "the council has been rigged" (453). First, the narrator implies that Beelzebub serves as a mouthpiece for Satan (2.379-80). Yet a representative putting forward a scheme hatched by a more politically threatening or divisive member has been a conventional tactic in republics since ancient times. A second and stronger proof is that Satan volunteers for the mission to the new world in peremptory fashion (380): "Thus saying rose / The Monarch, and prevented all reply" (2.466-67). Satan's aggressive assumption of the role of chief executive, however, follows a period in which, according to the narrator, other candidates were silenced by fear of the undertaking, not of Satan (2.420-26). It seems probable, therefore, that the perception that the voting devils are cowed or beguiled is not engendered by the facts presented by the narrator so much as by the presumption that Satan, as archfiend, would not subject his designs to the unpredictability of free debate.

Even if legitimate, the process may not be open to all. The voters are "great Seraphic Lords and Cherubim" (1.794) – lower-level devils seem to have no input. With that said, one passage that accords with Selfridge's vision of subordinate demons clamouring to be heard is the famous simile comparing the fallen angels in Pandæmonium to a swarm of bees:

> but chief the spacious Hall
> . . . .
> Thick swarm'd, both on the ground and in the air,
> Brusht with the hiss of russling wings. As Bees
> In spring time, when the Sun with Taurus rides,
> Pour forth thir populous youth about the Hive
> In clusters; they among fresh dews and flowers
> Flie to and fro, or on the smoothed Plank,
> The suburb of thir Straw-built Cittadel,
> New rub'd with Baum, expatiate and confer
> Thir State affairs. So thick the aerie crowd
> Swarm'd and were straitn'd; till the Signal giv'n.
> Behold a wonder! they but now who seemd
> In bigness to surpass Earths Giant Sons
> Now less then smallest Dwarfs, in narrow room
> Throng numberless . . . (1.762, 767-80)

Whereas in Dante's empyrean, angel bees pollinate a celestial rose of saved souls with messages from the light above (*Paradiso* 31.4-18), in Milton's hell, devil bees "expatiate and confer / Thir state affairs" as if they are the informed and engaged citizens of an ideal polis or democracy.[1] However, Broadbent points out that the bees resemble "amateur politicians" who "gossip, while the real work of government goes on inside" ("Milton's Hell" 190). These rank-and-file devils are not only "straitn'd" (i.e., spatially confined) but also straightened, or put in order, by signals from higher-ups. All but the worthiest thousand are ordered to reduce their size so that they may fit into the "spacious Hall." The dimensions of the court reinforce power differentials by allowing only a select few to remain "in thir own dimensions like themselves" (1.793). Among shape-shifting beings, size must be structurally enforced if it is to have meaning – all the devils may be "at large" (1.790), but some are more at large than others. The swarm has effectively been hived; that is, contained "in narrow room." Their volume probably diminishes aurally as well as spatially, and the "great consult" (1.798), which will confirm or dispel the rumours of the crowd, begins after a "short silence" (1.797).

It seems that only the thousand devils gathered in "close recess" (1.795) vote. If those in the hall are not privy to the "secret conclave" (1.795), their situation is akin to that of Agamemnon's armies in the *Iliad*, who can only gossip amongst themselves until their king finishes consulting with his ministers and delivers a sentence transmuting rumour into fact. Milton's bee simile is reminiscent of Homer's in his description of the Achaeans assembling to hear Agamemnon's announcement:

> Like swarms of bees, endlessly renewed, issuing from some hollow rock, pouring in dense clouds to left and right through all the flowers of spring, so from the ships and huts on the level sands, the many tribes marched in companies to the assembly. And Rumour, Zeus' messenger, drove them on

like wildfire, till all were gathered. Now the meeting-place was in turmoil, the ground shook beneath as they were seated, while through the din nine heralds shouted to subdue them, quiet them, and grant silence to their god-given kings. With difficulty the men were seated in their places, and settled there in quiet. (2.86-100)[2]

Rumour (Greek *Ossa,* Latin *Fama*), is deployed by Zeus to spur the Achaean soldiers on and, despite creating a temporary tumult, ultimately accelerates the process of coming to order, just as a honeybee swarm results in the settling of a new nest.

Milton thus follows Homer in portraying the subduing of a crowd whose political gossip seems mere noise, irrelevant to policymaking. Yet rumours can indirectly shape policy; Agamemnon's advisors are attuned to the opinions of the troops and Satan's strategy to target the denizens of the "new Worlds" (1.650) instead of Heaven is based on what he terms "a fame" (1.651). This now-archaic usage meant "a report, rumour" (*OED* 1a). Instead of "fame," Milton's prose Arguments to the first two books have "*report,*" "*Tradition,*" and "*Prophesie*"; although the last word implies divine inspiration, it shares with the others the sense of information emanating from and/or circulating outside of official channels. When it comes to information flow, therefore, the devils' decision-making is a grassroots process.

If the "hiss" or buzzing of a swarm suggests public political discourse, what does the reference to the "Straw-built Cittadel" or beehive imply about the type of government that has its seat at Pandæmonium? In Milton's time and stretching back at least as far as Plato's *Republic* (7.520b), the society of bees or ants was often compared to a well-functioning church or nation, with the beehive or anthill figured as a city, particularly a seat of government. Mid-seventeenth-century political philosophy viewed bees and ants as analogous to royalists and republicans respectively (Edwards 128–39; Sauer 17–18), due in part to the misimpression that the former had monarchs and the latter did not. Charles Butler had popularized the idea that the bee monarch was female with his treatise on beekeeping, *The Feminine Monarchie* (1609),[3] but the fact that an ant colony also has a queen was not well documented, possibly because ants, unlike bees, were not kept and, when their nest is disturbed, hide their queen in a secret chamber (Johnson 30–31).

It is tempting then to view the bee simile as a means of associating devils with royalists. On the face of it, however, the devils are rebels against a monarchy. Furthermore, although the queen bee is anointed from birth, proponents of a Cromwellian Protectorate could argue that she rules by merit rather than primogeniture: the only such bee in the nest, significantly larger than the rest, apparently deserving of her dominion. Samuel Purchas (the younger) underscored this innate superiority: "by nature hath hee the Sovereignty over all, excelling all in goodliness, and goodness, in mildness, and majesty" (16–17). The faulty masculine pronoun together with Purchas's republicanism and the timing of his argument (1657) indicate that he had Oliver Cromwell in mind as the human equivalent of a queen bee.

For his part, Milton refrained from endorsing any political insect analogies until the Restoration, during which period he evinced a preference for ants over bees. With the government that he had so vigorously defended crumbling about him, Milton would cite Proverbs 6.6-8 and offer the pismire as a model for the nation in *The Readie and Easie Way to Establish a Free Commonwealth* (1660):

> **Go to the Ant**, thou sluggard, saith *Solomon; consider her waies, and be wise; which having no prince, ruler, or lord, provides her meat in the*

> *summer, and gathers her food in the harvest*, . . . neither are these diligent creatures hence concluded to live in lawless anarchie, or that commended, but are set the examples to imprudent and ungovernd men, of a frugal and self-governing democratie or Commonwealth; safer and more thriving in the joint providence and counsel of many industrious equals, then under the single domination of one imperious Lord. (*Complete Prose Works* 7: 427; subsequent citations of Milton's prose will reference this edition by volume and page number only)

In *Paradise Lost,* the angel Raphael anticipates the commonplace distinction between ant democracy and bee aristocracy:

> First crept
> The Parsimonious Emmet, provident
> Of future, in small room large heart enclos'd,
> Pattern of just equalitie perhaps
> Hereafter, join'd in her popular Tribes
> Of Commonaltie; swarming next appeer'd
> The Female Bee that feeds her Husband Drone
> Deliciously, and builds her waxen Cells
> With Honey stor'd . . . (7.484-92)

The admiration for ants that Milton evinces in these two passages reflects his longing for the Good Old Cause – the dream of "a free commonwealth without single person or house of lords" (7: 364-65, 429) – during and shortly after the Restoration. The "just equalitie" and "Commonaltie" of the seemingly genderless ants clashes with the inequitable relations between the "Female Bee" and "her Husband Drone."

Raphael conflates the functions of the queen bee and the worker bees under the single label "female bee," but accurately characterizes the role of male honeybees, or drones, who attempt to mate with fertile queens rather than gather nectar or pollen and are driven out of the nest each fall by the worker bees, a scenario that Virgil depicts in his *Georgics* (4.169). Milton's contempt for the drones of human society can be inferred from Samson's refusal to become a "burdenous drone" (*Samson Agonistes* 567). As for the worker bee, she not only feeds the drone but also "builds her waxen Cells / With Honey stor'd," language reminiscent of the devil bees who prepare "boyling cells" for the smelted gold they will use to fill the "various mould" of Pandæmonium (1.700-09).

Whereas Virgil makes a simile comparing the Tyrians building their city to bees making honey (*Aeneid* 1.423-36), in *Paradise Lost* it is not humans but devils who, despite their self-interest and hierarchies, seem capable of collaborating like bees or ants, as is evident in the choreographed efficiency with which they construct Pandæmonium and conduct their business within its walls. The narrator contrasts the solidarity of the devils' deliberations with the disunity of humanity's: "O shame to men! Devil with Devil damn'd / Firm concord holds, men onely disagree / Of Creatures rational" (2.496-98).

Should ants or bees be included in the category of "Creatures rational?" Milton's and Selfridge's analogies are milestones in the enduring quest to answer this question. Whereas Milton compared devils to bees, Selfridge compared neurons to demons (i.e., devils). It follows syllogistically that neurons should be like bees, and such is the hypothesis of twenty-first-century cognitive scientists who examine bee

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and ant colonies for insights into the workings of not only a city or government, as in previous millennia, but also the human brain. These scientists have found that ants and bees, like neurons, exhibit intelligence collectively rather than individually. According to some biologists, a eusocial insect society is a *superorganism*, which Bert Hölldobler and Edward O. Wilson define as "a colony of individuals self-organized by division of labour and united by a closed system of communication . . . that possesses features of organization analogous to the physiological properties of single organisms" (84, 513). Scaled up to human dimensions, superorganisms accomplish feats of industry that, like those of Milton's devils, surpass "Babel, and the works of Memphian Kings" (1.694). Garden ants, for example, dig underground nests proportional to downtown skyscrapers while fire ants make rafts and bridges from their own interlinked bodies. They do so by following pheromonal cues and obeying simple, innate rules rather than a leader's orders (Singer).

The devil bees also labour without central coordination. Although Mammon leads the miners (1.678) and Mulciber is "the Architect" (1.732), a hive mind seems to be directing the overall project. The teamwork in evidence is reminiscent of that practiced by the builders of the Tower of Babel, who, like a biblical superorganism, value group unity and notoriety over personal identity and reputability. They share a common language and a purpose to, in Michael's words, "get themselves a name, / least far disperst / In foraign Lands thir memorie be lost" (12.45-46). Similarly, the builders of Pandæmonium have had their names "blotted out and ras'd / By thir Rebellion, from the Books of Life" (1.362-63), and temporarily succumb to the notion that they can make a name for themselves in heaven again through cooperation with each other. This dream is shattered when they are transformed into hissing serpents (10.504-47), a pandemonium at Pandæmonium that prefigures the confusion of tongues at Babel and lends further support to Selfridge's reading of a demonic cacophony.

The "dismal universal hiss" (10.508) of the metamorphosed devils echoes "the hiss of russling wings" (1.768) from the bee simile. Yet whereas the earlier swarm was composed by plebeian devils who seemed to be acting under their own volition or at least according to their station, "thick swarming now" (10.522) are the peers of Satan, whose actions in their serpentine state are involuntary. Prior to their forced transformation into snakes and consumption of bitter ashes disguised as fruit, the devils believed that they acted under their own agency. We are left to guess whether they will come to regard this humbling experience as the exception that proves the rule or as evidence that their free will is as illusory as the fruit.

Pandæmonium, then, is the site of orderly, turn-taking debate and unruly mob action, two examples of decision-making that may not be as different as they appear; perhaps Selfridge read them as opposite perspectives on the same mental phenomena. In a human brain, sequential processing of thoughts – or of calculations in Hobbes's formulation – may be an illusion fostered by the bottleneck of consciousness, which only admits the froth that bubbles up from billions of agitated neurons. Much like ants, bees, or Milton's snaky devils, neurons behave mindlessly, but their unguided interactions generate thoughts and, at a more rudimentary level, perceptions of patterns.

Selfridge's demons did not outperform neurons: the error rate of the Morse-code program was slightly higher than that of a professional human operator and the letter-recognition program made 10 percent fewer correct matches than human readers do (Selfridge and Neisser 62, 68). However, the programs came close enough to matching human performance on these specific pattern recognition tasks to suggest

that the brain might have a mechanism for learning and recognition similar in some ways to a network of demons.

Selfridge could have adopted neurons instead of demons as his metaphor for the nodes of his network. Had he done so, his role in the history of artificial neural networks would be more widely recognized today. But there were reasons to downplay the brain analogy. For one thing, evidence for the existence of mental feature extractors was inconclusive.[4] More importantly, AI researchers disagreed about whether their systems should model the physical structure of human brains – the connectionist approach – or represent higher-level reasoning processes – the symbolic approach. The latter view was consistent with "the computational theory of mind," which characterized thinking as information processing through "rule-governed symbol manipulation" (Rescorla). This theory, which Steven Pinker traces back to Hobbes (33), dominated cognitive science during the 1960s and 1970s.

Despite its connectionist orientation, Pandemonium was embraced by some computational psychologists. Among them was Neisser, who published the first monograph on the topic of cognitive psychology in 1967. This book offers Pandemonium as a "feature-analyzing model" of pattern recognition in human "visual cognition" (71). Five years later, cognitive psychologists Peter Lindsay and Donald Norman published a widely used psychology textbook that not only contains a long and heavily illustrated section on Pandemonium as an explanation of cortical signal processing (114–31) but also depicts the authors as demons on the cover. It seems that Selfridge's demon metaphor appealed to cognitivists and connectionists alike, perhaps because it conjures an entity that is neither organic nor synthetic and therefore possesses equivalent qualifications to represent an agent of information processing in either a brain or a computer.

By the time Pandemonium became part of the standard model of human cognition, Selfridge had left it and MIT behind to work for Bolt, Beranek, and Newman, a private technology firm (Boden 926). His primary goal for Pandemonium had not been to offer cognitive science a colourful illustration of visual pattern recognition but rather to devise a blueprint and training methodology for programs that would learn to improve their own performance.

The projects that Selfridge oversaw at MIT pioneered a technique that AI developers now call supervised learning: a network of demons was trained with labelled examples from a character set and then tested with unlabelled characters drawn from the same set but differing from the examples in size, proportion, orientation, and/or position. During the training phase, the network estimated the probability that the presence of each known feature indicates the presence of each known character. During the testing phase, the network fine-tuned its estimates based on correct and incorrect matches (Boden 900–02). The success of this self-improvement method, which Selfridge termed feature weighting, only partially fulfilled his ambition to create an evolutionary network; Selfridge had anticipated that through "subdemon selection" the network would learn how to create replacements for unproductive feature demons by mutating and combining productive ones (Selfridge, "Pandemonium" 517–23). But the projects failed to initiate these adaptations. "The most important learning process of all is still untouched," lamented Selfridge and Neisser, "no current program can generate test features of its own" (68).

Today, supervised learning algorithms extract features directly from training data, eliminating the need for programmers to code these features (Goodfellow et al. 4). Deep Learning is not merely a buzzword; the rebranding distinguishes deep networks from their shallow predecessors. Two decades ago, cutting-edge networks

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had an input layer, two "hidden layers," and an output layer (Goodfellow et al. 13). Like Pandemonium, the earliest precedent for their four-layer architecture, these networks required months of training to recognize significant patterns. Now, such a network can be trained in less than a day, and networks of 20 or 30 layers are common; Microsoft has developed one with 152 layers.[5] Each hidden layer consists of artificial neurons that, when activated by the detection of a feature, signal neurons on the next highest layer to weigh a related but more complex feature of the data. For example, if the data is an image of an object, one layer might detect edges, the next corners and contours, the next shapes, and so on until the output layer identifies the object as a car, person, or animal (Goodfellow et al. 6). This matchmaking process typically moves in only one direction, upward from input to output, but news of a mismatch travels downward through a feedback technique known as "backpropagation," updating the weights (Goodfellow et al. 197). With enough refinement, the networks can overcome mislabelled data and correctly identify malformed inputs, such as a handwritten A that resembles an H. Even the comparatively simple autocorrect feature on smartphones provides evidence that computers are learning to interpret the intentions behind user errors and render obsolete the programming maxim "garbage in, garbage out."

In addition to speech recognition, image classification, and optical character recognition, practical applications of Deep Learning include automatic translation, spam/virus filtering, Internet searching, targeted advertising, fraud detection, and autonomous driving. Deep Learning also helps researchers in scientific fields process large datasets and make predictions. The accelerated pace of automation has revived a long-running debate about the impact of machines on labour, a topic that is beyond the scope of this article.[6]

Through his own efforts as well as those of others pursuing connectionist AI, Selfridge's "paradigm for learning" has now been fully realized. Unfortunately, historians of AI have undervalued the significance of Pandemonium as the first implementation of supervised machine learning in a multilayer network modelled on the nervous system, and the influence of Milton on Selfridge is all but unknown. This neglect is due in no small part to the paucity of Selfridge's peer-reviewed publications; he shared some of his best ideas orally and by circulating unpublished work (Boden 898).

For its legacy in cognitive science to continue, Pand(a)emonium must remain compatible with the prevailing theories of learning and cognition. In a 1949 monograph, the neuropsychologist Donald O. Hebb speculated that the infant brain starts out with a randomly connected network of neurons which then forges new connections and grows in complexity through environmental interaction. Although feature-generating algorithms provide support for Hebb's theory, the neuroscientist Michael S. Gazzaniga reports that "the current view of the brain is that its large-scale plan is genetic, but specific connections at the local level are activity-dependent and a function of epigenetic factors and experience" (21). Localized neuron circuits called modules run in parallel, each with a distinct specialty and a bottom-up hierarchy (69). A module, therefore, is comparable to Selfridge's Pandemonium.

The theory of a modular brain evokes medieval and renaissance faculty psychology, a tradition to which Milton subscribed (T. Butler 95–138). In *Paradise Lost*, Adam assumes that Reason adjudicates between the promptings of the imagination, the passions, and many other sources: "in the Soule / Are many lesser Faculties that serve / Reason as chief" (5.100-02). To this day, the notion that a privileged faculty of choosing exists passes for common sense. Yet neuroscience has

not uncovered a top-down command centre but rather networks of widely distributed decision-making centres (Gazzaniga 44). It appears that the cranium encloses a Pandemonium of Pandemoniums, with the output of one becoming the input of another.

In *Paradise Regained*, Jesus tells Satan that "he who reigns within himself, and rules / Passions, Desires, and Fears, is more a King" (2.466-67). Given this doctrine of self-control and inner autocracy, how would the finding of a leaderless brain have struck Milton? As a monist, he would have been disinclined to postulate incorporeal agency (Fallon chapters 3-5). He may have wondered why a state of cognitive pluralism is felt as a unified stream of consciousness. While even a mind free from the influence of psychoactive drugs or mental disorders can experience disunity and multiplicity, such conditions tend to be perceived as aberrant. In his poetry, Milton figures an unsettled or agitated mind as a swarm. When Jesus first wanders into the wilderness, he thinks to himself:

> O what a multitude of thoughts at once
> Awakn'd in me swarm, while I consider
> What from within I feel my self, and hear
> What from without comes often to my ears,
> Ill sorting with my present state compar'd. (1.196-200)

The conflict is not between what Jesus hears and what he thinks, but rather between both sources and his "present state." In *Samson Agonistes*, Samson describes much the same phenomenon:

>   I seek
> This unfrequented place to find some ease,
> Ease to the body some, none to the mind
> From restless thoughts, that like a deadly swarm
> Of Hornets arm'd, no sooner found alone,
> But rush upon me thronging, and present
> Times past, what once I was, and what am now. (16-22)

Jesus's thoughts on the future and Samson's on the past are incongruent with their present states and the cognitive dissonance stirs these thoughts into a swarm. Although neither Samson nor Jesus believes that rumination will lead to action – they await a sign from heaven – they can no more stop the mental revolution than they can stop breathing. Samson refers to his thoughts as "my Tormenters arm'd with deadly stings" (623).

At the centre of these thought swarms, Milton envisions a besieged core of identity, what Jesus refers to as "my self" and Samson as "the mind." Yet Gazzaniga reports that most neuroscientists believe that the self, mind, or soul amounts to nothing more than a continuous *post hoc* narrativization of the limited information that manages to rise into conscious awareness from the myriad processors below; a module in the left brain, "the interpreter," infers causal connections between thoughts and actions determined subconsciously (85–94). The role of the interpreter module, therefore, approximates that of Selfridge's decision demon, who will testify that it saw a pattern when all it really did was listen to the reports of cognitive demons, who relied in turn on the reports of feature demons. In both man and machine, a putative decider turns out to be a mere explainer, liable to be scapegoated for errors committed

by other parts of the system. Jesus and Samson perceive their swarming thoughts as a loss of control over their mental processes, but they never in fact exerted such control. The "calm of mind" (*Samson Agonistes* 1758) that they seek will deaden but not silence the cacophony of competing voices.

Milton's swarm-of-thoughts metaphor anticipates the colony-as-brain analogy in cognitive science. Due to the ethical and practical challenges of brain research, some scientists have turned to insect colonies as evidence for the connectionist theory that intelligent behaviour emerges from the interactions of relatively simple units. From 2013-2016, for example, neuroscientist Mark Goldman joined ecologist Deborah Gordon and others in a study of the foraging behaviour of red harvester ants. Previous research had shown that ants decide to forage or stay in the nest based on the frequency of their antennal contact with ants returning to the nest (Greene et al.). Goldman and Gordon hypothesized that a closer investigation of this leave/stay decision-making would shed light on the release/don't release responses of synaptic vesicles (Arnold).

While comparisons between insect and human societies are still common today, the traditional distinction between republican ants and royalist bees was overturned by the discovery that both have queens and yet, counterintuitively, neither has monarchs. A queen's role is not to give orders but rather to mate with drones from other nests and lay eggs. Due to her long life span relative to her offspring, a queen often becomes the mother of the entire colony and her daughters dutifully attend her. Proto-entomologists and beekeepers from Virgil to Purchas remarked on this devotion but failed to note that bees engage in supersedure, smothering an unproductive queen when a replacement becomes available (Winston 197–98). Milton would have been interested to learn this fact when composing his defences of regicide.

If the societies of bees are not monarchies, enlightened or otherwise, neither are those of ants the communes of pre- and early modern imaginations. In some ant species, most of the so-called workers only stand and wait until needed. Gordon finds that among red harvester ants, the oldest 25% of the colony performs the four exterior tasks (foraging, patrolling, nest maintenance, midden piling) that make up the bulk of the colony's work (27). While this division of labour may be a collective decision, the choice of nest site is not. After mating, the queen digs a hole in the ground where she will found her colony (Khan 201–202). Honeybees, on the other hand, select nest sites by committee. According to biologist Thomas D. Seeley, when a swarm sets out to find a new home, a scout committee of several hundred bees assembles from the ranks of the foragers and searches for promising sites. The scouts then return to where the swarm has bivouacked and perform "waggle dances." The orientation and duration of each dance indicates the direction and distance of the site, respectively. The scouts that located the site with the most desirable features dance the longest and recruit others to either join their dance or inhibit competing dancers by head-butting them until all the dancers are doing the same dance. The swarm then departs for the winning site (131–35). Seeley compares this process to mental decision-making models in which sets of neurons representing different options inhibit each other to an extent proportional to each set's level of activation (Seeley et al. 108–11). The process also resembles a Pandemonium in which demons can change their votes based on the relative exuberance of their neighbours.

Seeley's findings are evocative of Milton's association of swarms with a mind or society debating how to achieve a life-altering goal; the swarm ends when a course of action is decided upon and implemented. But like the devils in the great hall of Pandæmonium, non-scout bees do not vote. Seeley finds that only 3-5% of a swarm

participates (78). That range is high for representative decision-making, but low for direct democracy.

Such limited, qualification-based suffrage is comparable to the elitist franchise Milton recommends in *the Readie and Easie Way*. Although Milton's admiration for ants shows that he favoured equality among equals, he inveighed against plebiscites in a commonwealth of unequals:

> Another way will be, to wel-qualifie and refine elections: not committing all to the noise and shouting of a rude multitude, but permitting only those of them who are rightly qualifi'd, to nominat as many as they will; and out of that number others of a better breeding, to chuse a less number more judiciously, till after a third or fourth sifting and refining of exactest choice, they only be left chosen who are the due number, and seem by most voices the worthiest. (7: 442-43)[7]

Don M. Wolfe diagrams the electoral scheme from the above passage as a four-stage "sifting" of both voters and candidates (301). In his interpretation, an elector is eligible to vote in one, two, three, or all four rounds depending on his merits. The most refined electors, therefore, vote four times, and the least (males worth two hundred pounds) only once. But Wolfe reads "that number" as referring to the nominators, despite "less number" and "due number" clearly referring to the nominees. Milton's stipulation "others of a better breeding" further suggests that he envisioned four separate groups of voters, each voting in only one round, with the most elite group having the final vote. A precedent for dividing voters into separate groups based on their qualifications can be found in the most well-known of the commonwealth-era alternative electoral schemes, that of James Harrington's *The Commonwealth of Oceana* (1656). Such a system would be less conducive to oligarchy than that of Wolfe's interpretation because the patricians who ultimately select the representatives would not have the power to nominate those same individuals (or themselves). A four-group election also conveys a parallel, bottom-up process like Selfridge's Pandemonium: a data set (candidate pool) is filtered through layers (voter classes) based on features possessed by a subset of that data (desired qualifications). Either way, a body so formed might well be deemed, like that summoned to the "solemn Councel" (1.755) at Pandæmonium, "By place or choice the worthiest" (1.759).

Wolfe attributes Milton's vision of the franchise to a genuine and long-held disdain for the voices of the people, whom Milton terms "the misguided and abus'd multitude" (7: 388). The Restoration-era Milton viewed the masses as unfit to discern good from bad. *In Paradise Regained*, Jesus remarks, "what the people but a herd confus'd, / A miscellaneous rabble, who extol / Things vulgar, & well weigh'd, scarce worth the praise" (3.49-51). This seems a damning judgment, but is there any hope that the common people can learn to make the right choices? In this respect, ants and bees can hardly serve as models, for their actions appear instinctual and unlearned. Milton was unaware, of course, that their behaviour is the product of natural selection. He regarded these insects as, in a sense, pre-programmed by God. Selfridge, conversely, was a proponent of the theory of evolution who saw that computers were being programmed by men. He aspired to invent, in Pandemonium, a way for machines to evolve through trial-and-error.

The learning process that Milton advocates in *Areopagitica* (1644) is not trial-and-error but rather trial-by-error: "that which purifies us is trial, and trial is by what

is contrary" (2: 515). In this idealistic vision, one learns to recognize errors by considering them, not by committing or avoiding them, because "the knowledge and survey of vice is in this world so necessary to the constituting of human virtue, and the scanning of error to the confirmation of truth" (2: 516). For these reasons among others, Milton opposes the imposition of a top-down book licensing process in which an imprimatur is passed from licensors to stationers to printers. It is important to note that Milton defends "the liberty of unlicensed printing" rather than the liberty of publishing. In the publication process, information travels upward from printers to stationers to readers, the last group including those with the power to censor books "found mischievous and libelous" (2: 569). Milton condones post-publication censorship as an alternative means of regulating the press, but pre-publication obstacles exist with or without licensing. Publishers, booksellers, and readers choose which books they will print, stock, and buy respectively.

It is from this perspective that Pandemonium and the publishing system outlined in *Areopagitica* illuminate each other. At each level, there is an audience that analyses data for features or patterns of interest. Only when these are found can the data move up the hierarchy. Consequently, any audience that is not receptive to a wide spectrum of features/patterns poses a bottleneck. Selfridge found that his demons would only recognize those patterns on which they had been trained already; similarly, Milton predicts that the licensers will "let passe nothing but what is vulgarly receiv'd already" (2: 534). Since licensers have nothing to gain and much to lose from authorizing new or uncustomary ideas, they are impediments to the growth of knowledge, which depends on "searching what we know not, by what we know" (2: 551).

Supervised learning follows a similar procedure – searching for features through knowledge of patterns. However, in a budding technique called unsupervised learning, artificial neural networks identify patterns in unlabelled data without first being trained with labelled examples (Goodfellow et al. 105). Although some if not all of the detected patterns will be familiar to researchers, the approach has great potential for situations where they may be unaware of a pattern (unknown unknown) or fail to acknowledge it (unknown known). For example, networks can alert investigators to irregularities that, after further study, may indicate terrorism or corruption.

Selfridge probably did not foresee these and many other applications of machine learning, but his colleagues J. C. R. Licklider and Robert W. Taylor credit him with being the first to conceive of a computerized personal secretary (38). A twenty-first-century virtual assistant can, as Selfridge prophesized in his 1958 paper, "adaptively improve itself to handle certain pattern recognition problems which cannot be adequately specified in advance" ("Pandemonium" 513). Selfridge's faith that computers, given the proper architecture, could learn without the guiding hand of a programmer parallels Milton's faith that readers, given a free press, could self-educate without the regulation of a licensor, much less a king.

Milton's belief in the autodidacticism of the common people was shaken by the Restoration, but even in the midst of that crisis he did not dismiss them entirely. In *The Readie and Easie Way*, he proposes to enlarge the ranks of the electorate and the elected by raising educational standards rather than lowering eligibility standards: "To make the people fittest to chuse, and the chosen fittest to govern, will be to mend our corrupt and faulty education" (7: 443). Through the spread of education, the government would become less centralized and hierarchical, gradually coming to resemble the pure commonwealth he envisioned ants as inhabiting in contradistinction

to bees. The election of assemblies at increasingly local levels would result in a commonwealth of commonwealths, each with its own legislature and judicature (7: 383-85, 458-61). These bodies, if not also the Grand Council overseeing them, would be accessible to supplicants (7: 383, 458). In *An Apology for a Pamphlet* (1642), a younger and more idealistic Milton had praised the Long Parliament for such openness:

> the meanest artizans and labourers, at other times also women, and often the younger sort of servants assembling with their complaints, and that sometimes in a lesse humble guise than for petitioners, have gone with confidence, that neither the meannesse would be rejected, nor their simplicity contemn'd, nor yet their urgency distasted either by the dignity, wisdome, or moderation of that supreme Senate; nor did they depart unsatisfi'd. (1: 926)

This parallel between his early and late polemics shows that even as his disillusionment with commoners grew, Milton held fast to the belief that non-voters should have access to government. This conviction is evident in the rhetorical framework he adopted explicitly or implicitly in many of his tracts, most formally in *Areopagitica*: that of a private person appealing to Parliament. Although Milton neither expected nor desired decision makers to judge the merits of petitioners and petitions separately (2: 489-90), the form of hierarchical government he supported has no autocrat at the top and receives input from the bottom, whether that nethermost tier be occupied by England's lower classes, Pandæmonium's shrunken devils, or, presumably, Pandemonium's data demons. Selfridge's paradigm reflects Milton's prescription for human information processing and decision-making due to the similarities in the problems the two men addressed, albeit in quite different domains, and Selfridge's dual interpretation of the word pandemonium. In its application to insect societies and neural networks, Pand(a)emonium's legacy in cognitive science and AI lives on.

Notes

1. See chapter two of Hollingsworth for an extended treatment of how and why Milton inverts Dante's simile.

2. For 18 other bee similes prior to Milton's, see Whaler.

3. In the late 1670s, the queen bee's gender was scientifically verified by Jan Swammerdam (1637-1680), a Dutch biologist who conducted microscopic investigations of dissected bees and other insects (Munz 195-98).

4. Contemporary experiments had found evidence for feature extractors in the brains of frogs (Lettvin et al.) and octopuses (Sutherland). Selfridge's work on pattern recognition is credited with inspiring the former study. For a survey of the evidence of feature extractors in humans, see Grainger et al.

5. In 2015, at the annual ImageNet Large Scale Visual Recognition Challenge, an ensemble of Microsoft neural nets surpassed human performance at classifying objects in an image (He et al.).

6. For an account of the debate over the impact of machines on labour in the early nineteenth century, see Berg. For a survey of modern opinions about AI, see Brockman.

7. At seventeenth-century elections, votes were often cast orally and, in the case of a large crowd of voters, simultaneously. Robert W. Ayers's note to this passage cites an account of a county election from J.E. Neale's *The Elizabethan House of Commons* (1950), in which everyone at the courthouse shouted the names of their preferred candidates at once. Neale writes, "During the pandemonium, the Sheriff was supposed to discern the greatest number of voices." See Milton, *Complete Prose Works* 7: 442 n154.

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