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News and Views

From Connectome to Cognition: Building the First Digital Organism

Melvin M. Vopson[1,2,*]

[1] School of Mathematics and Physics, University of Portsmouth, PO1 3QL Portsmouth, UK
[2] Information Physics Institute, Gosport, Hampshire, United Kingdom, www.informationphysicsinstitute.org

*Corresponding author: melvin.vopson@port.ac.uk

Abstract - The long-standing ambition of neuroscience to move from static maps of the brain, called connectomes, to predictive, mechanistic models of behavior, has taken a decisive step forward. Advances spanning 2024 to 2026 have transformed the complete connectome of an adult *Drosophila melanogaster* (fruit fly) from an anatomical achievement into a functioning, virtually embodied system. Together, these developments mark the first instance in which a fully specified animal nervous system has been rendered into a dynamic computational model capable of generating behavior. In this News and Views article, we briefly review these fascinating developments and their scientific, technological and philosophical implications.

Keywords - Connectome; Brain simulation; Physical world simulation.

In October 2024, a global consortium of scientists, the FlyWire Consortium [1], published a major scientific breakthrough in the journal Nature [2]. Their main goal was to map the entire brain structure of an adult *Drosophila melanogaster*, i.e. fruit fly. This is known as the complete connectome, which is a literal road-map of an entire brain.

Over a 10-year effort, the FlyWire Consortium scientists achieved this goal by taking 7,000 ultra thin slices (about 40 nm thick) of a fruit fly's brain embedded in resin [3] using a diamond knife on an ultramicrotome. They then imaged every slice using serial-section electron microscopy, so the brain was imaged at nanometer resolution to map and identify the precise location of neurons and synapses contained within each slice and connecting all the neurons.

These images were then painstakingly stitched together using AI-driven segmentation to map every single neuron and the synapses connecting them. The result was a complete map of 139,255 neurons and more than 50 million synaptic connections of the entire brain of a fruit fly, i.e. connectome, which was published in Nature [2].

Unlike previous attempts at brain modeling, which relied on ”black box” artificial neural networks, the FlyWire project [1] produced a connectome: a literal road-map of biological intent. Prior to Flywire, the most complete connectome was achieved in 2018 in the OpenWorm project for a round worm called *C. elegans*, containing 302 neurons [4].

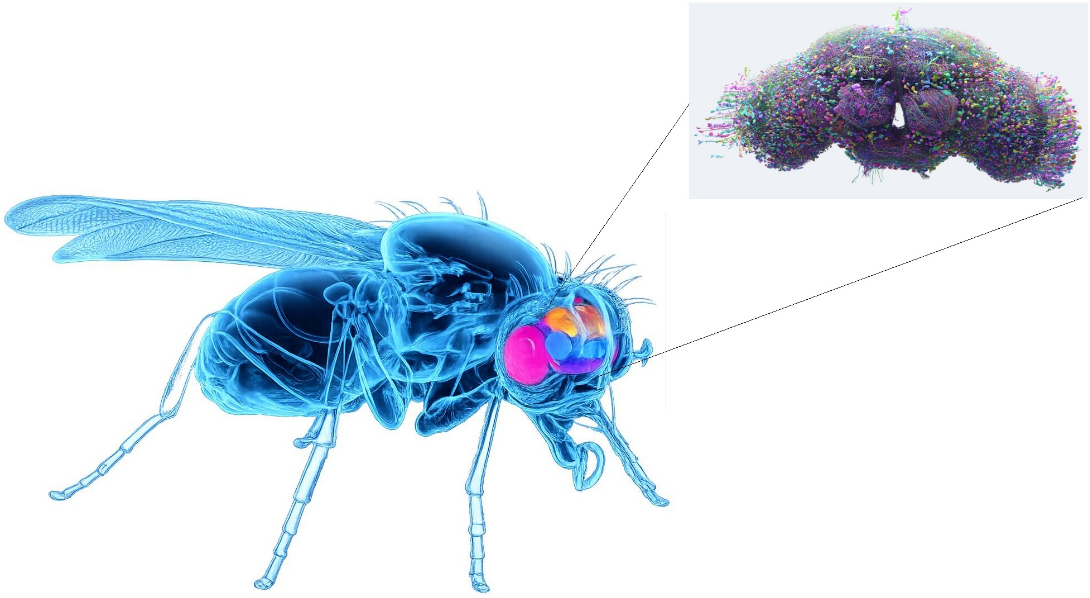

Figure 1: A digital construct of the *Drosophila melanogaster* (fruit fly), including its complete brain connectome, developed by a Princeton-led team of researchers and gamers. Images adapted from [1] and from Amy Sterling / FlyWire / Princeton.

In their 2024 paper published in Nature, researchers demonstrated that the fly's brain is a masterpiece of efficiency. They discovered dedicated circuits for complex behaviors such as the "looming detector" circuit that triggers an escape reflex when a predator approaches.

What distinguishes this effort from previous connectomic studies is not simply its scale, but its completeness and functional granularity. Individual neurons, their synaptic partners, and the directionality of information flow were all resolved, allowing researchers to move beyond structural description toward mechanistic interpretation.

Critically, the connectome was not treated as a static dataset. The researchers constructed a computational model in which neurons interact according to biologically grounded rules of signal propagation. When sensory neurons associated with taste were stimulated in this model, activity propagated through the network in patterns that recapitulated known feeding circuits, achieving behavioral predictions with greater than 90 percent accuracy. This result provides compelling evidence that the structure of synaptic connectivity contains sufficient information to determine function when coupled with appropriate dynamics.

However, a brain does not operate in isolation. Nervous systems evolved to control bodies in physical environments, and it is in this context that the second follow up advance of this research project becomes decisive.

In March 2026, Eon Systems, a San Francisco-based start-up [5], took the Flywire Connectome and did something nobody had done before. They embedded the connectome-based model into a simulated fly body within a physics engine, creating a closed loop between neural activity, motor output, and sensory feedback. Essentially, using the MuJoCo (Multi-Joint Dynamics with Contact) physics engine [6], which is the same physics engine used by the DeepMind and OpenAI for robotic research, they placed the digital fly into a world with gravity, wind, obstacles and other stimuli. This step effectively transformed the connectome from a descriptive map into an executable system, by implementing the entire neural blueprint, every neuron, every connection, every synapse, inside a computer simulation, called a brain emulation. The emulated brain was then connected into the virtual fly body, created using a biomechanical model of the fly built from the actual X-ray micro tomography scans of a real fly. The virtual fly has 87 independent joints and it synchronizes with the brain emulation every 15 milliseconds.

The idea is that sensory events in the virtual world activate the right sensory neurons, the brain processes them and motor outputs go to the virtual body. In response, the body moves, the movement changes the sensory state, which feeds back into the brain in a closed loop.

The results were staggering. When activated, the virtual fly began walking, grooming, and looking for food, behaving like a real one. It produced naturalistic behaviors without a single line of explicit behavioral programming, without any training, data-driven optimization or machine learning involved. The behavior emerged directly from the brain's wiring in the simulated construct.

Locomotion emerged spontaneously as a tripod gait, mirroring the characteristic walking pattern of real insects. When the researchers introduced a virtual ”odor” into the simulation or an environment containing virtual food cues, the digital fly navigated toward them using strategies consistent with biological foraging. This marked the first time a complex animal behavior had been recreated entirely through biological architecture in a virtual environment rather than machine learning algorithms, making the fruit fly one of the first organisms whose brain has been both mapped and functionally executed. The remarkable fact is that the displayed behaviors were not programmed in advance, nor were they learned through training. Instead, they arose from the interaction between the network's wiring, the dynamical rules governing neural activity, and the constraints imposed by the simulated body and environment.

Figure 2: A print screen of the digitally simulated construct showing the fruit fly searching for food and feeding itself when sugar / food stimuli was simulated.

This distinction is crucial. In most contemporary artificial intelligence systems, behavior is the outcome of training processes that adjust parameters to fit data. In the digital fly, behavior is instead an intrinsic consequence of biological architecture. It demonstrates that the connectome functions not merely as a description of the system, but as its underlying program.

The implications of this work extend well beyond the study of insects. The efficiency of the fly brain, operating with minimal energy consumption while supporting robust sensorimotor integration, offers a compelling template for neuromorphic engineering and edge computing. At the same time, the ability to simulate a complete nervous system at synaptic resolution opens new avenues for in silico experimentation, enabling researchers to perturb circuits, test hypotheses, and explore pharmacological effects in ways that are difficult or impossible in vivo. More broadly, these results provide an empirical foothold for scaling efforts in connectomics of larger brains. Essentially, the methodology demonstrated here does not obviously break when applied to more complex organisms. Within two years, Eon plans to attempt a mouse brain emulation, which is roughly 70 million neurons, or 560 times larger than a fly's count. The human brain contains approximately 90 billion neurons, which is orders of magnitude larger than a fruit fly's brain. However, if this approach scales successfully to more complex brains, the implications become huge. In theory, the same brain model could be placed in different environments or bodies: robots, virtual worlds, or simulations. It also raises a deeper question: if one day a human brain could be copied this way, what would actually wake up inside the simulation?

Beyond its technical significance, however, this work raises deeper conceptual questions. If a digital system reproduces the structure and dynamics of a biological brain closely enough to generate indistinguishable behavior, what distinguishes simulation from reality [7]?

The conceptual leap enabled by these studies naturally invites comparison with the long-debated simulation hypothesis. If a biological organism can be reduced to its structural and dynamical principles, i.e. its connectome and the rules governing signal propagation, and if those principles can be instantiated in a computational substrate to produce behavior indistinguishable from the original, then the boundary between reality and computation becomes less ontologically rigid. What the digital fruit fly demonstrates is not merely that life can be simulated, but that under certain conditions, simulation may be functionally equivalent to instantiation.

This raises a provocative possibility that what we interpret as physical reality could itself be the emergent behavior of an underlying computational architecture [8], governed by rules analogous to those we now extract from neural systems.

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