Artificial Morphogenesis via 3D Neural Cellular Automata

Marco Ravelo, Etienne Vouga

This project presents a computational model of morphogenesis, the biological process by which an organism grows and takes its form. We employ three-dimensional neural cellular automata (NCA) to grow from a starting seed state into a target object from a series of update steps. NCA, a modern derivative of classical cellular automata (CA), makes novel use of a neural network within its update step. Akin to real-world cells, each artificial cell acts independently of one another and is only able to perceive local neighboring cells. Despite lacking a global control mechanism, the cells are able to act as a collective such that a trained NCA model displays morphogenic properties such as growth in size, shape, and complexity over time, regeneration after cellular damage, and isotropic self-organization. Understanding the intricacies of morphogenesis has the potential to provide beneficial insights for the development of regenerative medicines, self-organizing robots, and other bio-engineering endeavors.

Our NCA model is built from a collection of cells depicted as unit cubes (voxels) situated at integer coordinates within a regular 3D orthogonal grid. We represent each cell's state as a vector of 16 real number values between 0 and 1. The update step is what propels an NCA model forward through time, such that one step takes a model from time-step *t* to time-step *t+1*. It is comprised of four distinct sub-steps: (1) local cell perception via depth-wise 3D convolution, (2) a neural update, (3) a stochastic update, and (4) a living cell update. Cell perception utilizes fixed 3D convolution kernels such as the 3D discrete *Laplace* operator and the 3D *Sobel* operator and its transposes; Different perception types make use of different sets of fixed kernels. The neural network located within the neural update sub-step is what allots NCA as being *neural*. It is constructed from two dense layers with a non-linear ReLU function between them. Analogous to a residual neural network, the update step adds its result to the current state of the cells.