Artificial Morphogenesis via 3D Neural Cellular Automata

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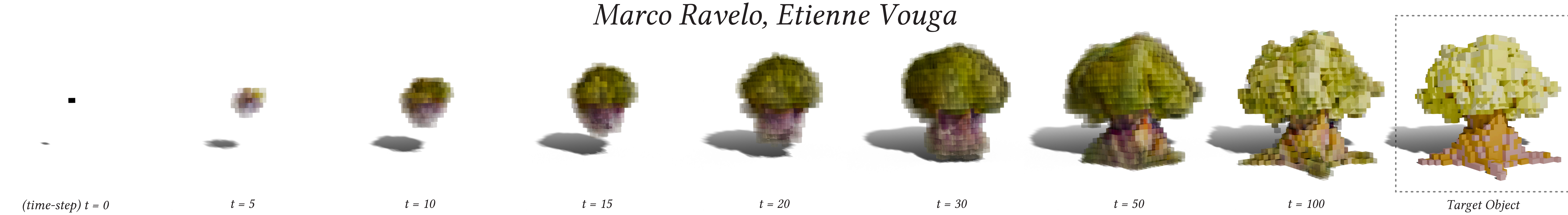

Figure 1: An NCA model growing into an oak tree object over the course of 100 update steps. This model uses a single cell as its starting seed state and anisotropic perception as its perception type. The framed image on the right shows the target object the model was trained to grow into.

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.

The NCA model is built from a collection of cells depicted as unit cubes (voxels) situated at integer coordinates within a regular 3D orthogonal grid. Each cell's state is represented as a vector of 16 real numbers valued between 0 and 1. The first three channels in a vector describe a cell's color (RGB) while the fourth channel describes a cell's transparency (α). Additionally, α values characterize a cell's living state, such that cells with $\alpha > 0.1$ are considered *alive*, otherwise they are considered *dead* and consequently ignored. The update step (illustrated in the diagram to the right) 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, (2) a neural update, (3) a stochastic update, and (4) a living cell update. The neural network located within the neural update sub-step is what allots NCA as being *neural*. Analogous to a residual neural network, the update step adds its result to the current state of the cells.

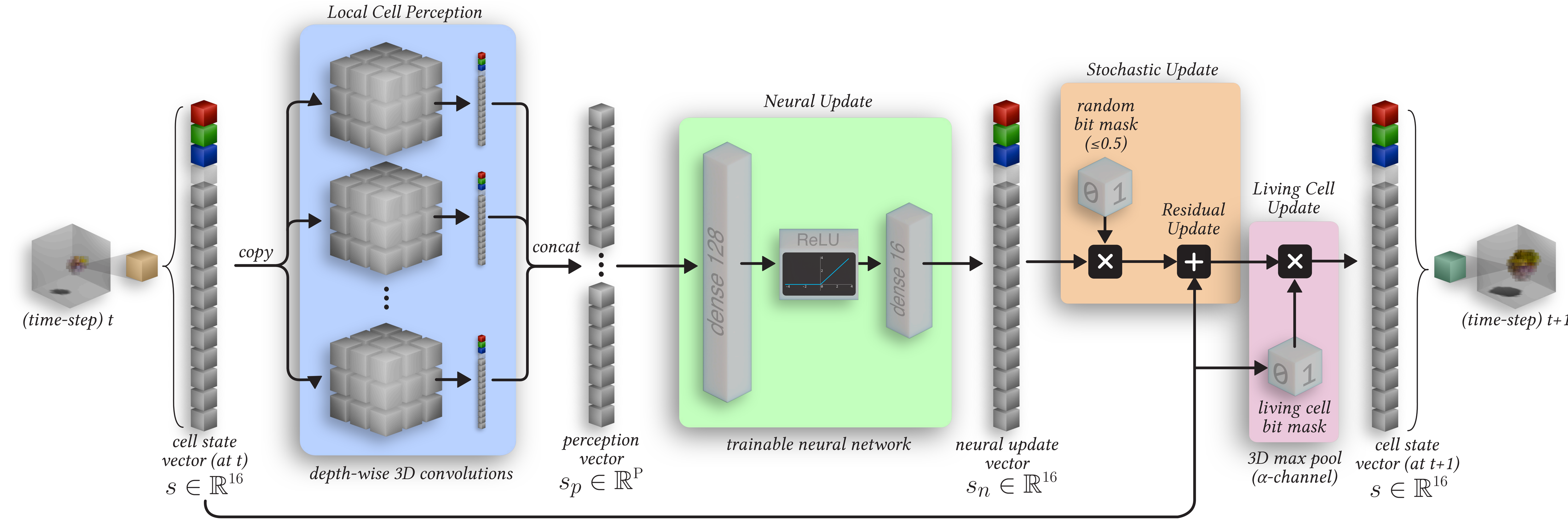

Figure 2: A diagram illustrating the update step for a single cell.

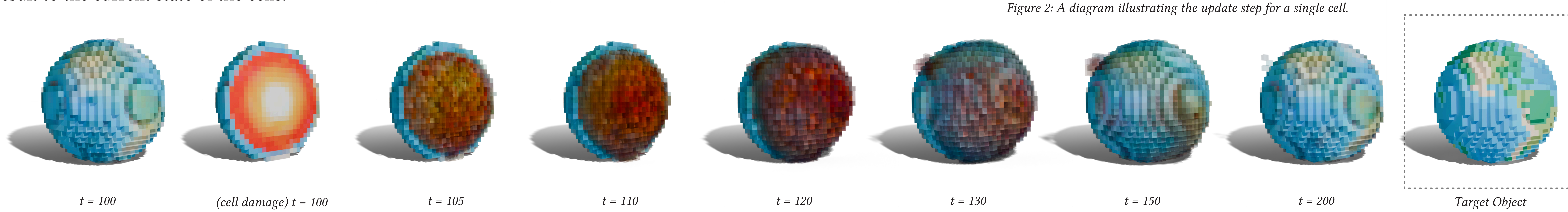

Figure 3: An NCA model showcasing regeneration after cellular damage. The model was first allowed to grow for 100 update steps; thereafter, cellular damage was applied in the form of a half volume bit mask. The model was able to fully restore itself after another 100 update steps.

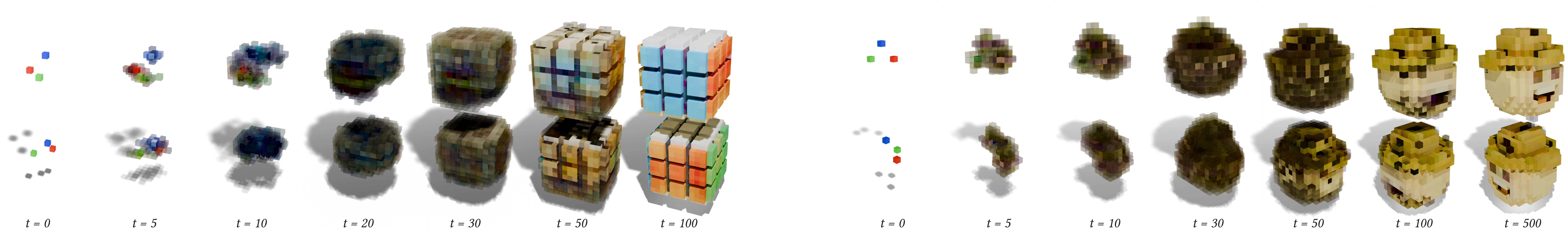

Figure 4: Two NCA models showcasing isotropic growth. In both examples, a pair of starting seed states are positioned such that the bottom state is rotated 90 degrees clockwise about the y-axis from the top state. The orientation of the final object is dependent on the initial conditions.