The Neighbour-Sensing model of hyphal growth as an experimental tool

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What is it?

The Neighbour-Sensing model is a new, vector-based, mathematical model and computer program that provides a life-like tool enabling experimentation on fungal growth by visualising the virtual hyphal growth patterns. The Neighbour-Sensing model 'grows' a simulated mycelium in your computer using branching rules decided by you the user, and calculates everything else it needs to generate a mycelium. As the cyberhyphal tips grow out into the modelling space the model tracks where they've been and those tracks become the hyphal threads of the cybermycelium.

But that's not all. Most mathematical models leave you with the mathematics. And not everyone is entirely comfortable with that. We give you a fully-fledged Java™ application with user-friendly interface to interact with the mathematical model and an on-screen, 3-dimensional visualization. So you can SEE your cyberfungus growing. Interact with it. Pause the visualization, change the growth characters. Produce complex morphologies.

How does it work?

The Neighbour-Sensing model produces an extremely realistic simulation, and careful choice of its growth rules can produce simulations that closely mimic real fungi. The realism comes from the fact that the computer hyphal tips are given life-like characteristics

The essential part of the Neighbour-Sensing model is a hyphal tip able to venture into cyberspace itself, as an active agent following the rules it has been given. Each tip has position in three-dimensional space, it has a growth vector and it has length, and an ability to branch. The program starts out with just one hyphal tip, which is equivalent to the fungal spore. Each time the program runs through its algorithm the tip advances by a growth vector (initially set by the user) and may branch (with an initial probability set by the user). These simple features (or 'parameters'), where direction of growth is random, are sufficient to result in a spherical colony (circular if growth is restricted to a flat plane).

So the first conclusion of the modelling experiments is that the characteristically circular colony of fungi does not need to be contrived - it is a natural outcome of the exploratory apical growth of fungi.

Real fungi, however, do not grow in random directions. Real hyphal tips grow in accordance with their reactions to the effects of one or more tropisms. In this Neighbour-Sensing mathematical model of hyphal growth the growth vector of each virtual hyphal tip depends upon values derived from its surrounding virtual mycelium. Effectively, the virtual hyphal tip is sensing the neighbouring mycelium.

Tropisms are implemented in the Neighbour-Sensing model using the concept of a field to which growing hyphal tips react. In the real physical world, the field might be an electrical field for a galvanotropism, the Earth's gravitational field for a gravitropism, or a chemical diffusion gradient. In the mathematical model, the same basic field equations can be used for all, the different tropisms being distinguished by the different physical characteristics ascribed to the field.

The published model features seven tropisms: negative autotropism, based on the hyphal density field; secondary long range autotropism (that attenuates with either direct or inverse proportionality to the square root of distance); tertiary long range autotropism**,** which attenuates as rapidly as the negative autotropism but can be given a large impact value; two galvanotropisms based on the physics of an electric field produced by the hypha which is parallel to the hyphal long axis; a gravitropism, which orients hyphae relative to the vertical axis of the user's monitor screen, and a horizontal plane tropism, which provides a way of simulating colonies growing in or on a substratum like agar or soil by imposing a horizontal geometrical constraint on the data space the cyberhyphal tips can explore. The user can determine how strongly the hyphal tips are limited to the horizontal plane, and the permissible layer thickness.

What does it do?

The Neighbour-Sensing model provides the user with a set of abstract mathematical tools which amount to a culture of a newly arrived fungus. What do you want to do with it? The rate of growth of the cyberfungus is up to you and the power of your computer, so you could do more experiments in an afternoon's computing than you could do in a year in the laboratory.

There might be some experiments that are impossible, or at least very difficult, to carry out with live fungi. Could you measure the total length of mould mycelium in a leaf as it develops an attack of mildew? Yes, probably, if you cut up the leaf and use a lot of microscopy - but by the time you've finished the leaf's dead! Yet a computer program can easily calculate the total length of hyphae – and how many branches, and show you where they all are; and do it again 5 minutes later, and 5 minutes after that.

Something else you could try, is to find out how long it takes a fungal pathogen to grow across a forest floor to attack an entire forest. You could do that in a real forest. If you live long enough, that is, because it might take 50, 60 or 70 years in a real forest. But set up a good computer model and it will give you the results tomorrow; with a complete set of distribution maps!

What might it do in the future?

The Neighbour-Sensing model is now sufficiently advanced for parameters to be defined that simulate specific *in silico* cyberfungi. Do it for one – do it for many: establish a 'culture collection' of cyber species that can be chosen from a menu like the characters of a computer game.

The potential utility of these cyberspecies is that they provide a means to model the morphogenetic effects of a variety of factors, from environmental and nutritional features to mutations, in experimentally realistic situations, offering a valuable addition to the experimental toolkit of all those interested in fungal growth and morphology.

We're working on the mathematics of hyphal anastomosis. Inclusion of anastomosis will enable the model to generate biologically inspired networks and so provide a tool to analyse these networks to yield information about connectivity, minimum path length, etc.

Since the Neighbour-Sensing model 'grows' a realistic mycelium and tracks all of the hyphal segments so generated, looking further into the future, it should be possible to assign to those hyphal segments the algebraic characteristics defined to describe substrate uptake, utilization and translocation kinetics.

With these features added, the cybermycelium will follow realistic rules to grow; use substrates; produce products; translocate metabolites. The cybermycelium will live!

Experience the model at http://www.davidmoore.org.uk/Cyberfungi/index.htm