A synthesis of Ant Colony Dynamics, Embryonics and Artificial Chemistry.

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The Problem: How to design a self-assembling circuit that handles defects and faults dynamically in the absence of any top down control.

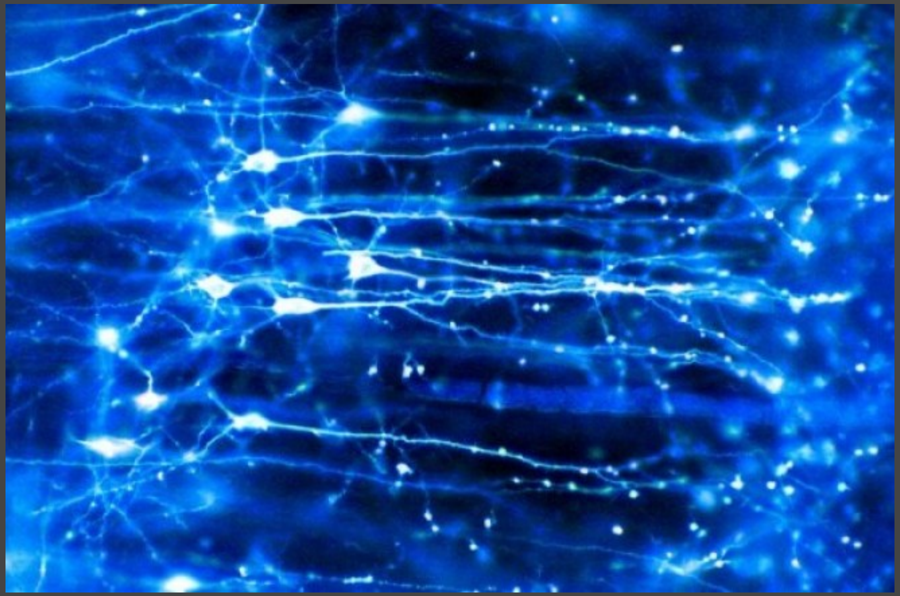
Sounds easy.

Actually quite difficult. The stochastic environment means that structure must emerge from the bottom up.

One of the main challenges was how to address macro-level questions from a micro-level perspective.

Things like:

Is the circuit connected?
What direction is the current flowing?
How does the signal propagate down a wire?



So I took some inspiration from ant-colony optimization, but expanded it to have a set of concentrations, rather than just one.

Finding paths isn't the only thing ants use pheromones for.

Communicating status, sounding alarm, attracting mates, differentiating members of other colonies, nest construction, etc etc

My idea is that the particles communicate through messages left in the environment.

Each particle can sense the concentrations of the various types of markers in its own square and the squares surrounding it.

Each particle can deposit or absorb any concentration of any type of marker only in the square it is occupying.

Some of the markers dissipate with time while others are permanent.

But none of the markers propagate on their own.

Only particles may affect the concentrations of the various markers.

I thought of it almost as a multi-headed two-dimensional stochastic Turing machine.

Each particle is a head, reading the concentrations and writing concentrations, then moving one direction or another on a two-dimensional plane.

Randomness as a computational element

There are two main types of concentrations the particles use as communication.

: Alarm :

Used to signal that a defect is along this band and in this orientation. This signals to any wire growing along this band in this orientation to dissolve and seek other areas.

: Growth :

These are generated by particles the terminals of growing wires and propagated by undifferentiated seeking particles to form a gradient along which other particles can navigate towards growing wires.

Each particle starts out in the blank state, and differentiates itself based on things it encounters in the environment.

Particles can be in one of three states: Seek, Grow or Gate.

This is the embryonics idea that each particle houses the entire program, beginning undifferentiated and developing in response to external signals.

So each state is really a function which defines how a particle will behave in the given circumstances.

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function [particle, concentrations] = particleGrow(particle, grid)
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The states are self-contained and each refer to each other. Thus any given set of functions with the right signature can act as the states for the system.

I have this set of functions as a parameter given when the grid is created, so that it may behave in any desired way.

This is, in essence, how the system is programmed.

SEEK

the undifferentiated state

SEEK: Particle exploring the environment.

During the seeking phase, the particle has a variety of activities.

If a defect is discovered, the particle lays the alarm marker in its current location and moves away from the defect, continuing to lay the alarm marker along a line emanating from the defect.

Alarm markers are directional, so there is one each for the horizontal and vertical directions. This allows valid wires to be lain perpendicular to the defect bands implied by the defect.

SEEK: Particle exploring the environment.

If no defect or alarm marker is present the particle spreads the growth concentrations surrounding it in the environment.

On the other hand, if an input or output pad is found and there is no pre-existing growth concentration, it affixes to it and changes to the GROW state, becoming the first root of a new wire. Once in the GROW state, it begins emitting a growth concentration to attract other particles.

If no specific force acts on the particle in this way, it moves in the usual random fashion.

GROW

particles binding together

GROW: Particles forming a wire.

The GROW state is very simple, the particle stays rooted where it is and emits a concentration proportional to the length of the wire. As a new particle becomes attached, it notes a length one longer than the particle it is attaching to, and the original one stops emitting a concentration while the new one starts emitting a stronger concentration.

To avoid a multitude of particles affixing as tiny wires along the length of the input or output pad, particles in the GROW state also look for surrounding concentrations higher than the ones they themselves are emitting. This is a signal that a larger wire exists in the environment, and triggers the GROW state to revert back to SEEK. As it reverts, this reverts the next particle down, triggering the dissolution of the shorter wire.

These particles are now available to affix to the longer wire.

GATE

integrating signals into a logical function

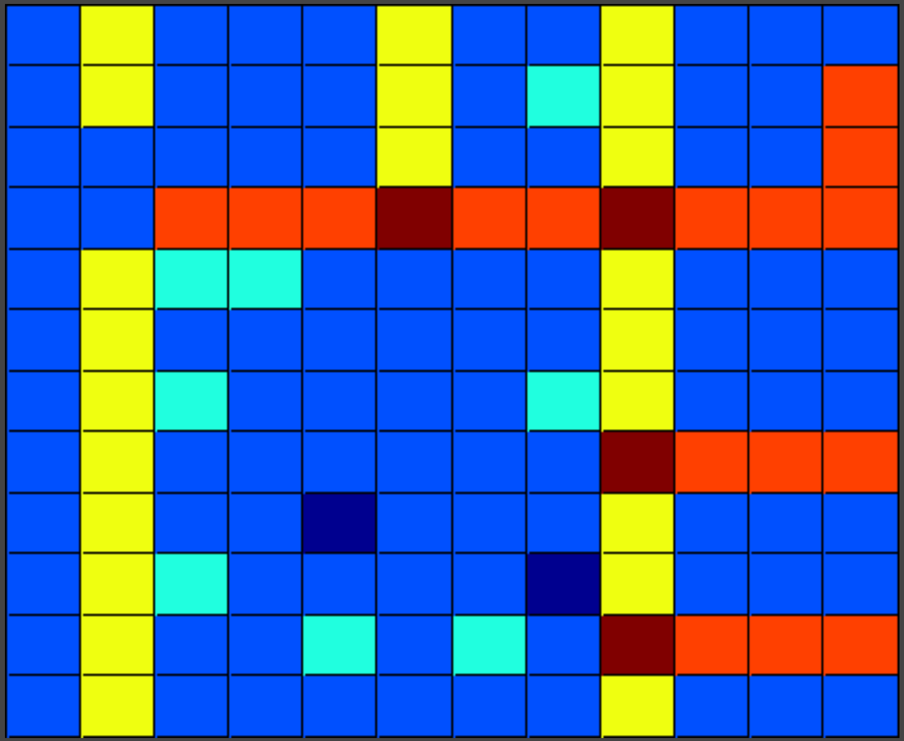
GATE: Executing a logical function.

When two perpendicular wires meet, the particle at the hub transitions into the GATE state. It elevates its contact level to the maximum possible value, letting the lower values propagate down the wires, establishing the orientation of the wires and the direction of signal flow.

It then reads the signal values of the two inputs and attains the signal state of applying the gate's logical function. This signal state is later read by the particle at the base of the output wire, and propagates down the wire towards the output pad.

After between 30-100 timesteps the circuit would usually have self-assembled, many times with redundant structure as shown. This redundant structure provided no down time at all was incurred in the case of faults that lay in the redundant structure.

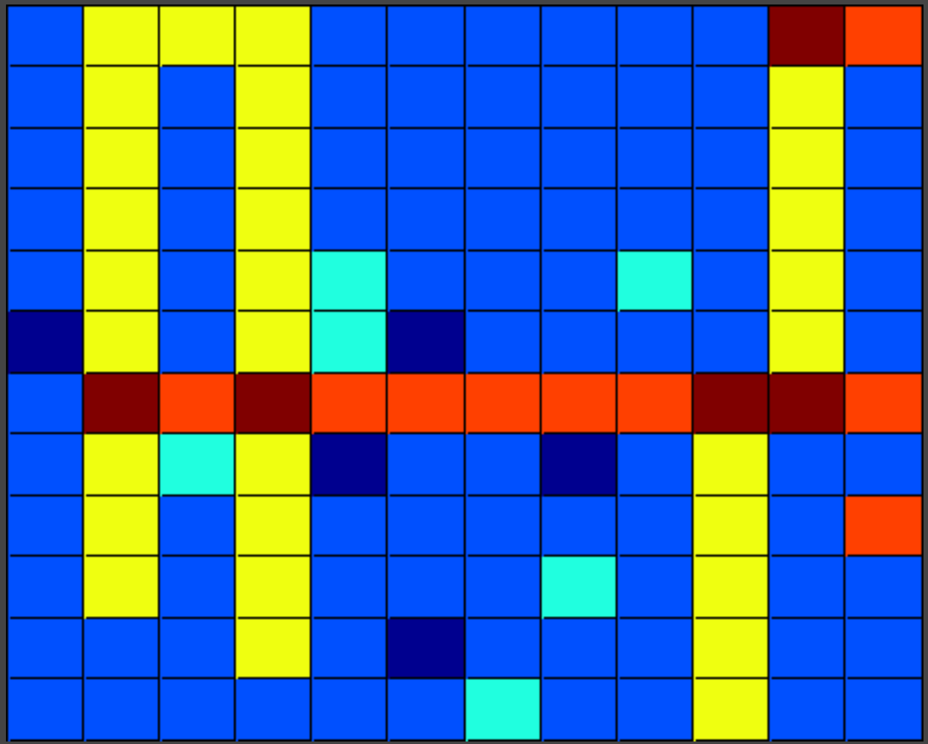
If faults did appear, they were quickly patched if open particles were available.



RESULTS

An interesting side effect of this approach is that the circuit was still able to function if the inputs were not in the same band. This circuit still functioned correctly when switching the input pads back and forth, with signal propagation taking between 10-15 cycles.

This is mostly due to keeping two signals flowing, one for each input pad.



RESULTS

Benefits

The fact that the particles are always able to change states or revert back to being undifferentiated means that the system is ultimately flexible. There is no need for separate phases of construction and signaling, all particles are constructing and signaling all the time.

The use of concentrations of markers rather than gradients means that the system was simply a direct consequence of the behavior of the particles and the markers they laid, rather than a gradient present in the background that affects all particles simultaneously. This also allowed fine-grained spatial messages to occur in the environment, like the defect bands.

This was the simplest system, with the least number of independent mechanisms, I was able to find.

Problems

The diffusion of the concentration messages depend on a particle being present in the environment and open to propagate it. This can take time if there are not many unattached particles left.

Particles still get wasted being attached to a pad yet alone or being trapped in the region between two wires.

Sometimes if a fault occurs and there is no particle around to read or propagate the signal, it takes an unnecessarily long time to patch the fault (sometimes never).

This all assumes there is some kind of mechanism for a particle to read and deposit messages in the environment for any practical implementation.

Improvements

Some mix of gradients and communication markers could make fault recovery more effective, for instance when there are not as many particles remaining that are not already performing duties as part of another wire.

Make some means for it to be easier to define states and the behaviors that occur. Possibly a domain specific language.

Allow circuits to perform arbitrary logical operations, and have the operations that are performed be a consequence of the structure of the circuit.

The behavior could be more rich if a wider variety of concentrations were used that represented a greater depth of conditions and communication.

Find a way to break down unused or incomplete structures to a greater degree. This was achieved partially using concentrations and strand dissolution, but there are still wire fragments littering the grid.