# THE THEORY BEHIND ECOBOTS

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The key to simulating life in Ecobots is the combination of these dynamics:

- Self replication within population limits

- Randomness

- Destruction

- Feedback loops

In combination these can give rise to a system which is semi-stable in size yet is constantly adjusting itself, and will mostly likely end up circling around an attractor state to which the system is drawn... which is pretty much what life on planet Earth does.

## REPLICATION AND LIMITS

The key equation in Ecobots is this:

$p = mr - d$

Where:

$p$ = the population limit at which replication is stopped

$m$ = how many times larger than the radius the population can grow

$r$ = the radius around each bot which counts as being within its population

$d$ = the dispersal radius, i.e. how far away a new bot can be spawned from its parent.

This seems to be the threshold between stasis and exponential growth (although I can't say for sure. Perhaps someone more mathematically gifted can figure this out? You perhaps?).

Below the threshold structures grow to a set size then become locked, or end up with a single growing point (depending on *m*). Too far above the threshold and new bots are able to spread into new areas and grow exponentially - quickly covering the entire universe in a fifty-quadrillion deep layer of bots.

## EXAMPLE:

This is a fully grown structure:

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| | A2 | A | B | C | D | |
| | | A1 | B1 | | | |
| | | A1' | | | | |
| | | | | | | |

This image shows how the structure grew, starting from A, until every block hit its population limit and stopped.

Colored cells are blocks. The letters represent lines of descent starting from block A. The colour represents the generation.

A through D is our main line of growth.  A1 is a sibling of B from A. A1' is a child of A1 and so on.

In this example blocks are placed clockwise into empty cells, at right angles. Each block continues creating offspring until it hits it's local population limit.

This example used $r = 4$, $m = 2$, $d = 1$

Therefore

$p = mr - d$

$p = 2 \times 4 - 1$

$p = 7$

If we look at this in table form we can see when each block hit $p = 7$. In this case they all reached it after three generations. (with other set ups some will stop early, and sometimes one single block continues forever)

| Generation | **A** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0 | 1 | **B** | | | | | | |
| 1 | 2 | 2 | **A1** | **C** | | | | |
| 2 | 4 | 4 | 4 | 4 | **A2** | **A1'** | **B1** | **D** |
| 3 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |

Therefore we are able to use replication but keep it under strict control. But a locked structure is hardly alive.

We need  more...

## RANDOMNESS

Let’s add some randomness. This is the same as above, but now instead of rigidly going clockwise, blocks go in a random place.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | | | B1 | | | | |
| | | | | B | | | |
| | | A2 | A | | C | D | |
| | | A1 | | | | | |
| | A1' | | | | | | |
| | | | | | | | |
| | | | | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| T | **A** | | | | | | | |
| 0 | 1 | **B** | | | | | | |
| 1 | 2 | 2 | C | A1 | | | | |
| 2 | 4 | 4 | 4 | 4 | D | A2 | B1 | A1' |
| 3 | 8 | 8 | 8 | 8 | 7 | 8 | 8 | 7 |

Again the structure locked itself up in the same amount of time, but it was not guaranteed.

Let’s run it again...

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | | | | | | | |
| | | | | | | D | |
| | | | | | C | | |
| | | | | B | | | |
| | | | A | B1 | | | |
| | A1' | A1 | | | | | |
| | A2 | | | | | | |
| | | | | | | | |

This time four of the blocks are still below their population limits. They will keep growing.

| T | **A** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0 | 1 | **B** | | | | | | |
| 1 | 2 | 2 | **C** | **A1** | | | | |
| 2 | 4 | 4 | 4 | 4 | **D** | **A2** | **B1** | **A1'** |
| 3 | 8 | 8 | 6 | 7 | 5 | 6 | 8 | 6 |

It is easy to imagine that if we we're to try this again and again that sometimes they would spread out and get further, and sometimes they would clump up and halt early.

Randomness adds variability and unpredictability to our structure. Yet, these will still lock themselves up into a static shape eventually. They run out of luck, choose a bad shape, and stop.

We need something else...

## DESTRUCTION

It's a cliché that destruction is necessary for creation. In this case it is also true.

If we were to take a locked up structure from our examples above and destroy a few blocks it would release some of them to replicate again. They would be able to roll the dice again, possibly choose a better shape and keep on growing.

However, once the structure has recovered from the damage, it will still end up static eventually.

We need something more...

## FEEDBACK LOOPS

We can do two things. Either we keep damaging the structure, or better yet, we tie growth and destruction together.

If growth can be made to cause destruction then the structure can get caught in a loop. New growth will lead to destruction which will lead to new growth which will lead to destruction....

So long as growth and destruction are kept in balance the system will exist in a state of constant rearrangement. It will randomly try all the possible states in which it can exist.

The likely outcome of all this is that the system will gravitate towards some attractor state. The nature of this attractor state will then govern what the system spends most of its time doing.

That attractor will probably be whatever state enhances the total number of blocks in the system. Those states that enhance the structure’s ability to survive and grow will get locked into the system, while those that don’t will die out. The structure will be at a basic level adaptive.

With all of these components put together the structure behaves as a truly complex system. It embodies a few of the basics of what allows life to be alive.

## MAKING CREATURES

So far we’ve merely made adaptive structures, but nothing that behaves like a real organism. Moving from blocks to block-forests is done by imposing conditions.

When will a bot replicate?

When will it die?

Must bots be attached to other bots?

Can they attach anywhere? Only on the top? The side? To bots of a different species?

For example: all the plants can only grow in sunlight and will die if they get too much shade. These two rules alone will lead to tree like growth. Bots will expand into the light. Those beneath will get shaded to death. Eventually canopies and trunks will form , spontaneously mimicking the way real trees grow.

Ecobots uses these conditions and many others to create life-forms adapted to different conditions, and with differing growth forms... some for shade, others for snow, some that form tall trees, others that grow dense shrubs....

## SWARM INTELLIGENCE

What we’ve covered so far isn’t the only way simple blocks can create complex adaptive behavior. Ecobots also includes an example of swarm intelligence with the Eusocial Bot. It uses the same ideas of randomness, creation, destruction, and feedback loops but in a different way.

The Eusocial Bot is based on the behavior of ants. It uses its collective intelligence to locate food (in this case the pioneer grass), and deliver it to a central nest where the food is used to maintain and grow the nest and the swarm.

No individual bot has any idea where it is or what it is doing. It just follows these rules.

- All bots lay down trails.

- trails disappear over time.

- Bots can be in one of two states: searching or returning.

- Searching bots move randomly until they find food. They sometimes follow trails, but mostly go anywhere at all.

- When a bot has found food it eats it and switches to the returning state. Now it mainly follows trails.

- When a returning bot finds a nest it feeds it, then it switches back to the searching state.

That's it.

The only other rules are about defense, building tunnels, and so on. But these are all extras. They mainly just help with traffic flow.

Why does this work?

If a bot finds food then it will mostly likely head back to the trail it made getting there. It will then reinforce that trail. If more bots find food using that trail then the trail will be further reinforced.

If a bot fails to find food then it's trail will tend to disappear. It won't revisit it much because it will still be searching. That trail will fade from lack of use.

Therefore only trails that lead to food will be maintained in the long run.

The result is a series of trails that lead from the nest to food sources, that funnels bots between the nest and the food supply. A successful nest will end up with a central core of nests surrounded by a spider's web of trails all being maintained by an army of bots.

This whole swarming business is so effective I've had to place severe limits on where the Eusocial bot can live and what it can eat. Grass and Savannahs. They're yours swarm bot.

## NETWORK INTELLIGENCE

Another form of self organization Ecobots includes is based on the way networks behave - brains, the internet, or in this case... fireflies.

During the night the Herbivore Bot randomly produces flashes of light whenever it is in a suitable breeding and feeding site. This can become the basis for intelligent behavior.

Combined with some principles from the way real world networks behave, the bots can use these light flashes to learn about the global state of their entire population, and then congregate in whatever location has the best food supply.

How does this work?

Each bot aims to synchronize with all the others. They pull this off by creating a *small-world* network. Ever run into a stranger and found out you both have a friend in common? That's a small-world network.

Each bot will flash its light if enough of its neighbors do. That's an obvious requirement. But the trick is this - it has a small chance of turning on if a distant bot does.

Therefore, it's local cluster gets linked to other clusters, which are in turn linked to others. Within a few jumps the entire population across the whole landscape gets linked together. Six degrees of separation - firefly style. The result - any synchronization that arises can spread through the entire network.

The bot is able to use this to its survival advantage.

- Only bots on food supplies light up to begin with.

- The more bots around the quicker they synchronize.

- All bots will move towards the brightest group .

The best connected and best fed will be the most likely to synchronize first, therefore they will be the brightest. Everyone will move towards them which makes them even brighter. This sets up a positive feedback loop which slowly draws the entire population together in one place.

Then during the day they disperse, explore and find new food supplies... ready to begin anew the next night.

## ECOLOGY

Ecobots uses all the above to simulate an ecosystem. Instead of one structure it produces dozens, or hundreds, of interacting structures which then together make a much larger complex system which embodies the same ability to change, grow, and adapt.

Here's what each of the broad categories of blocks does in the system:

Plants :

> All ecosystems are open systems, that is they take in matter and energy from the outside. Plants are the doorway in.
>
> They limit all the other populations by controlling everything's food supply. They add matter to the system, and ultimately control it's physical shape, light conditions, quantity of soil and so on.

Herbivores:

> They clear old plant growth thereby stimulating new plant growth (the destruction aspect), and they redistribute plant matter dispersing it to new areas (by making it fall), and sending it to the forest floor to feed the decomposers.

Dead Matter and Decomposers:

> The dead matter and wood feeds the decomposers who break down all the mass which the plants are adding to the system. They stop the overall system from accumulating enormous amounts of mass. However they do create some persistent soil - this enables the ecosystem to do terraforming, coating even bare rock in soil, which then allows more plant growth.

Predators:

> The predators should add stability. They create negative feedback loops on the growth of their prey populations. Without this there is the potential for plague like explosions of herbivores killing all the trees, or outbreaks of fungus eating all the wood, both of which could make the system collapse.

In combination these components capture the bare basics of how ecosystems work. Real ecosystems are of course orders of magnitude more complicated than Ecobots, containing hundreds to thousands to even millions of species (if you count all the bacteria!). Even the most sophisticated computer simulation will only ever capture the smallest slice of all this wondrous complexity.

## A CRASH COURSE IN ECOLOGY

If you want to understand what's going on in your Ecobot forest you'll need to learn a little ecology. Here's just a few key concepts that are relevant to Ecobots. This is a fairly light smattering of the things that your Ecobot forest might get up to.

### POPULATION DYNAMICS

Building our structures at the start we imposed strict population limits around each bot. But these don't apply at a large scale. Instead the Ecobot populations grow and are limited like real species.

The big limit on exponential growth is the *Carry Capacity,* or *K*. This is the maximum (sustainable) size of the population. *K* is determined by the availability of resources: space, food, etc.

Below *K* and the population will grow. Above *K* and the population will deplete it's resources and crash - this is called overshoot, and could happen with the Ecobot animal populations. (The plants don't deplete anything so they should just stop growing when they run out of space).

### BIODIVERSITY

Ecobots includes many different species (mostly of plants). This isn't just for aesthetics. Biodiversity is extremely important for maintaining functional ecosystems. It not only allows life to occupy all the available habitats, but more importantly, it makes the system as a whole more robust.

No matter what happens something will always survive.

Burn the forest down and the fast-growing light-loving pioneer species will come in. Floods? The swamp species can move in. Blast the landscape into a desert hell-scape? The desert species will thrive.

Diversity also stabilizes the food webs. If, say, the herbivores eat one species to near extinction they won't also go extinct themselves. They can switch to another food supply and (hopefully) let the first recover.

### FOOD WEBS AND TROPHIC CASCADES

However, Ecobots' food web is still extremely simple - chances are Ecobots will suffer from *Trophic Cascades*. This is where a disturbance in one part of the system cascades through the food web causing everything to dramatically change.

Let's say you cut down all the trees.  Now the herbivore population will crash. Then the predator populations will crash. Then the remaining herbivores will be free of predators, so their population will explode, and eat all the surviving plants driving everything extinct (okay... this is kind of extreme, but it is possible).

Because the system is so simple nothing is able to switch to a new food supply. Their populations are tightly bound together. The whole system can suffer from a *Cascade Failure* - damage ripples out killing everything.

This kind of linked behavior is why human changes to real world ecosystems have often lead to bizarrely unexpected outcomes -  such as introducing shrimp to a lake causing eagles to go extinct.

A more common occurrence may be *predator-prey oscillations*. As prey numbers grow so to do their predators, which then drives down the prey numbers, which drives down the predator numbers, which allows prey numbers to grow again. Up and down. Round and round.

Adding diversity also allows Ecobots to model  a lot of other important ecological phenomena  too...

## NICHES

In the real world all species have to specialize to some extent. What makes you good at living in a swamp tends to be the opposite of what makes you a good desert-dweller.  Ecobots imposes many of these real world trade offs onto its species.

Broadly these niches are based on growth form, and habitat type. Desert dwellers are generally restricted to deserts, forest trees die in the desert. Some plants tolerate shade but grow slow, while others grow fast but need light. Some grow spreading canopies, others shoot straight up through that canopy....

Each species will have a fundamental niche, and a realized niche: the area they could inhabit, and the area they actually do inhabit. This will arise in part due to historical accident (namely the map spawner ), and partly due to other species....

## SPECIES INTERACTIONS

Each species will have an impact on the success of other species.

-*Exploitation*:  herbivores and predators obviously have a negative impact on their prey. But other more complicated forms of exploitation may arise.  The Hill Tree is able to grow up other tree's trunks - it may act like a Strangler Fig, using their trunk to reach the light then shading them to death.

-*Competition*: All the plants need light. This could lead to competitive exclusion - where one species drives all others out. Important in both exploitation and competition  is the existence of *Refugia* - safe places. Somewhere to escape to where they can't get you. These help keep species alive.

-*Commensalism*: Some species benefit from others, but have no real impact on them in return... like the bacteria growing on your toes, or in Ecobots the small shade-loving plants under the forest giants.

-*Mutualism*: this is where two species team up for a double win. I haven't made any special effort to include this, but it might arise naturally - see if you can find any!

## SUCCESSION

All these niches and interactions allow the whole system to change over time. As the system grows, the niches which are most successful will change. The pioneers will be best early on, but later they will get shaded out and the shade tolerant trees will succeed them.

This is ecological succession - the means by which ecosystems repair themselves, moving from bare dirt to grassy fields, to towering forests.

A big question is whether Ecobots will form *Climax Communities* - mythic stable end states which can go on forever. It's an open question for real ecosystems too.

## SPATIAL PATTERNS

Because different species live in different areas many spatial patterns will arise.

- *Patches*: landscapes have structure. Each different ecosystem type consists of a patch surrounded by patches of other ecosystem types. The shape and size of these patches will have a big impact on what goes on inside them.

- *Landscape Heterogeneity*: the more varied the landscape then the more different types of patches it will have. This boosts species diversity.

- *Edge Effects*: the edge of a patch typically has different conditions than the core. Different species will thrive at different distances from the edge. In a forest light loving species will end up near the edge, and shade-lovers in the core.

-*Source and sink populations*: Some patches are not big enough to sustain a viable population in the long run. They act as "sinks", plug-holes down which individuals get sucked into oblivion. They move in, they die out, some more move in....

- *Patch connectivity*: patches that are well connected to other patches are able to be re-colonized if a species goes extinct. Isolated patches stay down. This can have a big effect on populations and species diversity. Islands (in the loose sense of the word) tend to have fewer species as a result.

## KEYSTONE SPECIES AND ECOSYSTEM ENGINEERS

Some species are more important than others. These are *Keystones*, without them everything else falls apart. In Ecobots the forest trees can act like keystones, supporting animal populations and undergrowth. The pioneer grass is also a major food source for animals.

*Ecosystem Engineers* are a particular type of Keystone species. Instead of adapting themselves to their environment they do a bit of engineering, and adapt their environment to them. Think Beaver dams.

Ecobots does include one true Ecosystem Engineer, but I didn't put it there - it's called *Homo sapiens*. You. Ecosystem Engineer. Super Predator. Keystone species. Just like in real life.