SIMEARTH: A GREAT TOY

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Summary

SimEarth is a game that simulates the major environmental factors on a global scale. It uses a multilayered cellular automata. The simulation covers geologic activity, weather systems, plant life, animal life, and the effects of civilization on planet Earth.

1. Introduction

SimEarth was first conceived by Wil Wright while he was reading James Lovelock's *Gaia Hypothesis*. This theory proposes that the living matter of a world modifies the planetary environment to suit its own needs. Wil began working on a planet simulator trying to incorporate all major aspects of environmental science into a single model. I came on board for the last year of the project helping out with the geologic, biologic, and sapient models.

Our target machine for the game was the Macintosh 512k. At the time, this was the pinnacle of personal computers. We were constantly running into memory limitations. Between our large maps, window displays, and code segments we had to make choices that frequently limited our representation. Our final map had a total of ten bytes of information per tile. At the time this seemed lavish. Most of our values were a subsection of a byte and so have a binary range such as 0 to 7 or 0 to 31.

Another limitation on the simulation was our desire to make the resulting application into a game. We had to consider what would be interesting for the player, and we had to give him the power to change the environment. Ironically, we sort of failed in our initial attempt to make SimEarth into a game. Players could frequently win without touching a key. Our attempt to mold the simulation into a game worked best with the models of Mars and Venus. Without player intervention, life would never form in these environments and thus player intervention was vital to success.

We had fun creating SimEarth. Wil and I had the opportunity to apply our theoretical knowledge of the physical sciences into a fascinating toy. I garnered quite a few insights into the ways that environmental systems in our world interact. It gave me the feeling that good old Gaia can survive a lot more punishment than Man has yet dished out. I hope that feeling is correct.

2. Overview

The model is broken down into five general systems areas over four developmental eras. The five general model systems are Lithosphere, Aquasphere, Atmosphere, Biosphere, and Civilization. Lithosphere is the “solid” model—mantle, core, and plate tectonics. Aquasphere is the “liquid” model—ocean levels, temperature, and motion. Atmosphere is the “gaseous” model—air composition, temperature, motion, cloud formation. The Biosphere is the “life” model—biomes, creatures, evolution. Civilization is the “sapient” model—development of technology, philosophy, and other intelligent endeavors. Player intervention is a sixth model that is beyond the scope of this article.

The game eras are Geologic, Evolutionary, Civilized, and Technological. The geologic era covers the formation of oceans and continents and the evolution of early biology to the point that creatures crawl onto land. The evolutionary era concentrates on the alteration and evolution of species to the point that tool-using creatures invent fire. The civilized era concentrates on the development of an intelligent species up to the point that they figure out how to utilize nonrenewable sources of energy. The technological era is identical to the civilization era except that the prime species is using fossil fuels and atomic fuels. The game can advance forward through the eras or go backward depending on random events and player interaction.

There is a time limit built into the simulation. Over the course of time solar temperature increases and planetary core temperature decreases. After 10 billion years game time, the sun has expanded to the point that it engulfs your world, ending the simulation.

2.1. Modeling Methods

The basic model in this game is a state-based cellular automata. Cells maintain information on all five systems mentioned above. Our cells are organized into a number of two-dimensional arrays collectively called “the map.” Generally speaking, cells are only affected by themselves and the eight adjacent cells—although there are exceptions. There are also a number of global values. These values record systemic state changes (such as the current era), summarized values (such as biomass or zoomass), and cumulative values (such as fossil fuels or nitrogen levels). Finally there are the model variables. These values adjust the behavior of the diverse models. Because I will not be discussing player interaction, I will be ignoring the model variables.

Each cell has 10 bytes of information. Here is a list of the values each tile contains: terrain altitude, magma drift direction, magma drift speed, ocean existence bit, ocean temperature, ocean motion direction, ocean motion speed, air temperature, air motion direction, air motion speed, air cloud density, random events, biomes, creatures, sapient objects, and a city preclusion bit. We think of these values as existing in “layers.” When I refer to the “air temperature layer,” I mean the cell value for air temperature across the entire map.

The basic layer is a rectangular array of 128 horizontal tiles by 64 vertical tiles. Many of the games layers are half this size: 64 horizontal by 32 vertical. These smaller layers have “fat” cells. One fat cell will correspond to four “tiny” cells from the basic layers. For example, an animal in cell (10,10) would look into the fat weather cell (5,5) when looking for air temperature. A tiny cell with coordinates (X,Y) would correspond to a fat cell at (X/2,Y/2). The fat cell with coordinates (H,V) would correspond to the four tiny cells at (H×2,V×2), (H×2+1,V×2), (H×2,V×2+1), and (H×2+1,V×2+1).

Tiles on the right side wrap around to the left. Tiles on the top will “offset” wrap to another top tile halfway around the map. The same applies at the bottom. We did not adjust the representation of the tiles to account for the deformation of a sphere. Our only concession to the need for a spherical representation is to adjust the values of the model so that systems that occur near the “poles” are generally correct. For example, since arctic biomes usually appear at the poles, we adjust their effect on global temperature and water storage.

2.2. Responsive Updates

Most cellular automota update all the values of all their cells simultaneously. For our model this was too much work. What I mean is that updating everything took up so much processing time that the player found the game to be jerky and unresponsive. We use two techniques to make the game more interactive. The first is layered updating. The second is transfer map updating.

Layered updating simply means that we update the simulation one layer at a time. During the evolutionary era we first update the ocean temperature, then the ocean motion, then the air temperature, then the air currents, then animal life, and so on. Each layer update is performed completely before beginning another layer. This method also allows us to ration the simulation time between the layers. If one era requires more geologic simulation, we simply call the magma and altitude layer simulations more frequently.

Transfer map updating means that we copied our new cell values into a temporary map. Upon completion of a layer simulation we copy the new values back into the original map. This is a standard technique for cellular automota—it is used in the game of Life. When cells depend on adjacent cells for their new value, the mechanism of program looping can alter the results. By placing the new values into a temporary map we more effectively simulate simultaneous updating. For SimEarth this method has another benefit. We can update part of a layer, respond to the player, then continue updating the layer.

2.3. Approximations

Many of the numbers we use to create the simulator can only be described as "proximate." We frequently create value ranges that merely look correct. As commercial game designers it was more important for us to create an environment that felt right than to create a simulation that was accurate. For example, we use an air temperature range of eight bits equal to 0 to 255. When we created the model we were more concerned with how the temperature map looked than with what each number represented. After we finished balancing the model we went back and created functions that interpret the temperature value into something that looks more correct: a value range of from –50f to +150f.

3. Lithosphere Model

The lithosphere simulates the motion of magma and the collision of continental plates. The core model is linked to the planet's age. Magma motion is driven by earthquake events. Plate formation is the result of volcano events. Terrain altitude is the result of magma motion driving plates into collision. The terrain altitude is five bits equal to a range of 0 to 31. Values of more than 3 are considered to be tectonic plate material. The magma drift uses three bits for directions 0 to 7 (north, northeast, east, southeast, and so on), and four bits for speed equal to the range 0 to 15. A speed of 0 indicates that the magma is motionless.

It is possible to examine the planet's core in SimEarth. You will see the various layers—magma, mantle, core. This was included mostly as an educational tool. The thickness of these layers varies over time, but only in direct correlation to the planet's age. We found numbers indicating current magma layering and an estimate on values from several billion years ago. We did a simple linear extrapolation to find mantle thickness over time. The age of the core is expressed by the global value core heat.

3.1. Driving Events

During the geologic era the drift model is applied every 30 million years. Every time the drift model is called, the collision rules are applied and a "massive upwelling" event occurs. We also called this event the Nemesis Effect. This upwelling is the driving event for the magma model. When the upwelling hits a thick section of crust (terrain > 1), it becomes an earthquake. When it hits a thin section of crust it becomes a volcano. The power of these events is inversely proportional to the core heat of the planet.

The earthquake event alters the magma flow layer. The magma flow is altered over a circular region. All tiles in this area are set to a randomly selected direction and speed value. Magma flows are "smoothed" over time. Each time the magma motion model is called, some number of randomly selected cells will change their values to copy an adjacent cell. Over time this gives the appearance of fluid turbulence and helps to generate interesting terrain maps.

The volcano event randomly adds to the terrain level terrain over a circular region. This addition to altitude creates the crustal material that forms our tectonic plates. High terrain levels (terrain>3) are considered to be tectonic plates that are subject to collision rules. Each time the model is called, tiles with an appropriate speed will be pushed onto adjacent spaces. Tiles with high magma speed are moved more frequently.

3.2. Collision and Smoothing

When the terrain from a moving cell collides with terrain in a slower cell, collision rules are applied. First, if the target cell altitude is below plate level, then the moving cell value overrides the target cell, or else apply the second rule. Second, if the moving cell altitude is below plate level, then the moving cell is overridden by the target cell, or else apply the third rule. Third, if the speed of the moving cell exceeds the sum of the moving and target cell altitudes, then the altitudes are summed and placed in the target cell, or else no movement occurs. This third rule implies that mountain ranges will appear when tectonic plates are pushed together by fast magma flows.

The drift model will move all the tiles without repeating or skipping. When operating a two-dimensional cellular model, we scan the cells from left to right, top to bottom. In this case we have to be sure that the tile we scan has not already been moved AND that collision occurs on the wave front of a magma flow. We need three programming tricks to ensure this. First, tiles are moved onto a transfer map. Second, when we try to move a tile, we examine the cell it is entering and try to move that cell first. Moving the target cell first leads to recursion which necessitates our third trick: we mark the cells with a bit to indicate whether they have already been processed during this simulation cycle.

The final part of the geologic model is erosion. When eroding a cell, we begin by creating a target value which is the average of all the adjacent cell altitudes. If the current cell is more than one level higher than this average, we lower the current altitude by one. If the current cell is more than one level lower than this average, we raise the altitude by one. This results in an extremely gentle smoothing algorithm that halts when slopes reached a 1:1 rise/decline.

One tricky question of smoothing is how to handle altitude level zero. Zero level terrain is usually created by magma flows pulling terrain away from a tile. During development, “cracks” would appear in the map and did not erode away fast enough for our tastes. We created a special smoothing algorithm for the case of altitude level zero. If a crack appears in the middle of a tectonic plate, we replace the altitude with half the average of the adjacent tiles. This represents plates stretching. If the crack appears in the middle of an ocean, we assume that the crack is an oceanic trench. For this case we generate a small random addition to the altitude to represent magma upwelling.

4. Aquasphere Model

The water model concentrates on the effect of oceans. Lakes and rivers are ignored. Ocean volume and position are determined by the lithosphere model. Oceanic heat comes from the atmosphere. Oceanic heat releases into the atmosphere and generates atmospheric moisture. We originally intended to move ocean temperature based on ocean currents, but we never managed to balance that part of the simulation, and finally discarded it.

Ocean temperature is a byte value equal to 0 to 255. Sea level is calculated from the terrain and a DeltaSeaLevel constant. Terrain altitude below sea level is marked as ocean. Ocean motion is stored by four bits representing nine values; the eight grid directions and one "not-moving" value.

The timeframe for the ocean simulation is radically unbalanced. During the evolution era, ocean activity is simulated once every half a million years. During the Civilization model it gets simulated every 150 years. These time choices were a balance of how much time we were trying to represent versus our limits of processing power.

4.1. Ocean Regions

Ocean volume is approximated by a single constant called DeltaSeaLevel. This value is added to the average land altitude to create the Sea Level. The size of the ice packs can modify the Sea Level by at most +1 or −1. The Sea Level value is compared to the land altitude in each cell to determine if the cell is covered in water.

During development, we had to carefully select our DeltaSeaLevel constants. A value of zero will generally mean that 50% of the surface is ocean. Our geologic model will generally create a map with an average altitude of from 12 to 16 and a deviation of about 6. We selected a DeltaSeaLevel of 5 for Earth. This gave us the 70% water to 30% land ratio we desired. For random worlds DeltaSeaLevel was a random range of 0 to 6. For the Aquarium scenario, DeltaSeaLevel was an 8.

Two events can modify DeltaSeaLevel. The Boil Off event will occur when the average air temperature exceeds the value of 240 (255 is the maximum). In this case, the DeltaSeaLevel is decremented and atmospheric moisture is set to maximum—creating clouds whose albedo will cool the planet. The Ice Meteor event is an extremely rare random event that increments our DeltaSeaLevel.

Ice Packs modify the Sea Level by from +1 to –1. In the biology model, arctic biomes develop near the poles. Ice Pack is a count of the number of arctic biomes. High Ice Pack levels (more than 12% of the surface) will decrease the Sea Level. This represents water from the oceans being bound into the Ice Packs. Low Ice Pack levels (less than 3%) will do the opposite. Increased oceans mean decreased land, which means lower CO_2 production. The decrease in a hothouse gas will lower global temperature. This means that, barring other considerations, Ice Pack growth is a self-regulating system.

4.2. Ocean Temperature

During the first cycle of the geologic model we start with no visible water. As oceans develop, uncovering or covering new cells, we take their initial cell temperature directly from the atmosphere model. After this initial value, ocean heat slowly follows changes in atmospheric temperature. Ocean temperature acts as a brake to the mercurial changes in air temperature.

In every cycle a small amount of heat is added to the ocean cell from the air cell. We add four if the air is warmer, or subtract four if the air is cooler. Please note that we

DON'T remove any temperature from the air cell. By ignoring conservation of heat we managed to decrease our processing overhead. If we modified atmospheric heat at the same time as ocean heat we would be updating two layers simultaneously. This way, we only update one layer at a time.

Temperature is returned to the air during the atmosphere model. When we add heat back to the air, we do so by adding back half the difference: air temp = [air temp + ocean temp] / 2. This means that water-to-air transfer can be as large as 127, although the transfer is generally fairly low, 20 or less. This discrepancy in transfer rates, water-to-air being larger than air-to-water, was deliberate. We did this to simulate the ocean's greater capacity for storing heat.

4.3. Ocean Motion

Ocean currents are determined by sea depth, planetary spin, and the doldrums. We designed the currents to follow the shoreline. The doldrums are a region near the equator that has no movement. We create the doldrums by pretending that the ocean depths near the equator are actually shoreline.

Ocean cells look for the deepest adjacent cell. If the current cell is the deepest tile, then no motion occurs. Direction of motion is tangential to the direction of the deepest tile. Planetary spin determines the tangent. In the southern hemisphere the direction is rotated ninety degrees in the clockwise direction. In the northern hemisphere the opposite occurs. Between planetary spin and the doldrums, we see circular motion around the ocean basins, rotating clockwise in the northern hemisphere.

As I said at the start we do not use the ocean currents to move the ocean temperatures. In fact, ocean currents are not really used anywhere in the simulation. The sole exception is in the geologic era, where we use the ocean currents as an approximation for air currents. This saves on processing time and gives reasonable results.

5. Atmosphere Model

The atmosphere model calculates the effects of weather and atmospheric composition. Air composition derives from the effects of land, ocean, and biology. Air temperature comes from the sun and the ocean. Clouds and arctic biomes reduce solar input, cooling the planet. Air currents derive from air temperature and move both heat and clouds. Air temperature is an eight-bit value equal to from 0 to 255. Air moisture is an eight-bit value equal to from 0 to 255. Air direction is four bits representing nine values: the eight grid directions and one "not-moving value." The atmosphere components are long integers with a range of zero to four billion.

I would like to note that air temperature is probably the most important model in this application. James Lovelock's Daisy World Model used the albedo of daisies covering a world to alter the surface temperature. This model clearly demonstrated the power of life to regulate a planet's environment. In our model, arctic biomes and dense clouds reflect sunlight with their high albedo. Air temperature drives air motion, feeds into oceanic temperature, and limits the survival of land-based biomes, animals, and sapients. The air model, and in particular the air temperature model, received a great deal of consideration from Wil Wright.

5.1. Atmospheric Composition

We recorded six values for our atmospheric composition: nitrogen, oxygen, dust, water (H_2O), carbon dioxide (CO_2), and methanogens. We designed the system so that gasses leak slowly into space. To accomplish this we measured our components using absolute volumes (not percentage volumes). During our geologic and evolutionary eras we sum the inputs, perform atmospheric reduction, and then leak 5% of the volume into space. Slow leaking gives us a big lag time on atmospheric changes.

Atmospheric reduction occurs between oxygen and methanogens, producing water and CO_2. The formula is 2 oxygen + 1 methanogen $\rightarrow$ 2 H_2Or + 1 CO_2. Each cycle we calculate the maximum possible reduction and apply them to each of the components. This would typically cause either oxygen or methanogens to vanish, but because of concurrent inputs they rarely reach zero.

Our only source of free nitrogen in the simulation is volcano events. In the geologic and evolutionary eras these are common events. Volcanoes actually add to three different components as follows: nitrogen +7500, dust +1500, CO_2 +500. Nitrogen is chemically inert (in our model), so it tends to stay in the atmosphere for a long time.

Oxygen is increased by biomass (plant matter); then decreased by zoomass, atmospheric reduction, and fire events. Biomass is calculated based on biomes and eukaryotic single-celled life. Zoomass is calculated from all multicelled life. Typical values during an earthlike simulation (70% ocean to 30% land) would be +4000 from biomass, –2500 from zoomass, and –100 from reduction. Fire events are triggered by oxygen levels above 20%. Twice as many fires appear for each percentage above 20%. Each fire destroys 400 oxygen and destroys four cells worth of biomass and zoomass. This geometric progression rapidly brings oxygen back into balance. Oxygen affects death rates in the life model.

Dust enters the model through events: meteors, volcanoes, pollution, and nuclear strikes. Meteors are +2000, Volcanoes are +1500, Nukes are +500, and Pollution is +50. Dust settles faster than other gasses—they have atmospheric leaking applied twice each cycle. The purpose of dust in our model is to kill life. Dust affects the biosphere model, killing biomes and animals.

Water only enters the atmosphere from reduction. Typical inputs would be +100 from reduction. Let's use water as an example of the effect of atmospheric leaking. Since the input each cycle is ~100, and the output is 5% of the current volume, the total volume will approach $2000 = [1 / .05] \times 100$.

Carbon dioxide comes from land erosion, zoomass, reduction, and sapient use of wood and fossil fuels. $C0_2$ is decreased by biomass. Typical values are erosion +750, zoomass +500, reduction +25, human$C0_2$ +1000, and biomass –500. These numbers are balanced poorly with the rest of the composition model. Reduction doesn't match the other values, zoomass inhales more than it exhales. This discrepancy stems from a last-minute adjustment to game balance. Carbon dioxide affects the growth of plant life.

Methanogens come from pre-eukaryotic life forms and are removed by reduction. Typical values are +50 for pre-eukaryotic life and –50 for reduction. In the geologic and early evolution eras, methane is a large part of the atmosphere. As soon as post-eukaryotic life appears, methane is rapidly reduced to water and CO_2.

5.2. Atmosphere Motion

Air currents are calculated in a fashion similar to ocean currents. But instead of using ocean depth, we use temperature differentials. Hot air rises creating low-pressure zones. High pressure-zones move toward low-pressure zones with a twist added for the Coriolis Effect. This results in air currents that move in a circle around both high- and low-temperature regions.

Specifically, each cell examines its eight neighboring cells to see which is hottest. If the cell itself is the hottest, then no motion occurs. Direction of motion is tangential to the direction of the hottest neighbor. Planetary spin determines the tangent.

To get correct-looking jet streams, we had to divide the map into four vertical “bands.” For ocean currents we have a north rule and a south rule. For air currents, we divide into four regions using the rules for north-south-north-south. There are 32 cells vertically. Cells 0 to 9 and cells 16 to 25 use a counterclockwise tangent. Cells 10 to 15 and cells 26 to 31 use a clockwise tangent.

5.3. Atmosphere Temperature

Air temperature values start with solar input. This input comes from a table that represents the solar deflection at different latitudes. The air temperature layer is 32 cells tall. From cells 0 to 15 the solar input is 0 to 60 = [cell# $\times$ 4]; from cells 16 to 31 our solar input is 60 to 0 = {[31-cell#] $\times$4}. During the civilized and technical eras we use a “seasonal” model which moves the inputs up then down 6 spaces over 12 monthly cycles. Solar input has another small modifier based on the age of the planet: +1 per billion years.

Three things can modify the solar input: clouds, arctic, and desert. First we examine air moisture to see if it exceeds the critical value 128. If moisture is this high, then clouds are considered to deflect the sunlight and the input is halved. If the clouds don’t deflect, then the underlying biome may deflect. Arctic will quarter the solar input, desert will halve the input.

Air temperature will also radiate back into space. Twenty-five percent of the current value is slated for removal. This radiation is then deflected by the greenhouse effect (GHE). GHE is a value derived from the percentage of atmosphere that is carbon dioxide. One half a percent of CO_2 subtracts one from outgoing radiation, three percent will subtract six from outgoing radiation. Higher levels of CO_2 have no greater effect. Normally an input of 32 would approach a temperature of 128. With a maximum GHE of 6, this means that an input of 32 approaches a temperature of 152. This doesn't sound like much, but with the other effects of high temperatures a positive feedback loop can result from the greenhouse effect.

After inputs and outputs are calculated, a new air temperature value results. If the air cell is over an ocean cell, then the new value is averaged with the ocean temperature to calculate the final value. As with the air-ocean transfer, the ocean-air transfer is a one-way transfer of heat.

Air currents push the heat into orthogonally and diagonally adjacent cells. When moving air temperature, we copy the temperature from the current cell into a target cell specified by the air current direction. To prevent the temperature value from being moved multiple times, we copy the temperature onto a transfer map, then copy those values back when all the cells have been moved. This method violates conservation of energy, but gives correct-looking results.

5.4. Atmosphere Moisture

Air moisture simulation does not use long-term averaging. All values are calculated completely during each cycle from ocean temperature and air currents. Air currents are simplified for air moisture. Currents are reduced from their typical nine values to three values—east, west, and not moving.

We scan the map from east to west, then back again from west to east. As we scan through the cells, a moisture counter is incremented by warm ocean, then decremented over cold ocean and land. The moisture counter is also decremented by countervailing winds. The moisture counter has a maximum value determined by latitude. This gives us the ability to control how far moisture moves inland.

Over warm ocean (heat value 21+) the air moisture is calculated as half the ocean temperature plus a small amount based on the value of the water atmospheric component. Over cold ocean and land, the air moisture is calculated as eight times the moisture counter. This value is averaged between two sweeps, one east and one west. A typical moisture counter at the coast would be 10. But since there are two passes, the value from the opposite direction would typically be 0, averaging out to 5, thus giving a typical coastal moisture of 40.

The maximum value for the moisture counter varies from 5 to 15. At the poles, the value is 5. At the equator it is 15. The values do not transform smoothly across the latitudes. We have minimum values at 30º degrees north and 30º south, and additional maximums at 45º degrees north and 45º south. Once again, these values were selected because they gave give us correct-looking results.

During development, we wanted to implement plant respiration as the primary method of water transportation. Unfortunately, our experiments with that system proved to be too chaotic. Our simulation usually represents a very large time scale. This means that the biomes alter rapidly. As a consequence, when we use biomes for moisture transportation we see both biomes and air moisture cycling rapidly. This has a domino effect on the rest of the simulation, leaving us without stable temperatures or currents. We eventually decided to use the more deterministic method described above.

6. Biosphere Model

There are two important components to the biosphere model—biomes and animals. Biomes represent major nonoceanic ecosystems. Animals represent populations of major class/phylums in the animal kingdom. Biomes grow and die based on the weather model. Animals depend on the biomes for survival, and evolve into more advanced forms. When an animal has evolved far enough, it will become sapient, triggering the civilization era.

Biology starts during the geologic era. Microbes appear in the ocean. Biomes are restricted to "empty" and "arctic" until the microbes have advanced to multicellular forms. At that point the game enters the evolutionary era. Biomes will then appear on land, and animal evolution will head toward sapiency.

6.1. Biomes

There are eight biomes in SimEarth: empty, arctic, boreal forest, desert, grass, woodlands, swamp, and jungle. These are represented with a three-bit value equal to from 0 to 7. Biomes require differing values for air moisture and air temperature. Biomes depend on atmospheric carbon dioxide to prosper. They also have differing impacts on the air temperature and atmospheric composition models.

Table 1 shows the relevant biome information. Temperature is the air temperature the biome requires. Moisture is the air moisture the biome requires. Albedo is relevant for arctic and desert. Arctic will reflect 75% of solar radiation. Desert will reflect 50% of solar radiation. Biomass is the value used by the atmospheric composition model to respirate carbon dioxide and generate oxygen. The planetary biomass is the sum of the biomass values for all cells.

Temperature is divided into four levels. Low temperature produces arctic or boreal. Moderate temperature can produce desert, grass, or woods. High temperature can produce desert, swamp, or jungle. Very high temperature can only produce desert. High altitude will reduce the effective temperature by one level. High altitude is 12 above sea level.

Air moisture is divided into three levels. Low moisture can produce arctic and desert. Moderate moisture can produce boreal, grass, or woods. High moisture can produce boreal, swamp, or jungle. Carbon dioxide levels are factored into the air moisture value when deciding which biome will fill the cell. A growth-limiting factor is applied when CO_2 drops below 700. For every 7 points below 700, the effective moisture is reduced by 1. This means that when CO_2 hits zero, the moisture is modified by –100. Thus, low CO_2 means that the biome will tend to be arctic or desert.

Biomes are placed semi-randomly. When examining a cell, we first calculate a preferred biome. One time in 64 we place the biome without further examination. The other 63 times we randomly pick an orthoganally adjacent cell and examine to see if it has that preferred biome. If it does, then the biome "spreads" into our tile. If not, then the biome remains static. This method of placing biomes causes them to appear sporadically, then spread over habitable zones.

Biome	Temperature	Moisture	Albedo	Biomass	Description
empty	n./a	n/a	0%	0	no ecosystem
arctic	0–55	0–30	75%	0	ice and snow
forest	0–55	0–30	0%	5	coniferous forest
desert	55+	90+	50%	0	dry, sparse vegetation
desert	240+	n/a	50%	0	hot, dead vegetation
grass	55–160	30–90	0%	1	grasslands, plains
woods	55–160	30–90	0%	10	deciduous forest
swamp	160–240	90+	0%	4	tropical grasslands
jungle	160–240	90+	0%	17	tropical forests

Table 1. Biome description and values

One interesting consequence of our biome model is that the planet appears to "breathe." This occurs because low CO_2 limits plant growth, biomass consumes CO_2, and biomes spread slowly. As the CO_2 component and biomass chase each other, the biome regions will expand and contract rhythmically creating an impression of "breathing."

6.2. Animals

Animal life begins with microbes, advances to multicelled forms, then evolves toward sapiency. Each tile has eight bits of information to represent life. These 256 values are divided into 16 ranges of 16 evolutionary steps. Value zero is reserved to indicate no life. When a cell has an animal value, it represents a dominant population of that "species." Animals move around the map, seek favorable biomes, reproduce, die, compete, and evolve.

Life begins once oceans have formed. Animal value one represents the simplest of prokaryotic microbes. Throughout the geologic era, these microbes are randomly placed in the oceans. Evolution will soon create more advanced animals that will displace these simple life forms.

Animal movement starts by selecting a random orthogonal direction—north, east, west, south. We then select a random distance in that direction from one to three tiles. The animal then examines the destination tile for compatibility. It will move to the tile if all the following conditions are met. First, the biome is agreeable (see Table 2 for details).

Second, no sapients occupy the space. Third, any animals in the target cell have a lower competition value (see Table 3 for details). When these conditions are met, the target cell is set to the animal's value, the origin cell is cleared.

Type	Ocean	Arctic	Forest	Desert	Grass	Woods	Jungle	Swamp
prokaryotic	32	0	0	0	0	0	0	0
eukaryotic	32	0	0	0	0	0	0	0
radiates	16	0	0	0	0	0	2	3
arthropods	10	0	0	0	1	0	3	5
mollusks	10	0	0	0	0	1	5	3
fish	16	0	0	0	0	0	0	0
cetacean	8	0	0	0	0	0	7	0
trichordate	0	0	9	2	3	9	8	6
insects	4	0	5	5	5	6	6	6
amphibians	4	0	2	1	3	6	9	8
reptiles	0	0	5	8	9	8	6	6
dinosaurs	0	0	5	2	3	8	9	6
birds	0	0	9	2	6	8	8	4
mammals	0	0	6	2	9	6	8	5
carniferns	0	0	3	3	3	3	3	3
robots	8	6	6	6	6	6	6	6

Table 2. Animal biome preferences, a numeric value indicating preferred biomes

Biome preferences are not a strictly boolean value. When examining a target tile, the animal will generate a test value from 0 to 7. If the test value is greater than the animal's preference for the target biome, then the animal will accept the target cell. For example, amphibians are capable of entering desert, but much prefer swamp or jungle. When a biome preference value is zero, then that biome will kill the animal. This can occur if the animal fails to move and the underlying biome changes. Biome preference for ocean indicates how "deep" the animal will swim.

Reproduction can occur when the animal moves. Reproduction means that a copy of the animal is left in the origin cell. We use a reproduction rate of 25%. You might think that a rate this high would rapidly fill the entire map with animals. But between natural death rates, competition, and biome restrictions, map occupancy rarely exceeds 10%.

There is a natural death rate based on atmospheric oxygen. Prokaryotic life and robots are immune to this problem. Death Rate = Oxygen % − Dust% − [Air Temperature − 200] / 4. The temperature factor is not considered if air temperature is less than 200. Oxygen tends to be 20%. Dust can be fairly high after a meteor strike, but is usually less than 1%. Most of the time the death rate value will be ~20. This means that there is a 1/20 chance of the animal dying during each simulation cycle. High dust or high heat can raise this ratio radically. One consequence of this Death Rate algorithm is that animals die more frequently in desert biomes.

Competition occurs when an animal tries to enter a cell occupied by another animal. Table 3 shows the animal competition values. If the moving animal has a competition value that is greater or equal to the target animal's competition value, then the moving animal "consumes" the target. The target cell will remove the current animal and replace it with the moving animal.

Type	steps 0–3	steps 4–8	steps 9–12	steps 13–15
prokaryotic	0	1	2	3
eukaryotic	4	5	6	7
radiates	8	13	13	10
arthropods	14	15	17	13
mollusks	16	17	18	15
fish	25	25	25	24
cetacean	35	35	40	40
trichordate	21	26	31	36
insects	24	24	24	24
amphibians	30	35	35	40
reptiles	46	51	56	61
dinosaurs	46	51	56	61
birds	46	51	56	61
mammals	53	58	63	68
carniferns	26	26	26	26
robots	60	65	70	75

Table 3. Animal competition values

There are two forms of evolution: advancement and mutation. Every time an animal reproduces, there is a 25% chance that it will advance. Advancement means that the animal's numeric value is incremented. For example, the prokaryotic cell value equal to 1 would advance to value equal to 2. The basic mammal value equal to 208 would advance to value equal to 209. If an animal advances to the top of its 16-step ladder, then that class becomes sapient (see *section 6.3* for details).

Mutation can occur every time an animal advances. Any time an animal advances, there is a 25% chance that it will mutate. Mutation will transform the animal to a new class defined by Table 4. For example, an advanced reptile value equal to (160+10) can mutate into a basic mammal value equal to 208. The combined chances of reproduction, advancement, and mutation mean that there is a 1.5% chance of mutation every time an animal moves.

Type	class*16	steps 0-3	steps 4–8	steps 9–12	steps 13–15
prokaryotic	0	prokaryotic	prokaryotic	eukaryotic	eukaryotic
eukaryotic	16	prokaryotic	eukaryotic	eukaryotic	radiates
radiates	32	eukaryotic	arthropods	trichordate	eukaryotic
arthropods	48	radiates	mollusks	insects	arthropods
mollusks	64	arthropods	fish	fish	mollusks
fish	80	mollusks	amphibians	amphibians	fish
cetacean	96	cetacean	cetacean	cetacean	mammals
trichordate	112	radiates	trichordate	trichordate	trichordate
insects	128	carniferns	insects	insects	insects
amphibians	144	reptiles	reptiles	trichordate	amphibians
reptiles	160	mammals	mammals	mammals	reptiles
dinosaurs	176	birds	mammals	reptiles	dinosaurs
birds	192	dinosaurs	dinosaurs	reptiles	birds
mammals	208	reptiles	cetacean	cetacean	mammals
carniferns	224	carniferns	insects	carniferns	carniferns
robots	240	robots	robots	robots	robots

Table 4. Animal mutation table

6.3. Evolutionary Trends

There are a few subtle points in our evolutionary tree that I would like to comment on.

The animal competition and mutation tables organize the advancement ladder into four step groups. All the animals within a group have the same competition value. This means that marginally advanced animals can be swamped by their similar brethren. This factor significantly slows down the rate of advancement, but does not halt it. Lower values will continue to produce higher values, thus advancement is inevitable.

In our 16 classes of animals, there are 3 that are mostly fantasy. Trichordates appeared about the same time as the starfish, and actually made it onto land. They were not a significant branch on the evolutionary tree, but we decided to give them a larger role to spice up our game. Carniferns take the concept of the venus flytrap and extend it to motile plants. During the game’s development, we were reading some interesting studies on cross-species transmission of genetic material. We extended upon those ideas to have Carniferns branch out from the insect class. Robots were a “cookie” we added to the game. They can result from a decayed civilization, but won’t appear out of the evolutionary tree.

With the exception of prokaryotic and eukaryotic animals, all our classes have a chance to reach the top of the advancement ladder (step 15) and achieve sapiency. When we designed the competition and mutation tables, we weighted the values so that certain classes have a better chance to become sapient. First, we reduced the chances for radiates, chordates, arthropods, and fish by giving their highest group (steps 12 to 15) a lower competition value than their second highest group (steps 8 to 11). This makes it difficult for them to reach step 15, but not impossible. Second, the mutation table is designed so that it tends to produce new classes that can out-compete the older class. For example, a high step fish value (80+10) can produce a starting amphibian value equal to 144. The fish has a competition value of 25, the amphibian has a competition value of 30.

Our tree is designed to allow for "reversion." Sometimes an entire class will vanish because of competition or vanishing habitats. Later in the simulation, their specialized habitat may reappear. The lowest group (steps 0 to 3) in a class will mutate back to a lower class on the evolutionary tree. The highest group (steps 12 to 15) in a class will mutate back to the lowest step in the class. For example, mammal value (208+14) can mutate into mammal value (208+0). Then, mammal value 208 can mutate into reptile value 160. While the lower-class animal will usually have a lower competition value, it may be able to survive in a biome that the higher class will avoid.

7. Civilization Model

The civilization model has two major components. First, there is a civilization layer that contains sapient cities and nomads. Second, there is an abstracted global model which determines the energy production for the entire race and decides how the energy is spent. The human layer uses five bits. Three bits indicate the tech level of the unit equal to 1 to 7 (0 means nonexistent). Two bits indicate the size of the unit, 0 means a wandering unit; 1, 2, and 3 are small, medium, and large cities.

The sapient model is similar to the animal model. Sapient nomads move around the map, seek favorable biomes, reproduce, die, compete, and evolve. The major difference is that sapient units include nonmobile city units. In addition to the normal animal behaviors, sapients utilize limited resources and are subject to a number of civilized events.

7.1. Spreading Civilization

Sapients are still limited by biomes. Their preference for different biomes is inherited from their animal class. Aquatic animals are capable of building cities in the oceans.

Mobile sapients move exactly the same way that animals move. Sapient nomads that try to enter water have a restriction based on their tech level. Tech level one can only enter shallow water— depth four or shallower. Tech level two can enter deeper water—depth eight or shallower. Higher tech levels are not restricted by water.

When a sapient nomad successfully reproduces, instead of splitting in two as animals would, they settle into their current location creating a small city. Cities then continue to grow based on the value of their underlying biome. Poor biomes can cause a city to stagnate at size one or two. If the underlying biome changes, a city can shrink back so that the people become nomads again. When a city has grown into a large city, then the next attempt to grow will generate a nomad. Growth rates are directly proportional to the agriculture investment (see *Section 7.2*).

Cities have a radius that prevents other cities from building. This radius grows smaller as the tech level increases. Tech level one cities cannot be closer than four spaces apart. Tech level seven cities can build directly adjacent to each other. This restriction represents the need for infrastructure in the surrounding region. It emulates the historical pattern that puts more large cities closer to each other over time.

Sapients compete in the same way as animals, with the added consideration of nomads moving into cities. Sapient competition values are identical to their five-bit representation. A tech level one nomad would be binary 00100 equal to value four. A tech level one, size one city would be binary 00101 equal to value five. This means that nomads do not overrun cities unless that city has a lower tech level. Sapients automatically destroy any animals they step on, and animals are not capable of harming sapient units.

7.2. Collecting and Spending Energy

There are five sources of energy that sapients can use to perform work. Bioenergy represents muscle power, domesticated animals, and burning wood. Solar/wind includes everything from drying clothes in the sun to solar electric cells. Hydro/geo represents everything from waterwheels to hydroelectric dams. Fossil fuels are petroleum, coal, and natural gas. Nuclear energy uses radioactive materials. Table 5 shows the efficiency of the varying energy sources for each tech level.

Energy production is distributed between all five energy sources. At the beginning of the civilization era, the ratios are 30:20:10:0:0. This means that fossil fuels and atomic fuels are not used at all. Bioenergy is used 30% of the time. Solar/wind is used 20% of the time. Hydro/geo is used 10% of the time. The remaining 40% represents the leisure time of the sapient, affecting his happiness value. Production ratios are modified by the player. Without player intervention, the use of energy sources will not change, and it is unlikely that civilization will advance in technology.

Age	BioEnergy	Solar/Wind	Hydro/Geo	Fossil Fuel	Nuclear
1-Stone	40%	20%	10%	0%	0%
2-Bronze	40%	20%	30%	10%	0%
3-Iron	60%	20%	30%	30%	0%
4-Industrial	60%	30%	50%	80%	10%
5-Atomic	70%	50%	50%	80%	80%
6-Information	80%	60%	60%	90%	90%
7-Nanotech	90%	80%	80%	90%	90%

Table 5. Civilized energy efficiency

Each sapient produces energy from these sources based on their production ratios multiplied by their tech level efficiency. For Example: a tech level two unit would produce 0.12 from bioenergy equal to [30%×40%], 0.04 from solar/wind equal to [20%×20%], and 0.03 from hydro/geo equal to [10%×30%]. This value would be double for a small city, triple for a medium city, and quadruple for a large city. The total energy produced by the population would be the sum of all energy produced by all sapient units.

Energy is then allocated among five human endeavors. Philosophy reduces the War random event. Science is used to advance technology. Agriculture affects population growth. Medicine reduces the Plague random event. The Arts have a direct effect on the quality of life for sapients. Total energy is divided between these five fields, then normalized against the total population. The player has control over how much energy is spent in each field. Without player intervention, it is unlikely that civilization would advance past the Bronze Age.

Changes in energy investment accumulate over time. At each cycle, the current investment is reduced by 20% before the new energy allocation is added. This means that over time the energy investment in an endeavor approaches five times the allocation. This delay creates an interesting situation when a player attempts to advance technology. The player may put his entire energy allocation into science, but it takes ten cycles to reach 90% of the maximum value. During those ten cycles, war and plague can seriously reduce total population. After the player returns the allocations to normal, it still takes time for the philosophy and medicine investment to accumulate; so war and plague will continue to haunt the player.

To get an idea of how much energy a civlization is likely to produce, examine Table 6. This shows the energy investment needed before the next tech level can appear. We picked these values to make the game challenging. Exact numbers would vary widely from game to game, depending on how much of the map is habitable.

Age	Energy Investment
1-Stone	200
2-Bronze	600
3-Iron	2,000
4-Industrial	6,000
5-Atomic	20,000
6-Information	40,000
7-Nanotech	80,000

Table 6. Cost for technological advancement

Fossil fuels and atomic fuels are global values that accumulate during the geologic and evolution eras. Fossil fuels are a by-product of the biomass. Total fossil fuels approaches a number equal to the average biomass times 8000. At each cycle, the biomass times 250 is added to the total, then 1/32 of the total is discarded. Atomic fuels are a by-product of the exposed land and accumulate in the same fashion as fossil fuels.

Exposed land times 1000 is added to the total, then 1/32 of the total is discarded. The assumption is that radioactive materials are exposed by geologic activity. There is no justification for slowly accumulating atomic fuels, it just works for game play.

These two fuel sources are fixed at the start of the civilization era. They will not accumulate again until the next evolutionary era. One of the issues of game play is to develop past the need for these limited resources before their consumption becomes a critical issue. The use of fossil fuels generates large amounts of CO_2 which directly inputs to the atmosphere model. If you use too much fossil fuel, you can create a greenhouse effect transforming your world into a desert.

7.3. Civilized Events

War, plague, pollution, and nuclear strikes are all civilized events. Technological advancement is a beneficial civilized event. In addition, there are three super-events that occur in SimEarth. These are World War, Nuclear War, and the Exodus.

The chance of war striking is inversely related to the investment in philosophy. The typical chance that war will destroy a community during a single simulation cycle is 1/32. If the investment in philosophy is reduced to zero, the odds of war approaches 100%.

The chance of plague striking is inversely related to the investment in agriculture. The typical chance of plague striking a community during a single simulation cycle is 1/100. If the investment in medicine is reduced to zero, the odds of plague approaches 100%. Plague will move around the map like an animal, consuming sapients. Without sapient units, the plague will die.

Pollution occurs during the industrial era. Each cycle, every tech level four unit has a 1/32 chance of creating pollution. Pollution will kill any animals it touches. Pollution also adds 50 dust to the atmosphere. The only way to avoid pollution is to rapidly advance to tech level five.

Nuclear strikes can only occur during the Nuclear War super-event. Nuclear strike events only affect tech level five cities. Nuclear strikes result in a chunk of radioactive land that animals and sapients both have to avoid. It takes tens of thousands of years for the radiation to dissipate. During that time, the global count of radioactive tiles will effectively reduce the agriculture and medicine investments. This results in lower growth rates and higher plague rates. Nuclear strikes add 500 dust to the atmosphere.

Cities can advance in technology if scientific investment is high enough. Each city will compare its current tech level cost (see Table 6) to the current investment. If the investment is higher, then the city has a 1/500 chance of advancing. Once a city advances, it can create nomads for the same tech level. These nomads can move around, displacing lower tech units.

Fossil fuels are a limited resource. When technology reaches level four—the industrial era—cities will start consuming fossil fuel. The supply of fossil fuels will typically last for a two hundred or more simulation cycles. If the supply ever falls below the current demand times 30 (i.e. less than 30 cycles of fuel remain), then a World War super-event is triggered. During World War, the war event will occur 16 times more frequently for tech level four cities. The World War will end when the fuel supply will support current demand for 45 cycles. This can happen because the demanding cities have been destroyed, or because the player has altered the energy production ratios, thus reducing demand.

Nuclear War is almost the same as the World War super-event. Nuclear War will be triggered by low supplies of atomic fuels, and ended by high supplies. Nuclear war will affect tech level five units. War events over tech level five cities become nuclear strike events. Nuclear War will usually involve multiple nuclear strikes. Three or more nuclear strikes have a combined impact and simulate a nuclear winter.

The final goal of SimEarth has a Buddhist flavor; rebirth and reincarnation. At the point that civilization would advance to tech level eight, an Exodus is triggered. Each cycle, every sapient unit has a 1/8 chance of launching into space. Once the last sapient unit has left the planet, the simulation reverts to the evolutionary era. It is interesting to examine the wreckage left behind by civilization. The majority of the animal classes are gone, and radioactive waste will scar the surface for thousands of years. But most of the damage is healed by just a few cycles on the (larger) evolutionary scale.

8. Conclusions

SimEarth has been seen by thousands of impressionable children. Many of them formed their ideas about the nature of geology, weather, ecology, evolution, and the environment from our game. Schools still use SimEarth as an educational tool. If we had considered the impact this game would have on a generation of students, we probably would have panicked and never finished the project.

But we did finish it, filled as it is with both flaws and insights. And the great thing is, I can now see the flaws quite clearly. And I have my own insights on how to fix them. I have recently been in touch with Wil Wright, and guess what: he is interested in making another SimEarth. So maybe you will see SimEarth II on the game shelves.
And so the cycle of rebirth and reincarnation continues.

Glossary

Albedo:	The percentage of light reflected by a surface.
Aquasphere:	All oceans, rivers, and lakes across a world.
Atmosphere:	The ambient gasses surrounding a world.
Binary:	A number stored using 0s and 1s.
Biomass:	The total mass of all plant life on a world.
Biome:	A region of similar plant life, such as desert or jungle.
Bionary range:	A number whose upper limit is defined by its binary storage.
Biosphere:	All the life found on a planet.
Cellular automata:	A simulation method that organizes data into cells.

Coriolis Effect:	Planetary spin generates a sideways push that bends movement.
Decrement:	Decrease a value by one.
Doldrums:	A region near the equator where winds are stagnant.
Greenhouse effect:	Planetary heat will rise after an increase in greenhouse gasses.
Greenhouse gas:	A gas that will reflect light back to a planet's surface.
Eukaryote:	Primitive microbes that neither use nor generate oxygen.
Increment:	Increase a value by one.
Jet Stream:	A "river" of wind 20 kilometers above the Earth's surface.
Lithosphere:	For this paper, the tectonic plates and the magma layer.
Nemesis Effect:	The periodic drastic reduction in number of species every 30 million years.
Nuclear Winter:	A theoretical decline in global temperature due to nuclear war.
Prokaryote:	First microbes that generate oxygen.
Sapient:	A species that exhibits intelligence and extensive tool use.
Zoomass:	The total mass of all animal life on a world.

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Biographical Sketch

Fred Haslam, after ten years of study at three universities, during a period of time when computer science majors were still being formulated, gave up on his dream of collegiate degrees to become a professional programmer. His two most prominent works to date are *SimEarth: The Living Planet*, and *SimCity 2000*. Mr. Haslam now runs an online game site which supports his experiments in artificial intelligence.