Does body matters or brain is all we need?

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1 The world and Creature

1.1 World

World is everything else that is not part of the creature. For simplicity The world is kept static, exhibiting a consistent state across all of the generations and experimental conditions. It comprises solely a horizontal plane and a spherical object. The world has gravity of $-9.8m/s^2$.

1.2 Creature

Our simulated creature is composed of two fundamental elements: a bodily structure and a neural network, commonly referred to as the *body* and *brain*, respectively.

1.2.1 Body

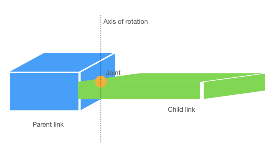


Figure 1: link joint example

The creature's body is made up of rectangular prisms of varying size. We'll refer these rectangular prisms as *links*. The size of these links is completely arbitrary and decided by evolutionary algorithm.

Each of these *links* can have a *touch sensor* attached to it. This sensor helps the creature in evaluating its surroundings, as well as providing insight into its present state. The touch sensor returns +1 when in contact with ground and -1 otherwise. In this study, we are denoting a *link* with sensor as blue and a link without sensor as green.

Each pair of links is connected through a *revolute joint*, characterized by a rotational axis and comprised of a parent and child link. This is illustrated in Figure 1.

Each joint is affixed with a *motor*, which imparts a rotational force upon the child link around the joint's axis of rotation. The motor's maximum torque is calibrated to 30 N-m.

1.2.2 Brain

Creature's brain has following fundamental components:

1. Sensory neuron: A sensory neuron is attached to each of the link that have a touch sensor attached to them. The sensory neuron retrieves and stores touch sensor values from the corresponding link.

2. Motor neuron: A motor neuron is attached on each joint. The motor neuron is responsible for controlling the motor of a joint by transmitting the desired rotational angle to the motor.

3. Hidden neuron: All neurons which are not part of input and output are referred as hidden neurons. In our case input are the touch sensor values and output are motor neuron values.

4. Synapse: Synapse are the connection between a pair of neurons. These are weight values ranging between [-1,1].

A sample brain is shown in Figure 2

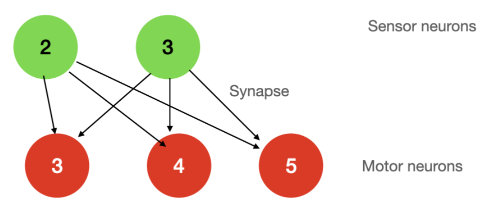


Figure 2: A sample brain with two sensor neurons and three motor neurons

A genotype and phenotype representation of the creature is shown in Figure 3

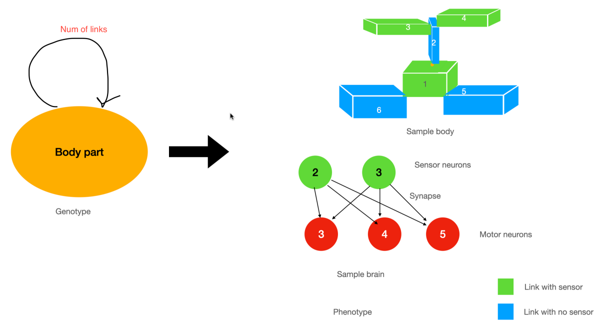


Figure 3: Genotype and phenotype representation of creature

2 Methodology

2.1 Optimization goal

We're trying to find the best morphology for locomotion. The best morphology is defined as the creature which moves farthest from the starting point in a fixed time frame.

2.2 Hypothesis

2.2.1 Null Hypothesis

For running task only evolving brain is enough i.e there is no need to co-evolve brain and body

2.2.2 Alternative hypothesis

For running task co-evolving brain and body is helpful

2.3 Experimental setup

For testing the hypothesis, We ran experiments under following setting:

1. Evolve only brain and keep the body fixed
2. Co-Evolve body and brain

For a fair evaluation of the hypothesis, we've kept other experiment parameters same under both experiments. Further we've fixed the random seed so that both of the experiments have same randomness.

2.3.1 Experimental parameters

Population size: Total number of parents at the starting of evolution i.e generation 0. We've used population size of 10.

Number of generations: Maximum number of offsprings that we're going to generate from the starting parents. We've used number of generations = 500.

Number of runs: number of times PHC is run with a different random seed. We've used number of runs = 10.

2.4 How evolution works

Parallel hill climbing (PHC) is used for evolving the creatures gradually. Parallel hill climbing is similar to hill climbing. The only difference is that there are multiple parents.

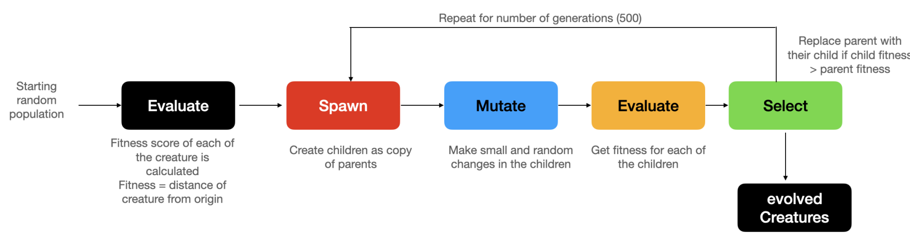


Figure 4: Genotype and phenotype representation of creature

Hill climbing is a simple and intuitive optimization algorithm used to optimize over a fitness function. The algorithm starts by generating a random population. In next step it looks at the neighboring points and selects the one that has the highest (or lowest) fitness function value. This process is repeated until algorithm finds a point where no neighboring point has a higher (or lower) function value. PHC has following key steps:

1. Random population generation
2. Evaluate
3. Spawn
4. mutate
5. Select

The workflow of PHC algorithm is shown in figure 4.

2.4.1 Random population generation

Our experiment starts with a random population. So we have to generate random creatures for generation 0. These creatures serves as the starting point of the PHC algorithm. The methodology of generating random creature is shown in Figure 5. This process is repeated until target population size is achieved.

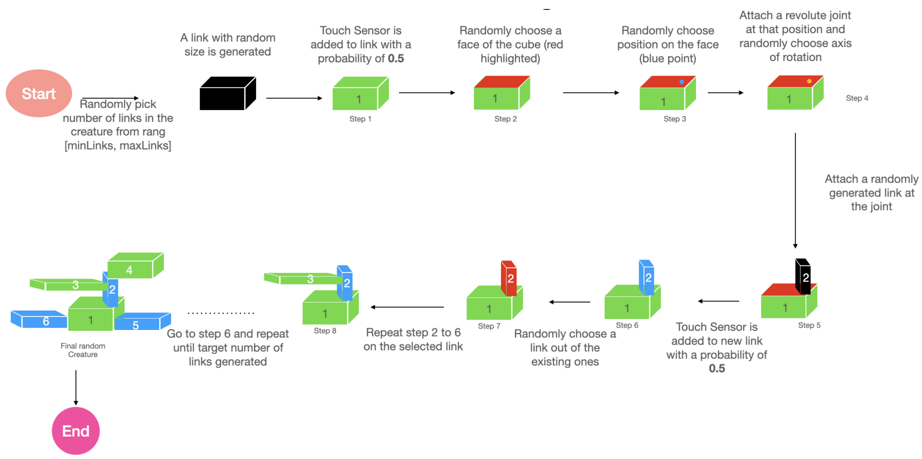


Figure 5: Random creature generation

2.4.2 Evaluate

During this step each of the creature is simulated in a virtual environment and the fitness score is calculated. The fitness score is assigned to the respective creature. The fitness score denotes how good the creature is for the task in hand.

Our fitness function is the euclidean distance of robot from the starting position. The fitness is normalized by body length so that creature with larger size don't have an unfair advantage. For simplicity we've kept the starting position of creature as origin.

$$fitness = \sqrt{x_{robot}^2 + y_{robot}^2 + z_{robot}^2}/(creature\ body\ length)$$

Here x_{robot}, y_{robot}, and z_{robot} are x, y and z coordinate of the robot at a given point of time.

2.4.3 Spawn

During this step, copies of the parent are created. These copies are also known as children.

2.4.4 Mutate

During this step, small and random changes are made in the children. This step differs for the two experimental setup we have. In Experiment 1 only brain is mutated, while in the Experiment 2 both brain and body are mutated.

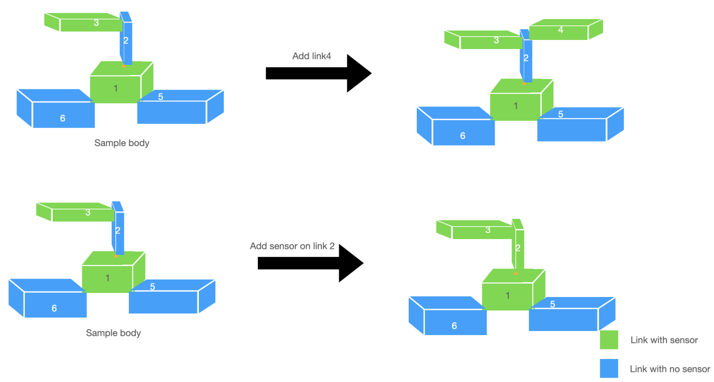


Figure 6: Add link and add sensor mutation

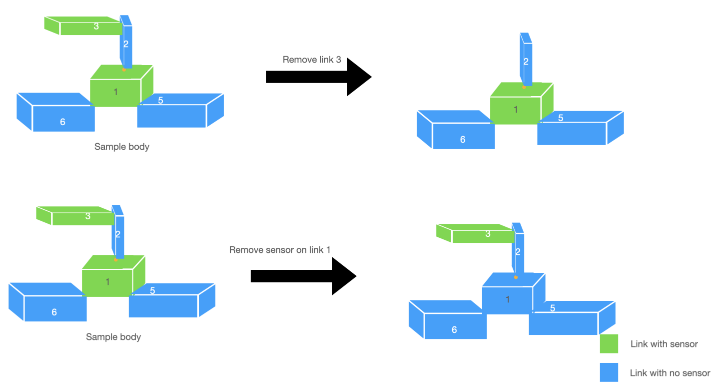


Figure 7: Remove link and remove sensor mutation

Body mutations First a link is randomly selected from the existing links on the creature. Then following mutations can take place.

1. Add new link to the selected link
2. Add sensor to the selected link
3. Remove the selected link

4. Remove sensor from the selected link

These mutations are illustrated in Figure 6 and 7

Brain mutations The core part of the brain are the synapse weights those decide how the different neurons are interconnected. For brain mutation a synapse is randomly selected and it's assigned a random value between [-1,1]. The process is illustrated by a toy example in Figure 8.

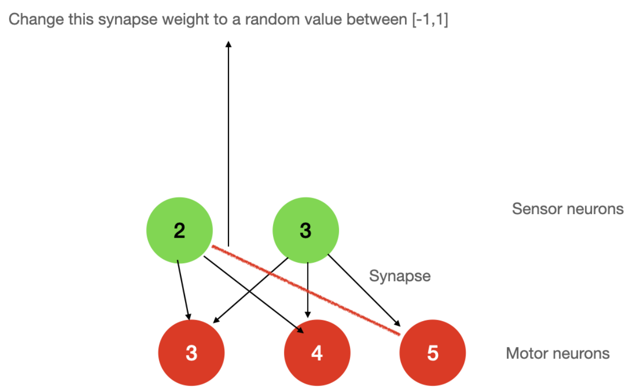


Figure 8: Brain mutation

2.4.5 Select

During this stage, each of the offspring produced by mutation is evaluated against its corresponding parent. If the fitness of the offspring is superior to that of its parent, then the offspring replaces the parent and becomes the parent of the next generation. It is important to note that the children are only compared to their repspective parent, this way the evolution of one family does not get affected by other family. This is illustrated in Figure 9.

3 Results

For comparing results of the experiments, we've plotted the fitness of best creature for every generation. For every generation the fitness of best creature is saved and is plotted in Figure 10b.

It was not very clear from the best fitness plot that which experiment gave better results so we decided to plot average fitness as well. Average fitness is

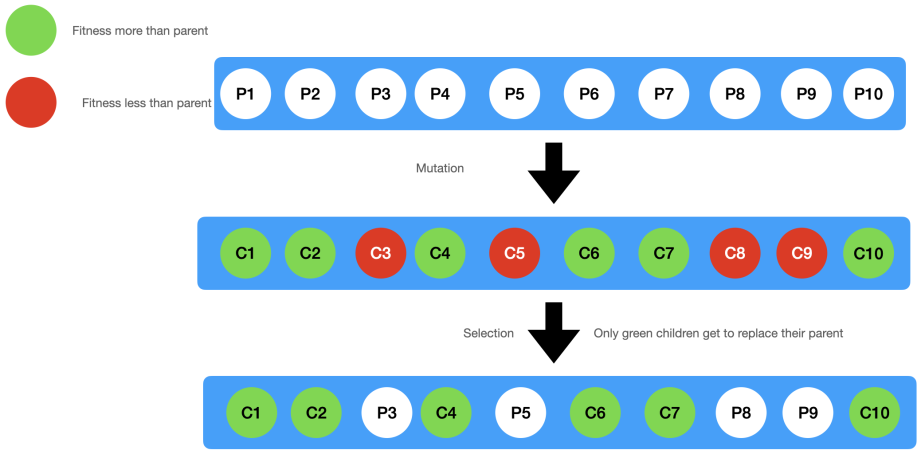
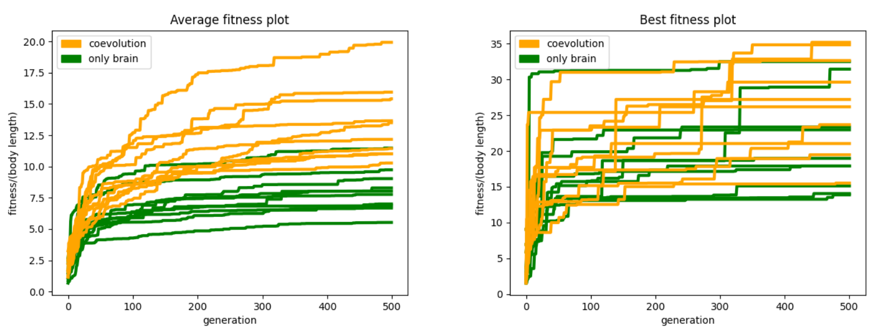


Figure 9: Selection



(a) Average fitness plot

(b) best fitness plot

Figure 10: Coevolution vs only brain

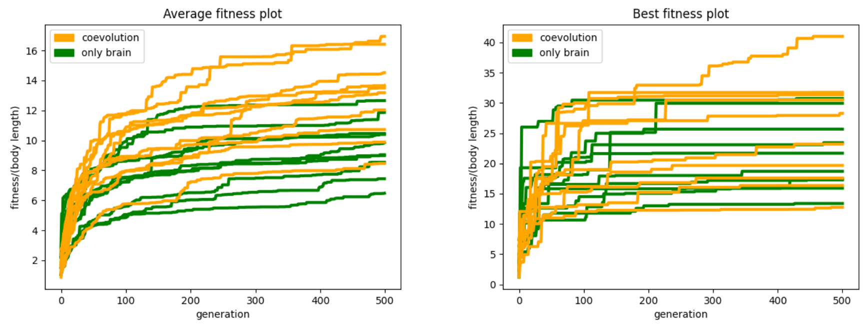
calculated as follows.

$$Average fitness = (\sum_{p=1}^{Population\ size} fitness\ of\ p^{th} creature)/(population\ size)$$

The average fitness plots are shown in Figure 10a

From the figure 10, We can clearly see that coevolving brain and body has a significantly better performance compare to evolving just brain. Hence by proof of evidence, we reject the null hypothesis. So alternate hypothesis "For running task co-evolving brain and body is helpful" is proved.

For further investigations, we performed another set of experiments. We have added a hidden layer of neurons to the brain of creature to make creature's brain more powerful. We've kept number of hidden neurons same as number



(a) Average fitness plot

(b) best fitness plot

Figure 11: Co-evolution vs only brain (with hidden neurons)

of sensory neurons. These set of experiments are performed to see making the brain powerful will help creature compete with co-evolving brain and body. The resulting plots are shown in 11

We can see from figure 11 that even after adding hidden neurons co-evolution is still outperforming the only brain evolution methodology. This confirms our hypothesis that co-evolution gives better morphologies compared to just brain evolution. Further Comparing Figure 10 and 11 we can see that the best creature performance with hidden neurons is around 40 compared to 35, without hidden neurons.