Create Your Own Active Matter Simulation (With Python)

Philip Mocz · Follow

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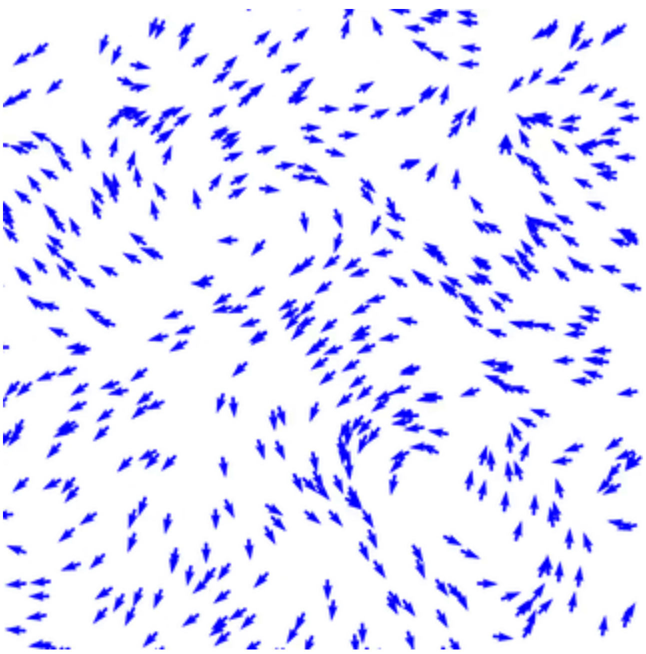
For today's recreational coding exercise, we simulate **active matter**, i.e., swarming. Such a system may describe a flock of birds or a school of fish. We will look at how very simple rules may lead to the emergence of self-ordered motions.

You may find the accompanying Python code on github.

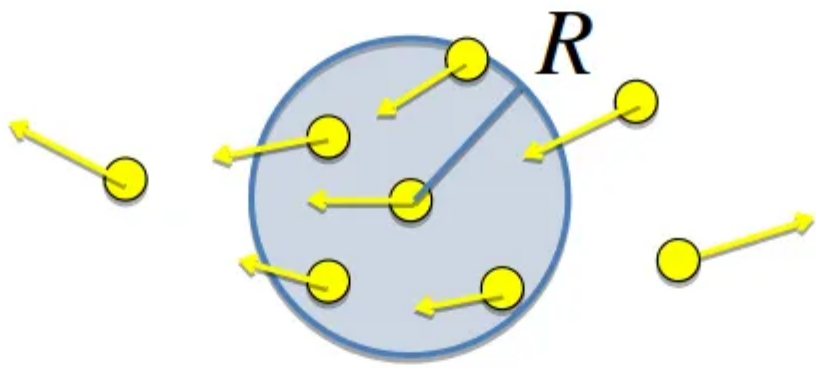
But first, below is a gif of what running our simulation looks like:



Viscek model for flocking behavior

We will describe a famous minimal model for active matter called the Viscek model (1995). Despite its simplicity, the model is able to describe universal properties of swarming behavior.

The model consists of *N* moving particles, indexed by $i=1,\ldots,N$. Each particle has an angle Θ_i representing the direction in which it moves. All particles move with the same speed v_0. Particles will interact with each other within an interaction radius *R*, which will force them to change their direction (angle).



At each timestep, each particle *i* has its position $\mathbf{r}_i$ updated as

$$\mathbf{r}_i^{n+1} = \mathbf{r}_i^n + \Delta t \times \mathbf{v}_i^n$$

according to its particle velocity $\mathbf{v}_i$:

$$\mathbf{v}_i^n = v_0 \begin{pmatrix} \cos\left(\Theta^n\right) \\ \sin\left(\Theta^n\right) \end{pmatrix}$$

The interesting dynamics of the Viscek model come from how the angles are updated. This occurs according to the rule:

$$\Theta_i^{n+1} = \langle \Theta^n \rangle_{i,R} + \eta_i^n$$

where the first term on the right-hand-side is the average angle of all the neighbors of particle *i* within distance *R* (including itself). The second term η_i is a random perturbation drawn from a uniform distribution [-*η/2,η/2*].

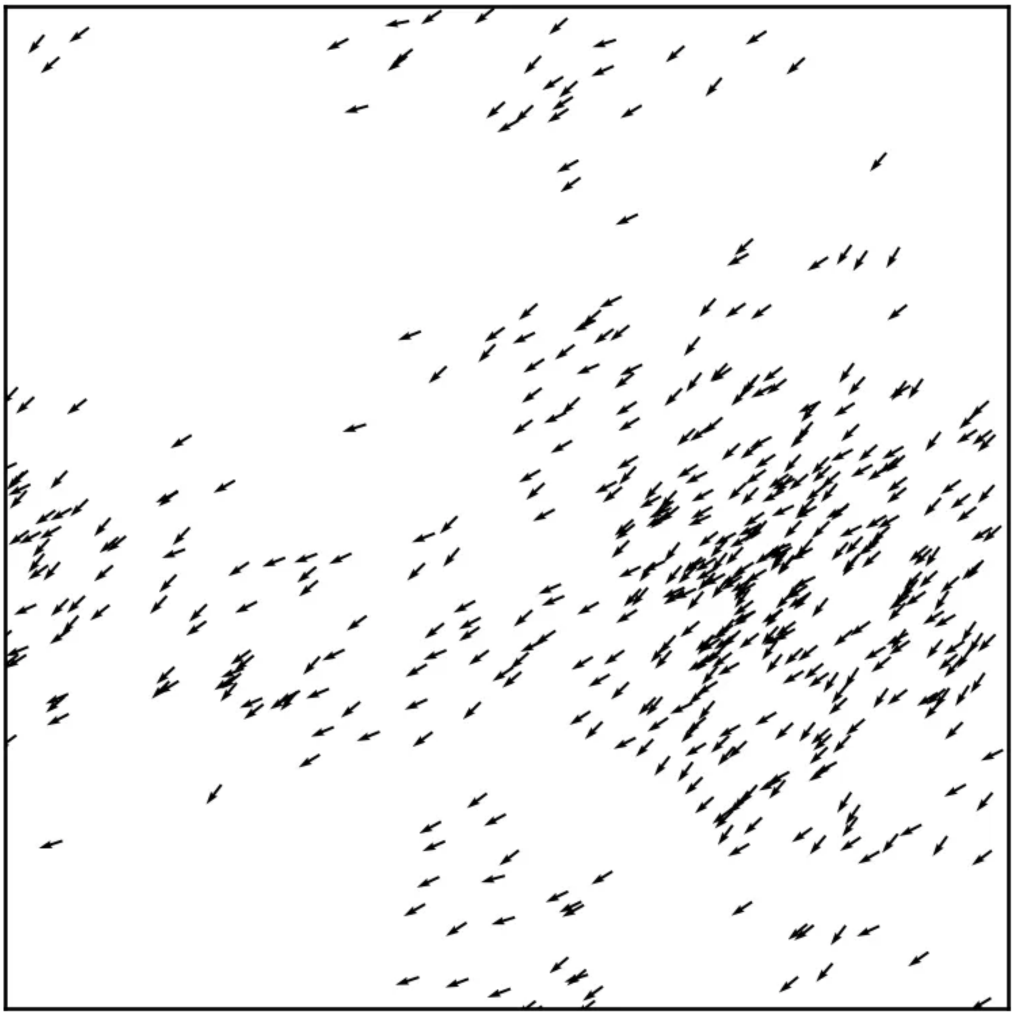
Simulation Code

The model is so simple that we can provide all the Python code in a single block below. To average the angles, we sum all the neighboring vectors and use numpy's arctan2 function to return its angle in the correct quadrant. We consider a periodic domain of size L.

```
# Simulation parameters
v0   = 1.0  # velocity
eta  = 0.5  # random fluctuation in angle (in radians)
L    = 10   # size of box
R    = 1    # interaction radius
dt   = 0.2  # time step
Nt   = 200  # number of time steps
N    = 500  # number of particles

# particle positions
x = np.random.rand(N,1)*L
y = np.random.rand(N,1)*L

# particle velocities
theta = 2 * np.pi * np.random.rand(N,1)
vx = v0 * np.cos(theta)
vy = v0 * np.sin(theta)

# Simulation Main Loop
for i in range(Nt):

        # move
        x += vx*dt
        y += vy*dt

        # apply periodic BCs
        x = x % L
        y = y % L

        # find mean angle of neighbors within R
        mean_theta = theta
        for b in range(N):
                neighbors = (x-x[b])**2+(y-y[b])**2 < R**2
                sx = np.sum(np.cos(theta[neighbors]))
                sy = np.sum(np.sin(theta[neighbors]))
                mean_theta[b] = np.arctan2(sy, sx)

        # add random perturbations
        theta = mean_theta + eta*(np.random.rand(N,1)-0.5)

        # update velocities
        vx = v0 * np.cos(theta)
        vy = v0 * np.sin(theta)
```

There we have it! Playing around with the simulation parameters allows different flocking patterns to emerge. In fact the system can undergo a *phase transition* between isotropic random motions to ordered behavior. The latter case is simulated with the present model parameters.

Running the code allows you to visualize the simulation in real time and will yield the figure depicting the position of the particles after 200 timesteps:



The Viscek model is incredibly simple and powerful. It describes collective motion where individual particles consume energy and thus are not in thermal equilibrium. Instead, large-scale ordered motion may emerge.

In nature, birds such as starlings exhibit similar behavior. Their dancing patterns arise because one bird tries to copy to motion of its neighbors as closely as it can (c.f. the angle averaging operator in the Viscek update step).

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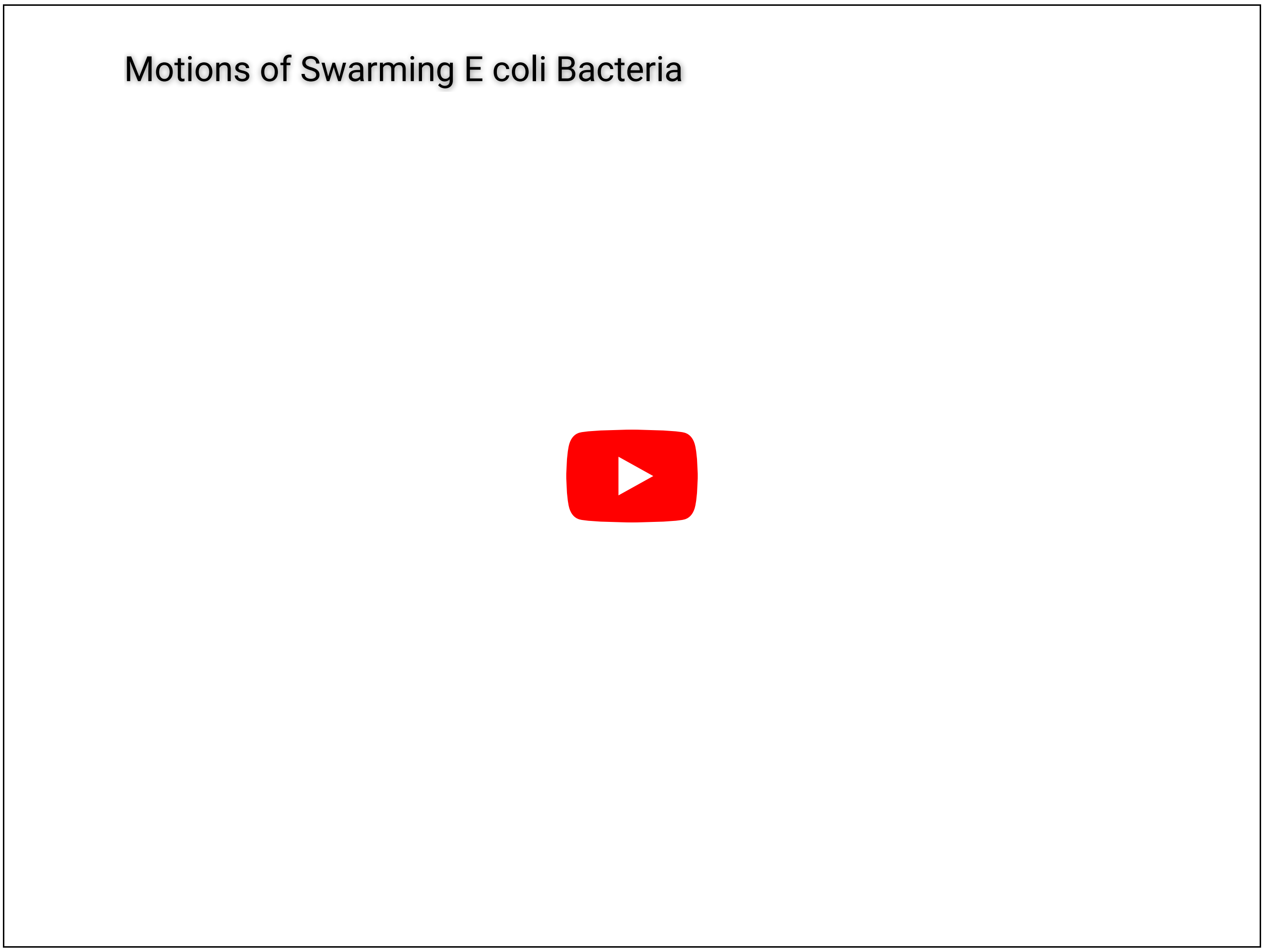
There are many extensions to the Viscek model and other models for active matter. A different classic example of active matter is how bacteria swim and flock on micro-scales.



Download the Python code on github for our Active Matter tutorial to visualize flocking behavior according to the Viscek model and play around with the parameters to explore different phase configurations. Enjoy!

Python | Physics | Simulation | Flocking | Coding

Written by Philip Mocz

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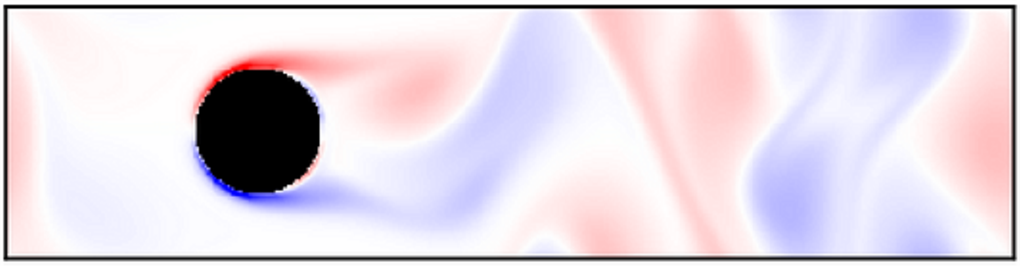

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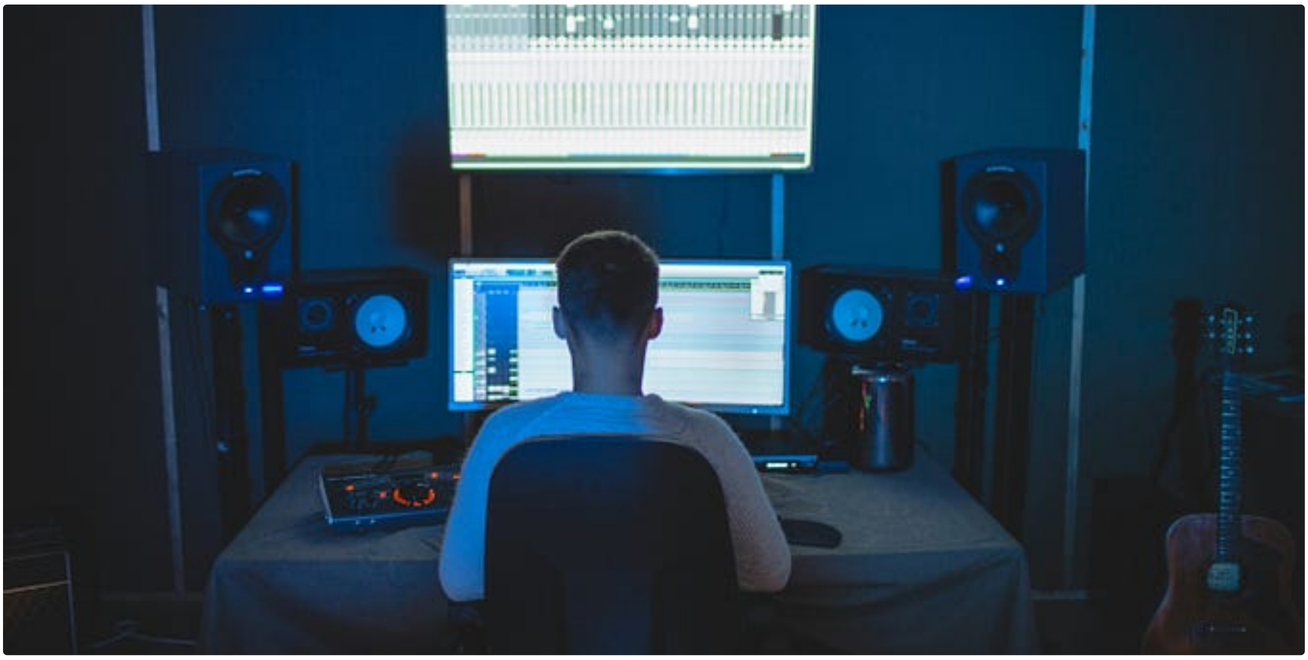

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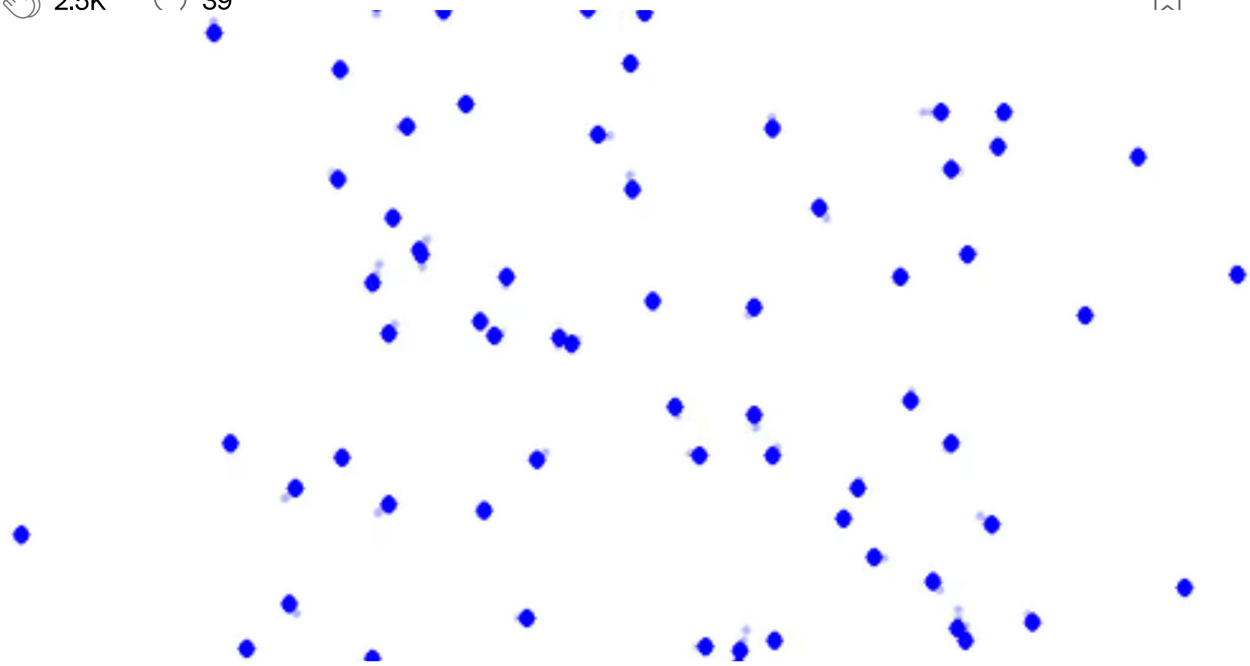

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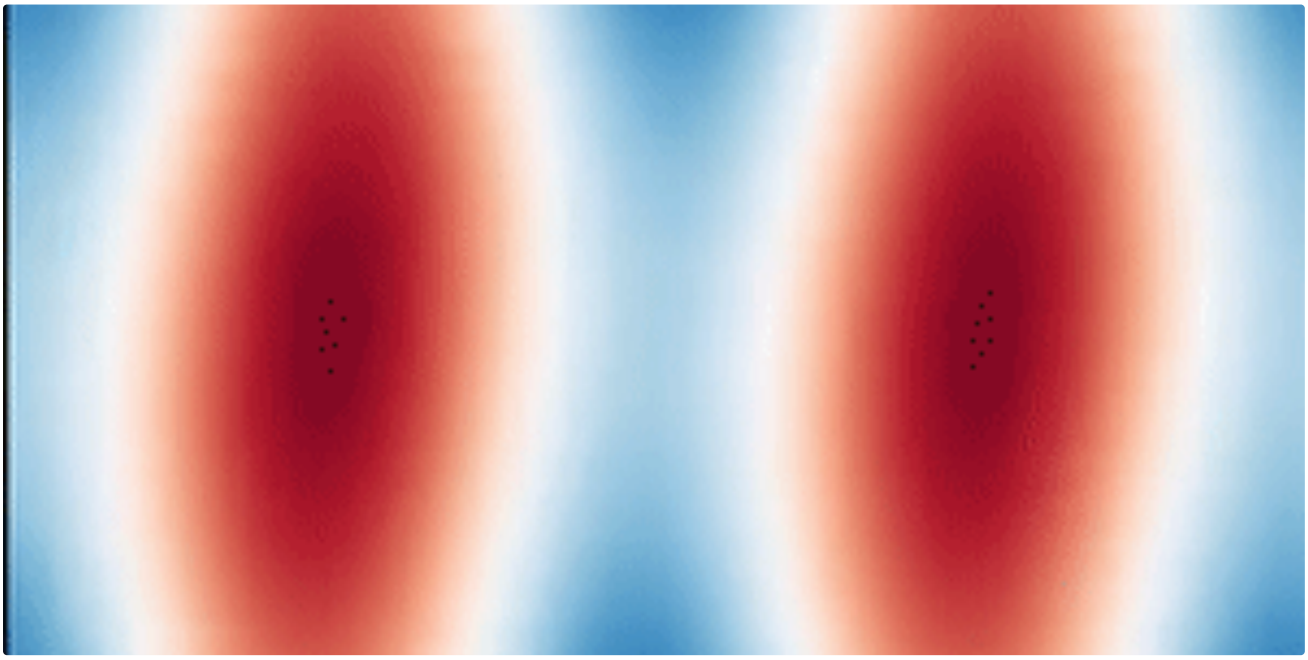

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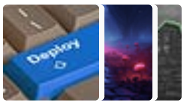

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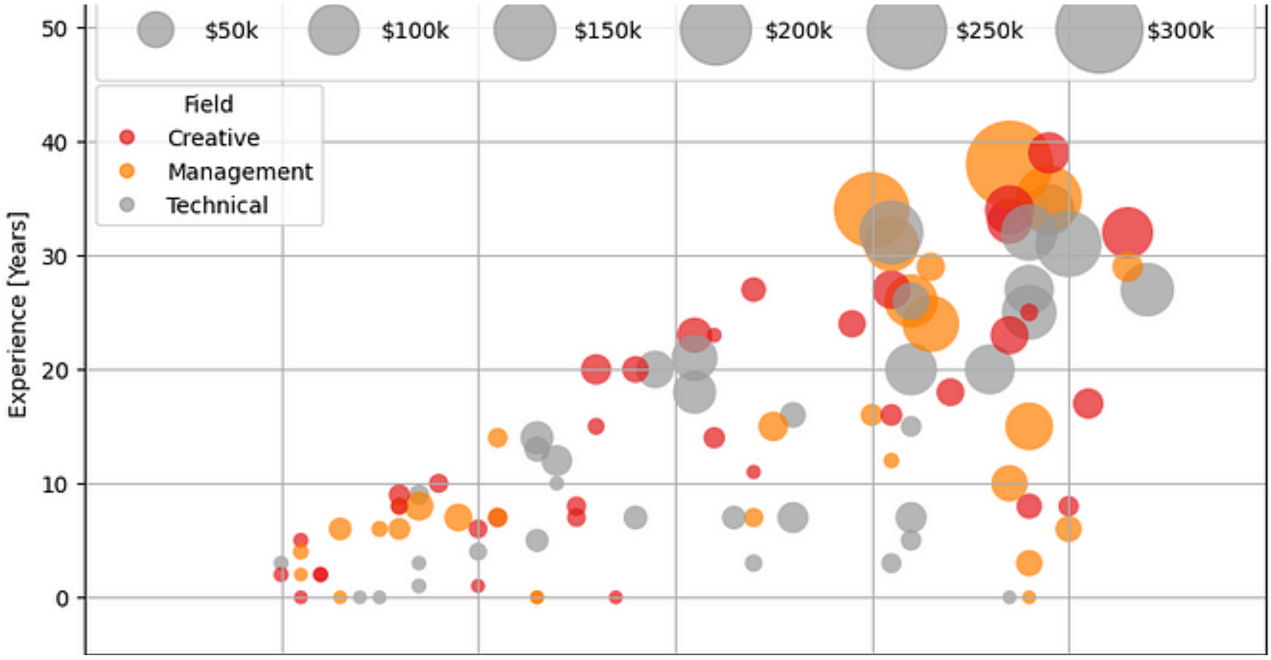

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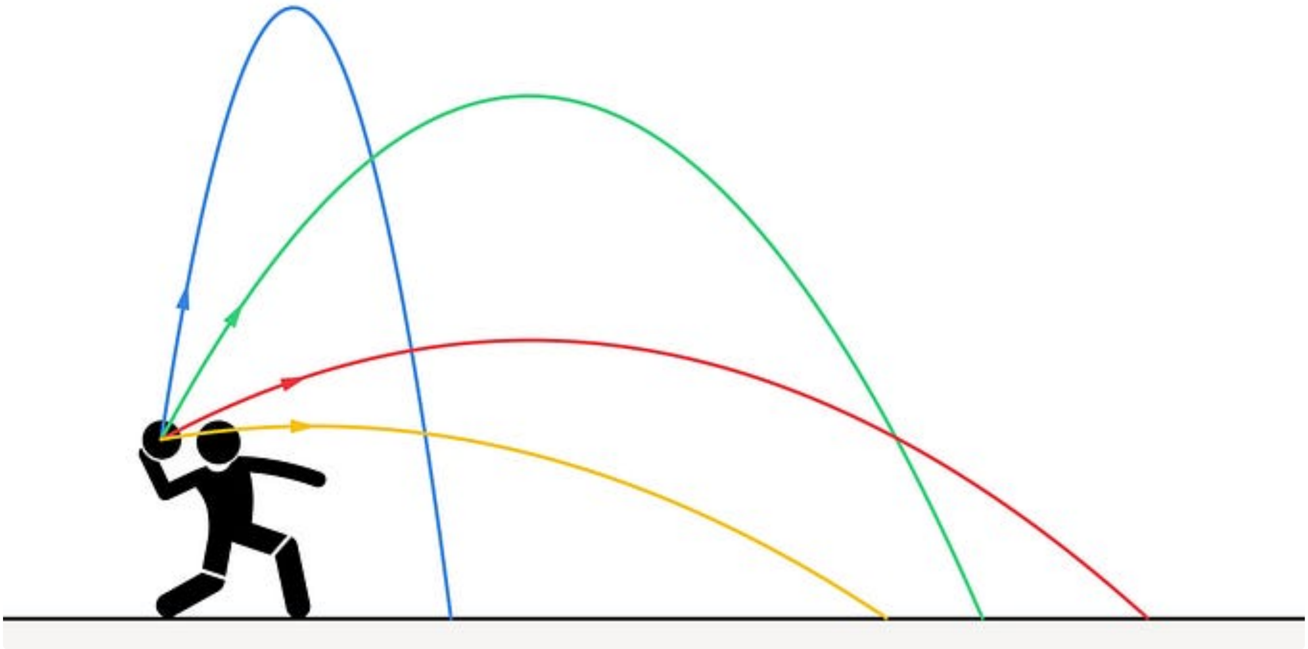

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