CHAPTER 2 Agent based approach

2.1 PRELUDE

Many interesting problems in nature and engineering deal with systems that have a large number of interacting sub-units[38]. Reductionist approach in science is the philosophy that believes that a system can be understood completely by examining its parts. But we know that understanding the atomic structure of the cell has not helped us understand a tissue or an organ or a human being or a society as a whole. Hence to comprehend such a system, one can adopt the complex systems philosophy where each sub unit is understood in relation with others. The crucial part that distinguishes the complex systems approach from reductionism is the final step where all the information is pieced together to predict the collective behavior of the system. Well known examples of complex systems are flocking birds, schools of fish, activity of the brain, human societies, ant colonies, traffic flow, human brain etc.

To model these systems, one can resort to what is called an 'Agent based framework' which is commonly used to understand and simulate problems like social behavior of animals in biology, traffic flow on roads, human interactions- crowd control, economics- rise and fall of markets and growth of cities, catastrophe modeling- spread of an epidemic etc. The idea is to look at every sub-unit of the complex system as an agent, a discrete entity that is defined by a set of states and can interact with other agents and the surroundings. In biology, when studying social behavior of ants, an agent would refer to an ant or when studying growth of cities, an agent could refer to a human being or a group of individuals who exhibit same behavior. These agents are generally regarded as autonomous, because they do not take direct orders from any 'leader agent', rather they

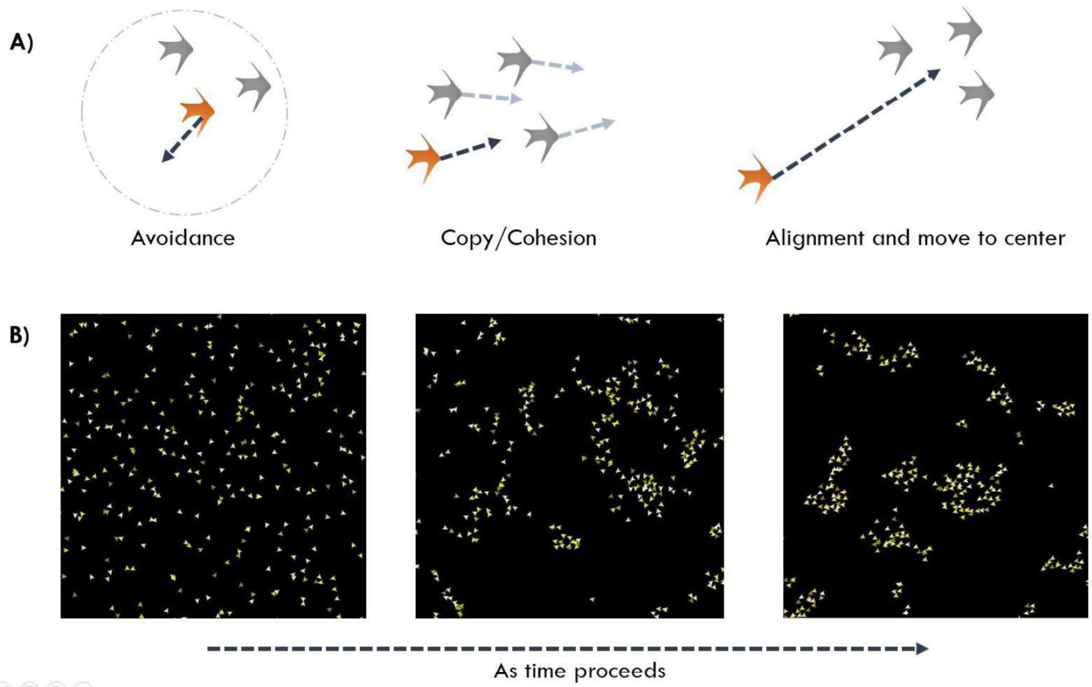

Figure 2-1 A) Rules for the agents (birds) that determine the direction of movement during flight: [Inspired by Figure 16.6 in Flake[116]]; B) Agent based simulations using a freeware *NetLogo* [http://ccl.northwestern.edu/netlogo/] on a periodic domain. Simulation starts with an initial configuration where birds are randomly placed and randomly directed. Then as time proceeds they start to flock together and choose a direction eventually along which all birds align.

follow simple rules, which offer a minimalistic description of the entity level interaction. These rules generally couple the behavior of an agent, non-linearly with other agents and inputs from the surrounding environment. Then the collective behavior of the system is examined using a multi-agent framework that simulates the dynamic behavior of all agents simultaneously. In reality, sub-units of a complex system are complex systems themselves. But it has been shown that simple descriptions for the sub-units can show complex emergent dynamics that are non-intuitive.

2.2 AGENT BASED MODELS- EXAMPLES

Let us consider an example from biology- flocking of birds. Each bird in itself is a complex entity with complicated flight characteristics/aerodynamics. The pressure fields created during a cycle of a bird's flight (up and down stroke) can influence objects nearby which can either be pulled towards or pushed away from the bird as a result of the flow fields generated, collectively they may also be able to reduce the drag on the bird and the object- peloton effect. When the object is another bird which is also in the state of flight, the birds' motion gets coupled. Depending on the interaction between the flow fields generated, the phase difference in the flight cycles, the birds may either show effective cohesiveness or repulsion. With increase in the number of birds, the problem gets even more complicated. The birds disturb the flow field around them affecting the motion of other birds in the neighborhood, which feeds back and affects the motion of birds. From an arbitrary flapping configuration, the birds transition to an optimal one, that reduces the drag collectively, as a result of the feedback from the other birds through the flow[115].

Considering the flow fields involved with a group of birds, it is very difficult (computationally) to simulate a system with a large number of birds. Hence in an agent based formulation we characterize the key interactions between different birds (agents) by simple rules, like avoidance (where birds cannot fly upon crowding), copy (fly in the general direction as that of the flock) and center and align (minimize exposure outside to protect itself from predators)[116,117]. These interactions are illustrated in Figure 2-1a. Each of these rules, though mathematically simple, are a result of the complex interaction between agents at the entity level which can be termed as 'simulated perception[117]'. Using these ideas quantitatively in a simulation framework, it is possible to capture the collective dynamics of flocking of birds that one observes in everyday life as shown in the Figure 2-1b. The simulation is carried out with an initial configuration of agents (birds) which are randomly placed and randomly directed. Each agent will have a velocity vector corresponding to each of the above interactions and the resultant which can be a weighted sum of all interactions will determine the direction of flight of bird at that particular instant of time. After allowing the birds to move in that direction for a small time interval, the new directions are recomputed and the process continues. The birds start to flock as they move in the domain and slowly align in a common direction. Due to the nature of coupling between the agents which is non-linear, the multiplicity of the agents and the recursion involved in applying the simple rules allows the model system to exhibit emergent behavior[116] which is characteristic of the system as a whole. The simplicity of the models/interactions make the agent based framework computationally efficient when compared to more detailed models that would consider the flow fields and the disturbances.

One can find other examples like, ant movement between a food source and its crater, where ants in large numbers collectively identify the best (shortest) route between the two points. The process involves ants choosing different paths to travel in random and as they move, they secrete pheromones which lead the path of the following ants. An ant at a

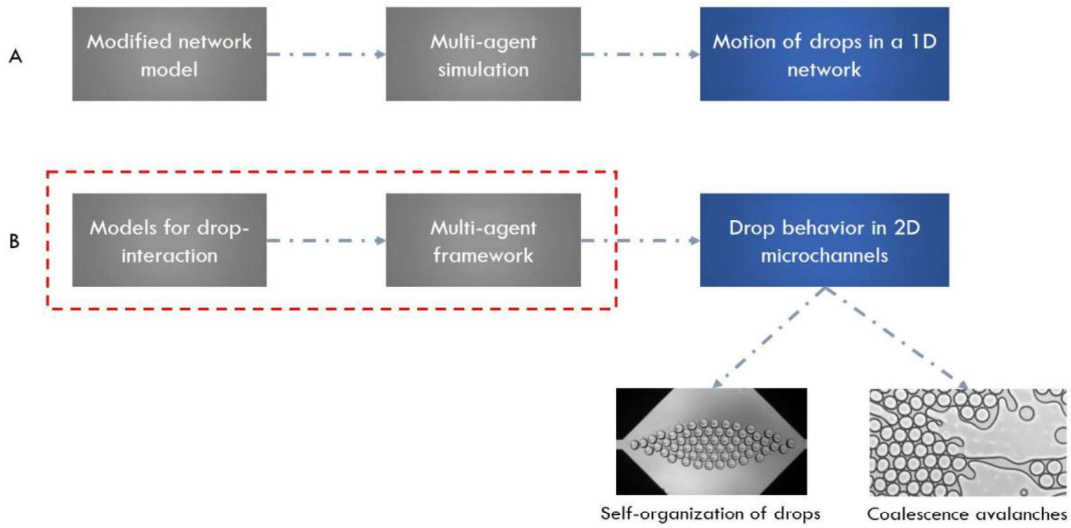

Figure 2-2 A) Agent based framework that Smith and Gaver[99] employed to study motion of drops in 1D channels; B) Work presented in this thesis (marked using a red box): models to explain drop-interactions and a multi-agent framework to simulate drop behavior in 2D microchannels- Predicting self-organization [Taken from [53]] and coalescence avalanches [Taken from [63]].

junction decides to choose a path based on the amount of pheromone in both the paths. Due to pheromone reinforcement, the shortest path is highlighted by strong pheromone trails which reduces the probability associated with the ants picking the longer route. One can model this phenomenon using a stochastic agent based framework, where the choice of an ant at a junction becomes probabilistic. If there are multiple paths between the source and food, one can carry out a Monte-Carlo simulation to identify the different choices that the ants make. This idea has been central in the development of the 'ant-colony optimization' algorithm[118].

2.3 Drops as Agents

Flow of drops in a microchannel is similar to the example of bird-flocking described above in that it exhibits collective behavior. As a drop travels in a microchannel it generates circulations in the flow as a result of the confinement and the circular nature of the drop. Hence a drop disturbs the fluid particles in its neighborhood. With an increase in the number of drops in the channel, the fluid flow around the drops are perturbed continuously and the drops start to interact hydrodynamically. The non-linear nature of the interactions results in collective drop behavior.

Agent based approach was first introduced in droplet microfluidics by Smith and Gaver[99] when simulating the flow of drops in a simple loop (Figure 2-2 a). The model considered was similar to the network model which is explained in section 1.5.5[97]. They posed the network model in the context of an agent based framework to show how drops behave autonomously in a microchannel like agents, as they interact with other agents (drops) indirectly by altering the environment. They were able to qualitatively predict the temporal pattern formation of drops as they flow through a two-branched loop device. Drops do not interact directly as they flow in the channels. Hence the framework cannot be extended to 2D channels where drops can approach each other, hydrodynamically interact to form spatio-temporal patterns.

In this thesis, the agent based framework is applied to study the complex behavior of drops in 2D microchannels. A two-step procedure is implemented in studying drop behavior. First, the entity-level interactions between drops are modelled using simple models or rules based on experimental observations and asymptotic theories. The final step involves setting up a multi-agent simulation which uses these entity-level descriptions to explain the collective behavior of the system. The models for interactions should capture the non-linearity in the drop-interactions and at the same time be computationally efficient. Using the agent based framework we have explored two interesting complex phenomena of drops: the problem of self-organization in a diverging converging microchannel as observed in the experiments of Jose and Cubaud[53] and the problem of propagated coalescence[63] which results in the destabilization of a 2D concentrated emulsion as observed in the experiments of Bremond and co-workers. Using the multi-agent framework, the nature of the phenomena and the dynamics of pattern formation are studied. The collective behavior is explored from a design perspective and several possible applications are proposed. Thumb rules for design are developed based on the understanding gained from the study of the complex drop behavior. Finally, the computational simplicity of the agent based framework allows its incorporation into an optimization routine to answer interesting design questions.