Chapter 1

Crowding Minds

In the book we exploit paradigms of non-linear psychology, artificial life and sociodynamics to simulate, analyze and characterize spatio-temporal dynamics of massive pools of mental entities, i.e. non-trivial dynamics of crowd-minds. In this chapter we give an informal introduction to the paradigms discussed, methods and techniques used, and provide a brief outline of the book's contents.

1.1 Non-linear psychology and sociodynamics

In 1949 Rashevsky proposed

> "... to construct a mathematical system of social sciences by starting with some plausible postulates about the interactions of two or more individuals. In principle these postulates should be derived from the equations of the mathematical biology of the central nervous system" [Rashevsky (1949)].

This idea was developed half-a-century later in physics-based approaches to sociology and collective intelligence. Results in pedestrian dynamics give us a good example of how social systems can be interpreted in physical terms. Thus, Helbing [Helbing (1992); Helbing *et. al* (1998)] successfully applied principles of molecular dynamics to the paradigm of social force. As Moscovici wrote

> "Physicists began to speak of crowds of molecules and to refer to such phenomena as mass phenomena. Thus we find the "same" atomization in nature and in society, a social image of "crowds" common to various branches of learning, a similar concern for a "science of confusion". For this is indeed a physics of confusion since all physical systems, all gases, tend towards confusion when the activity of some power is transformed into heat" [Moscovici (1985)].

Attractive analogies between reaction–diffusion, morphogenesis and pattern formation in social insect societies are made in [Bonabeau (1997); Bonabeau *et. al* (1998a)]. Dynamics of opinion formation [Kacperski and Hołyst (1999); Plewczyński (1998)] is another field where techniques of nonlinear physics are flourishing. As is reasonably highlighted in [Plewczyński (1998)], classical mathematical models of individual attitude change lead to entire uniformity of opinions in a collective of many persons (as in the case of a majority classification problem or voting). These models assume, sometimes implicitly, global interaction between the individuals, as in stirred solutions of reagents. Unfortunately, such situations quite rarely occur in the real world, which is ambiguous, uncertain and contradictory (see also [Axelrod (1997); Axelrod (1986)]).

New generations of models represent space–time dynamics of individual opinions. The models consider evolution towards stable clusters of individuals, who share minority opinions [Plewczyński (1998)]. Thus, for example, Plewczyński [Plewczyński (1998)] describes the social changes in a collective, with lattice topology, of individuals by a nonlinear Schrödinger equation by analogy with a superfluid and a weakly interacting Bose gas in an external potential. The approach proved to be fruitful not only in dynamics of opinions [Kacperski and Hołyst (1999); Plewczyński (1998)] but also in attitude change [Nowak *et. al* (1990)].

Studies of dynamics of excitation in a stadium give us probably the most impressive examples of physics-based interpretation of crowd dynamics. Thus, from video footage of people's behavior at a stadium it was derived that excitation waves travel with a speed of around 22 seats/sec and a wave width of around 6–12 m (15 seats) [Farkas *et. al* (2003)]. Further, the local behavior of participants can be interpreted in terms of a chemically excitable medium with the following reaction set [Nagatami (2003)]:

$$\begin{aligned}&\text{Passive } + \text{Activated } \mapsto 2 \cdot \text{Activated}\\&\text{Activated } \mapsto \text{Refractory}\\&\text{Refractory } \mapsto \text{Passive.}\end{aligned}$$

Other examples of physics of mentality include the Hameroff–Penrose theory of consciousness based on dynamics of quantum coherent superpositions [Hameroff (2001); Hameroff *et. al* (2002); Hameroff and Penrose (1996); Hameroff (1998)] and dynamics of intelligence [Zak (1998); Zak *et. al* (1997)].

The non-linear physics approaches are reinforced by automaton-based computational techniques, exemplified by cellular-automaton models of artificial societies and emergence of societal structure in collectives of simple agents [Epstein and Axtell (1996); Gilbert and Conte (1995)] and populations of interacting finite automata [Axelrod (1997); Doran (1998); Jager *et. al* (2001)].

These and other results in physical interpretation of collective dynamics in groups, crowds and societies led to the formation of the new discipline of sociophysics [Helbing (1995b); Weidlich (2003); Stauffer and Kułakowski (2002)], with the first dedicated conference held in 2002 [Sociophysics (2002)]. In his overview of sociophysics [Stauffer (2002)], Stauffer mentions pioneering results on a physics-based approach to social dynamics, which include dynamics of social segregation [Schelling (1971)], social imitation and opinion formation [Callen and Shapero (1974)]. We also refer to early papers on physics-based market analysis [Beckman (1971)] (in this particular paper the term "social physics" is introduced explicitly). More recent fields developed in sociophysics include social percolation [Proykova and Stauffer (2002); Goldenberg *et. al* (2000); Solomon *et. al* (2000)], belief and rumor propagation [Kabashima (2002); Galam (2002)], pedestrian dynamics [Helbing (1992); Helbing (1993); Helbing *et. al* (1998); Helbing (1991); Helbing and Molnár (1995); Helbing *et. al* (2000); Burstedde *et. al* (2001); Kirchner and Schadschneider (2002)], traffic simulation [Mahmassani (1990); Mahmassani *et. al* (1990); Helbing (1995a); Wolf (1999); Visser and Nagel (2001); Helbing *et. al* (2002)], opinion formation and voting [Weidlich (1991); Babinec (1997); Kacperski and Hołyst (1999); Kacperski and Hołyst (2000); Alves *et. al* (2002)], and formation of cultural domains [Castelano *et. al* (2000)], active Brownian particles and swarm dynamics [Schimansky-Geier *et. al* (1995); Schweitzer and Schimansky-Geier (1994); Ebeling *et. al* (1999); Holyst *et. al*

(2000); Ebeling and Schweitzer (2002)].

Battlefield simulation is yet another emerging field of sociophysics; a brilliant overview is provided by Ilachinski [Ilachinski (2004)]. Some analogs between chemical and physical instabilities and dynamics of combatant masses can be found in [Clements and Hughes (2004)]. There mathematical modeling of the Battle of Agincourt [Clements and Hughes (2004)] shows that instability of the battle front led to loss of the French and Burgundian army in favor of the English army:

> "The Battle of Agincourt was lost ... by the greater army because of its excessive zeal for combat leading to sections of it pushing through the ranks of the weaker army only to be surrounded and isolated" [Clements and Hughes (2004)].

In parallel with non-linear dynamics of societies, a field of dynamical, non-linear, psychology flourished [Lewis and Haviland-Jones (2000); Mayne and Ramsey (2001); Abraham (1992); Sulis and Combs (1996); Butz (1997)] on a fertile soil of Minsky's "mind as a society of many agents" [Minsky (1988)], Dawkins's memes as an evolving space–time configuration of global mental states [Dawkins (1976)] and Dennet's theory of consciousness as a space–time configuration of a many-agent collective [Dennet (1991)]. Foundations of non-linear analysis of social and psychological systems were laid in [Abraham and Gilgen (1995); Guastello (1995); Vallacher and Nowak (1994)], and a mathematical analysis of consciousness (see e.g. [Goertzel (1996)]). Amongst pioneering works, we also mention mathematical models of emotions [Lettvin and Pitts (1943); Colby and Gilbert (1964)] and a cybernetic model of persecutory delusions [Melges and Fougerousse (1966)].

1.2 Crowds

In the book we exploit the science of crowds.

> "If we think of crowds as large numbers of people we typically imagine them as packed together in close proximity to each other. "(Too) many people in (too) little space" may serve as a preliminary schema signifying some basic communalities between phenomena of crowds and of crowding" [Kruse (1986)].

Talking about formation of crowds, Everett Dean Martin wrote:

> "The complex of ideas becomes a closed system, a world in itself. Conflicting facts of experience are discounted and denied by all the cunning of an insatiable, unconscious will. The fiction then gets itself substituted for the true facts of experience; the individual has "lost the function of the real". He no longer admits its disturbing elements as correctives. He has become mentally unadjusted — pathological" [Martin (1920)].

Why are crowds more interesting than groups? Smelser outlines three basic differences between small groups and collectives [Smelser (1962)]: (a) in a small group an individual can personally control a scene of operation, (b) while in the collective there is a sense of "transcending power", (c) the communication in small groups is global, and it is local in large groups, (d) small groups are mobilized by "direct machinery" and in large groups by incitation and agitation. In contrast to groups, see e.g. [Klein (1956)], crowds have no structure whatsoever (apart from topological order imposed on spatially extended models), no hierarchies and often no leadership. Also, high group cohesiveness and physiological arousal of crowd members will "shut down the self-regulation of behavior through private self-awareness reduction" and "enhance the likelihood that the individual's acts will be influenced by environmental stimuli ..." [Prentice-Dunn and Rofers (1989)].

Crowds are unique phenomena, whose studies may bring impressive results and fruitful discoveries. This is because the behavior of each person in a crowd can be reduced to a level of an abstract finite machine – due to the deindividuation process, and spatio-temporal dynamics of crowds may expose non-trivial modes and regimes — due to irrationality of crowd global behavior. This is why a crowd psychology is sometimes attributed to a "science of the irrational" [Moscovici (1985)].

A derationalization — when an individual joins a crowd he loses his rationality [Graumann (1985)] — happens because of deindividuation. Amongst several characteristics of crowd formation developed by Martin [Martin (1920)], we would like to highlight that a crowd is a mental phenomenon occurring simultaneously with gatherings, where repressed impulses are released and thinking is primitivised (individuals become more automaton-like).

> "The crowd-mind is then not mere excess of emotion on the part of people who have abandoned "reason"; crowd behavior is in a sense psychopathic and has many elements in common with somnambulism, the compulsion neurosis and even paranoia" [Martin (1920)].

Why do people behave in crowds differently? Possible processes involved in deindividuation and irrationalization are listed in [Marx and McAdam (1994)]: (a) a large number of people within each other's view, (b) illusion of unanimity produced by group pressure, (c) diffusion of responsibilities, (d) anonymity ("In an impersonal sea of faces, the individual may come to feel that he or she cannot be called to account for the behavior in question" [Marx and McAdam (1994)]), (e) solidarity, (f) social facilitatio and (g) immediacy ("Some persons may become so immersed in the crowd that they respond more immediately and less reflectively to stimuli and suggestions for behavior than is usually the case" [Marx and McAdam (1994)]).

In the book we follow the idea of "pre-experimentalists" of group mind theory, by classification in [Turner (1987)], including Le Bon [Le Bon (1994)], Freud [Freud (1921)] and McDougall [McDougall (1921)], who explained unique features of crowds by three processes [Turner (1987)]:

- deindividuation: "the anonymity of crowd members and the sense of invincible power produced by being in a crowd lead to a diffusion of their feelings of personal responsibility, a loss of personal identity" [Turner (1987)],
- contagion: "actions and emotions spread through the crowd through a form of mutual imitation, leading to uniformity and homogeneity in which personal differences disappear" [Turner (1987)],
- suggestibility: "acceptance of influence on irrational grounds because some kind of emotional tie to and submissive attitude to a person or group" [Turner (1987)].

Deindividuation leads to automatic, delusive and irrational behavior. What is deindividuation?

> "... deindividuation ... is a state of affairs in a group where members do not pay attention to other individuals *qua* individuals and, correspondingly, the members do not feel they are being singled out by others ... such state of affairs results in a reduction of inner restraints in the members" [Festinger *et. al* (1952)].

In 1969 Zimbardo [Zimbardo (1969)] outlined basic precedents for deindividuation: (a) anonymity, (b) shared and diffused responsibility, (c) high group size, (d) temporal distortion (expansion of present and distantiating of past and future), (e) arousal, sensory input overload, reliance upon non-cognitive interactions, (f) unstructured situation, altered states of consciousness and (g) enhancement of affective–proprioceptive feedbacks.

In certain cases deindividuation caused by crowding arousal, diffused responsibility and reduced self-awareness may result in disinhibited and *sometimes violent* behavior [Prentice-Dunn and Rofers (1989)]:

> "Like the paranoiac, every crowd is potentially if not actually homicidal in its tendencies. But whereas with the paranoiac the murderous hostility remains for the greater part an unconscious "wish fancy", and it is the mechanisms which disguise it or serve as a defense against it which appear to consciousness, with the crowd the murder-wish will itself appear to consciousness whenever the unconscious can fabricate such defense mechanisms as will provide it with a fiction of moral justification" [Martin (1920)].

Deindividuation could also be considered as a defense against a threatening environment, as opposed to individuation desirable in a supportive social climate [Ziller (1964); Zimbardo (1969)].

Crowds are also irrational because changes in emotional arousal in crowds lead to derationalization [Kaufman (1999)]:

> "... too much emotional intensity causes the person to be so aroused that thinking and physical self-control become disorganized"[Kaufman (1999)].

Changing attitudes may be another reason for irrationality:

> "... The deeds of crowd members are not rationally controlled, because the thought process in crowds is used only to serve the prepotent interests, not to direct them ..." [Allport (1924)].

Association between a crowd and abnormality was also highlighted by Freud in his work on group psychology and the ego [Graumann (1985)].

Another explanation of a crowd's irrationality may lie in the mental regression of crowd members to childhood.

> "He himself may be but a miserable clod, but the glory of his crowd reflects upon him. ... In the finality of his crowd-faith there is escape from responsibility and further search. He is willing to be commanded. He is a child again. He has transferred his repressed infantilism from the lost family circle to the crowd. There is a very real sense in which the crowd stands to his emotional life *in loco parentis*" [Martin (1920)].

Crowd-minds are also seen as substrates of unconsciousness:

> "Simply that ideas and purposes, especially those contrived by science and rationality, have to undergo a series of metamorphoses before they can be accepted by the crowd. Once transformed into formulae, images, and similes they cease to be part of the conscious mind and enter the realm of the unconscious. Derationalized by passion, deactualized by memory, ideas and purposes are reborn as irrational beliefs and symbols" [Moscovici (1985)].

1.3 Quasi-chemistry and cellular automata

All through the book we use cellular-automaton and mobile finite automaton models and a paradigm of artificial chemistry.

Adopting an automaton approach we consider agents, affective and doxastic entities, as minimalist structures, atoms of emotions and cognition. Several attempts to build a framework of knowledge and belief automata have been successfully made before; see e.g. [Manevitz (1989)]. Emergent properties of automata networks were considered to be a possible tool to manage uncertainty; see [Ligomenidas (1991)]. One of recent examples of how someone can use finite automata when dealing with terminological representational languages is given in [Baader (1996)]. A cellular-automata-based interpretation of knowledge, belief and action distributed among agents is proposed in [Adamatsky (1995b); Adamatzky (1998b); Adamatzky (1998c); Adamatzky (1995a); Adamatzky (1999)]; there problems of the approximation, or reconstruction, of functions of local evolution of epistemic, doxastic and action components from the given set of global configurations of mental states are discussed.

Automaton models were already proved to be successful models of artificial collectives in the 1940s when discrete spaces of finite-state machines were employed to imitate social segregation (see [Hegselmann and Flache

(1998)]); in the 1950s chains of finite and locally interacting automata were studied in a context of game theory (see [Tsetlin (1973)]). A recent boost in automaton models of social behavior is due to development of paradigms of artificial societies [Epstein and Axtell (1996)], particularly automata models of growing societies [Gilbert and Conte (1995)] and populations of finite automata [Axelrod (1997); Doran (1998)], social impact on opinion formation [Nowak *et. al* (1990)] and automaton interpretation of logic [Schaller and Svozil (1996); Svozil and Zapatrin (1996)]. Hereby, we mention that even some of the connectionist models are rooted in cellular-automata semantics; see e.g. [Read and Miller (1998)].

Artificial societies is yet another field where automata models gained success. This deals with emergence of societal structure in collectives of simple agents [Epstein and Axtell (1996)]. The research focuses mainly on automata models of growing societies [Gilbert and Conte (1995)] and populations of interacting finite automata [Axelrod (1997)]. Behavior of automaton models of agent collectives becomes even richer, and obtains a sense of artificial social life [Bainbridge *et. al* (1994)], when agents are made believable [Hadley (1991a)], emotional context of belief is taken into account [Frank (1998)] or mutual belief is analyzed [Tuomela (1996)]. Thus, for example, it is verified in computer experiments with populations of mobile automata, competing for resources, that a collective misbelief, when co-existing in space and time with a collective belief, may increase survivability of the entire population [Doran (1998)].

Automaton models of crowd-minds seem to be capable for perfectly grasping intrinsic processes of crowd mental dynamics because crowds exhibit lower levels of control and have shorter time scales with more discrete and concrete standards:

> "... the crowd does not think in order to solve problems. To the crowd-mind, as such, there are no problems. It has closed its case beforehand" [Martin (1920)].

Members of a crowd "are impulsive and respond with little foresight", they are "inextricably wrapped up in the cues of the moment" [Prentice-Dunn and Rofers (1989)].

A cogitoid — a computational model of cognition, where knowledge is represented by a lattice of concepts and associations between the concepts [Wiedermann (1998b)] — is yet another example of "automaton mentality". It is demonstrated in [Wiedermann (1998b)] that cogitoids realize basic behavioral patterns including Pavlovian conditioning. In the cogitoid the concepts, like automaton states, can be represented by quantities of strength, non-negative integers, and by qualities, integers, whereas associations between the concepts possess a weight [Wiedermann (1998a)].

Several fundamental postulates, which support vitality of finite-automata models of consciousness are provided in [Alexander (1997a)], where a model of artificial consciousness is built on the basis of automaton models of neural networks. In automaton neural models in [Alexander (1997b)] consciousness is represented in the firing patterns of neurons: as soon as every neuron can be simulated by an automaton, up to some degree of correctness, the theory converges to a representation of consciousness in terms of finite state machines. There are some remarkable connections with cogitoids [Wiedermann (1998a)]; for example, when concepts are encoded by inner neurons.

Micro-tubules, which form neuron skeletons and indeed are simulated in cellular automata when every tubulin unit is represented by a cell, form a physical basis of the `OR` theory of consciousness [Hameroff and Penrose (1996); Hameroff (1998)]. It is claimed that consciousness occurs in multi-component systems, which are capable of developing and maintaining quantum coherent superpositions. Every superposition lasts until some event, e.g. exceeding of a threshold, occurs. The coherent state collapses after that. Thus, streams of self-collapsing particles represent a flow of consciousness. So, a subject of consciousness is seen as a massively parallel collective of very simple particles acting coherently.

A paradigm of computational chemistry — molecules represent computational processes — was firstly brought into effective action in a context of self-maintenance of a system and the autopoiesis [Varela *et. al* (1974); McMullin and Varela (1997)]. A molecule in computational chemistry is a symbolic representation of an operator, the molecule's behavior is the operator's action, and a chemical reaction is an evaluation of the functional application [Fontana and Buss (1996)]. Also, a chemical abstract machine — a stirred solution defined by a molecule algebra and rules of molecules' interaction — was invented in [Berry and Boudol (1992)] to realize a paradigm of interaction between molecules in algebraic process calculi [Berry and Boudol (1992)]. In Berry–Boudol's universe a state of a concurrent system is seen as a stirred solution, where molecules of reagents interact with each other according to some specified reaction rules. The process is parallel because all pairs of molecules can interact at once. To set up an architecture of a specific machine, one defines a molecule algebra and rules of interaction between the molecules. Recently, the artificial-chemistry paradigm emerged and formed a new field concentrating on such issues as self-organization and complexity, and non-standard computation; see an overview in [Dittrich *et. al* (2001)]) and an application of a chemical paradigm to simulate evolution of knowledge and emotions in [Adamatzky (2001c); Adamatzky (2002b)]. So, by representing mental states of agents as chemical species, we can design a quasi-chemistry-like reaction between the mental states. The idea has been around for some time and, already in 1967, while talking about social context of riots in the black ghetto of Milwaukee, Slesinger used somewhat chemical terminology:

> "... to distinguish between possible catalytic events leading to the outbreak of a civil disturbance and the presence of underlying social, economic, and political conditions which seem to be necessary before the catalyst can precipitate a reaction" [Slesinger (1968)].

To study artificial chemistry of well-stirred reactors in computational experiments we numerically integrate systems of first-order ordinary differential equations [Press *et. al* (1993)]. We represent thin-layer reactors, where chemical species and micro-volumes interact locally, as systems of partial differential equations, and also model these reaction–diffusion systems as cellular neural (non-linear) networks [Chua (1998)]), as well as cellular automata.

A cellular automaton is an array of uniform finite automata, which update their states in parallel, and each automaton calculates its next state depending on states of its closest neighbors (see e.g. [Toffoli and Margolus (1987); Ilachinski (2001)]); we experiment with a one-dimensional cellular automaton, each cell of which updates its state depending on states of its left and its right neighbors.

Using differential equations, cellular non-linear networks and cellular automata we can therefore represent quasi-chemical reactions between belief states and emotion states in the three following ways. Let a set of reactions be

$$\begin{aligned} &X + Y \to^{k_1} 2Z \\ &Z \to^{k_2} X, \end{aligned}$$

with reagents X, Y and Z and reaction rates k_1 and k_2. This may be interpreted as follows: a person expressing affective or doxastic state X meets a person expressing state Y, they observe each other's expressions and change their affective or doxastic states to state Z. Thus the dynamic of affective or doxastic species in a well-stirred reactor can be simulated as

$$\begin{aligned}
\dot{x} &= -k_1xy + k_2z = \varphi(x,y,z)\\
\dot{y} &= -k_1xy = \psi(x,y)\\
\dot{z} &= k_1xy - k_2z = \phi(x,y,z),
\end{aligned}$$

where x, y and z are concentrations of affective or doxastic states X, Y and Z.

The space–time dynamic of doxastic or affective reagent concentrations can also be modeled in a one-dimensional cellular neural (non-linear) network as

$$\begin{aligned}
\dot{x}_i &= \varphi(x_i,y_i,z_i) + D_x(x_{i+1} + x_{i-1} - 2x_i)\\
\dot{y}_i &= \psi(x_i,y_i) + D_y(y_{i+1} + y_{i-1} - 2y_i)\\
\dot{z}_i &= \phi(x_i,y_i,z_i) + D_z(z_{i+1} + z_{i-1} - 2z_i),
\end{aligned}$$

where i is a space index, and D_x, D_y and D_z are diffusion coefficients of affective or doxastic state reagents. In a cellular-automaton model every cell has two neighbors, left and right, takes three states X, Y and Z and updates its states by the following rule. A cell being in state Z takes state X. A cell changes its current state X (Y) to state Z if there is at least one neighbor in state Y (X). If c_i^t is a state of cell c_i at time t, then the cell's state-transition rule looks as follows:

$$c_i^{t+1} = \begin{cases} X \text{ if } c_i^t = Z,\\ Z \text{ if } [(c_i^t = X) \text{ and } ((c_{i-1}^t = Y) \text{ or } (c_{i+1}^t = Y))] \text{ or}\\ \qquad [(c_i^t = Y) \text{ and } ((c_{i-1}^t = X) \text{ or } (c_{i+1}^t = X))]. \end{cases}$$

Amongst these three models only the cellular-automaton one can be probabilistic, when, due to specifics of reactions simulated, a cell takes different states, corresponding to the same configuration of the cell's neighborhood, with certain probabilities.

In some cases, we used a chemical kinetics simulator [CKS], working on principles of discrete stochastic simulation. A chemical reactor there is portrayed as a system of discrete particles where each particle represents a certain amount of reagents; an interaction of reagent pools is simulated via interaction of particles.

1.4 Dual interpretation

In the book we allow for a dual interpretation of dynamics of emotional and cognitive collectives. First, we can talk about our models as representing dynamics of beliefs, emotions and irrational behavior of human crowds, where every person is reduced to a simple automaton or a chemical species. Second, we sometimes adopt a representation of the human mind as a collective of simple "mental" entities, affective and doxastic quanta.

A multi-agent representation of the human mind has a long history. We can find artificial intelligence, biological and philosophical backgrounds of a multi-agent mind in Minsky's ideas of mind as a society of many agents [Minsky (1988)], Dawkins's memes, ideas and beliefs, which diffuse in the noosphere and represent some kind of evolving space–time configuration of global mental states [Dawkins (1976)] and Dennet's theory of consciousness as a space–time configuration of a many-agent collective [Dennet (1991)]. Recent results in the field include Wiedermann's cogitoid [Wiedermann (1998b)], Hameroff–Penrose's `OR` theory of consciousness [Hameroff and Penrose (1996); Hameroff (1998)] and Alexander's artificial neural consciousness [Alexander (1997b)]. The processes of crowd dynamics can be interpreted in terms of an individual's mental dynamics:

> "The crowd-self ... is analogous in many respects to "compulsion neurosis", "somnambulism", or "paranoic episode". Crowd ideas are "fixations"; they are always symbolic; they are always related to something repressed in the unconsciousness" [Martin (1920)].

1.5 Emotions, beliefs and actions

In the book we aim to demonstrate rich spatio-temporal dynamics of crowds at three basic levels of cognitive behavior – emotions, beliefs and actions. They are discussed in a "natural order", from emotions to beliefs to actions:

> "... thinking, no matter how well articulated, is not sufficient for action. ... Emotions are prime candidates for turning a thinking being into an actor" [Frijda *et. al* (2000)].

Space–time dynamics of emotions in large-scale collectives is studied in the second chapter; this is followed by non-linear models of belief development in "unregulated" crowd-minds and crowd-minds constrained by norms. The first three forthcoming chapters build up a computational theory of disordered mentality expressed in terms of affects and cognition. Then we introduce logical systems derived from space–time dynamics of crowd-minds, to speculate about possible logics behind irrationality. Finally, we establish morphological correlates of irrational behavior, and uncover surprising facts about morphological complexity of irrationality.

In the second chapter we study affective mixtures. An affective mixture is a theoretical construct which represents emotions spreading and reacting one with another as a massive pool of locally interacting entities. Molecules of the affective mixture correspond to basic emotions – happiness, anger, fear, confusion and sadness — which diffuse and react with each other by quasi-chemical laws. In computational experiments with affective solutions, in well-stirred and thin-layer reactors, we uncover and classify varieties of behavioral modes and regimes determined by particulars of emotion interactions. We test applicability of affective solutions in an idealized situation of emotional abuse therapy. Results outlined in the chapter indicate that a paradigm of affective solutions offers an unconventional but promising technique for designing, analyzing and interpreting integral and spatio-temporal dynamics of mass moods in crowds.

The second chapter is structured as follows. We introduce an artificial chemistry of emotions, a theoretical paradigm, a vision of emotions as abstract chemical species interacting with each other by certain rules similar to quasi-chemical reactions. Several reaction schemes involving happiness, sadness, anger, fear and confusion are analyzed in detail, and spatio-temporal dynamics of the affective quasi-chemical mixtures is studied in cellular-automaton models. A case of emotional abuse therapy is provided as an example of possible practical applications of theoretical findings on behavior of affective mixtures. The second chapter is completed with discussions of affectons — finite-automata models of emotional interactions. An affecton is an emotional automaton which takes states from a set of basic emotions — happiness, anger, confusion, anxiety and sadness, and updates its state depending on its current state and a state of its input (which is also a state-emotion). We define several classes of emotional automata and study dynamics of reflecting affectons and automata in a random environment; we also analyze behavior of coupled affectons using their global state-transition graphs. These toy models of emotional automata are based on our early results in automata models of and algebraic approaches to the study of cognition — simulation of hierarchical groups of believers [Adamatzky (1998c)] and cellular-automaton and artificial-chemistry models of doxastic evolution [Adamatzky (2001d); Adamatzky (2001a); Adamatzky (2001c)]. In the second chapter we concentrate rather on formal properties of emotional automata and try not to draw any common-sense consequences from results of our studies. Finite-automata models discussed in the chapter should be considered as a preliminary step towards a full-scale formal theory of emotional interactions.

Why do we develop a formal theory of emotional interactions? First, emotions are a basis of cognition [Bates (1994); Chalmers (1996); Goleman (1996); Picard (1997)]. Emotions form a unique primary, fast, component of intelligent response to an external stimulus; beliefs constitute the secondary, slow, component [Eckman (1992); Goleman (1996)]. Therefore, formal models of emotions must be incorporated in mathematical models of computation and cognition. Second, emotions rather than knowledge govern behavior of crowds, which are better in feelings than in reasoning [Graumann and Moscovici (1985); Le Bon (1994); McPhail (1991)]. This is why emotions have to be taken into account in designing mathematical models of social dynamics and in developing algorithms of decentralized computing. Third, robotics lacks architectures of truly emotional robots, that do not simply express but also experience and communicate their emotions to other robots and humans [Breazeal and Scassellati (1999); McCarthy (1979); Scheeff *et. al* (2000)].

Do emotions really interact? They do not interact *per se* but via their carriers, persons. Emotions are contagious in a sense that emotional perturbations spread in groups and collectives (most members of which but a few are assumed to be initially in a "no-emotions" state!):

> "The precipitating stimuli arise from one individual, act upon ... one or more other individuals, and yield corresponding or complementary emotions ... in these individuals" [Hatfield *et. al* (1992); Hatfield *et. al* (1994)].

The contagion may be based on imitation and facial mimicry, which cause an affective feedback from facial receptors and neurons [Hatfield *et. al* (1992); Hatfield *et. al* (1994)]; sometimes the contagion is seen as a mechanism of physiological synchronization [Levenson and Ruef (1997)]. However, surprisingly few publications deal with interaction between emotions; see e.g. [Hatfield *et. al* (1994); Levy and Nail (1993); Marsden (1998)]. We know that persons in certain emotional states would more likely to change their emotions when they encounter persons in other emotional states, for example

> "It is happy people who are most receptive to others and most likely to catch their moods; the unhappy seem relatively oblivious to other' feelings and to contagion" [Hatfield *et. al* (1994)].

This means that a matrix of binary interaction of emotions may have quite a non-trivial form. Particulars of emotional interaction are usually dependent on emotions' strength, context of emotional interaction and vectors of interpersonal relationships, for example:

> "Angry faces sometimes stimulate fear as well as anger; another's fear may put us at ease" [Hatfield *et. al* (1994)].

What is a minimal computation model of emotional interactions? Given a finite set of emotional states one need only to define a binary composition of emotions to construct a minimalist model. The model would already represent how someone's emotion is changed when he or she interacts with someone else. To make the representation more close to reality one can say that the finite set of emotional states is a state set of a finite automaton and the binary composition is the automaton's state-transition function. This will also allow us to study linked evolution of emotions in automaton collectives.

Most examples of emotional developments, discussed in the second chapter, exhibited affective dynamics at the edge of pathology. Pathology is one of the key consequences of crowding; either it is a crowding of persons or a crowding of thoughts in our brains. We continue the theme of near-pathological mentality of crowd-minds in the third chapter of the book. There we use a conventional belief state to derive states of knowledge, misbelief, delusion, doubt and ignorance, and to construct and study non-trivial compositions of the doxastic states. We show that the compositions truly reflect "abnormalities" of crowd behavior, and that quasi-chemical and finite-automaton models of doxastic collectives express intriguing spatio-temporal dynamics.

Several interesting algebraic properties of the doxastic compositions are studied, and deterministic derivatives of the compositions are analyzed in terms of naive, conservative, anxious and contradictory agents. We study discrete dynamics of reflecting agents and stirred pools of agents in terms of finite automata. We show that non-stirred, or ordered, collectives of agents exhibit in their evolution the richest possible range of space–time phenomena from competing domains of regular patterns to random trees and triangles. They are analyzed in detail, including the possible influence of algebraic properties of doxastic compositions on space–time patterns of doxastic derivatives that emerge in the evolution of agent collectives. We also determine products of so-called interacting doxastic worlds, where every world is an element of a Boolean of the set of doxastic states, to enforce our insight in domains of attracting and impossible worlds.

To study well-stirred pools of doxastic entities we also adopt an artificial-chemistry approach. Five derivatives of belief — knowledge, misbelief, delusion, ignorance and doubt — are considered to be reactants of an abstract chemical solution. These quasi-chemical species react one with another by certain rules obtained though an unconventional interpretation of a belief update. Several types of reaction systems are studied in computational experiments with the doxastic solutions. A global dynamic of doxastic chemical solutions is also interpreted from a common-sense point of view. Non-stirred pools of doxastic "quanta" are simulated in lattices of doxatons — finite automata which take states of knowledge, misbelief, delusion, ignorance and doubt.

Such diverse fields of artificial intelligence as distributed intelligence, social dynamics, artificial society and collective mind and consciousness deal with believing agents. Despite being so long under the scope of philosophy, logic and computing sciences, only recently was a belief started to be considered as not ideal and believers themselves as not omnipotent. Some non-classical logics and computational models began to incorporate a fallible belief in their framework; see [O'Hara *et. al* (1995); Fagin and Halpern (1988); Gärdenfors (1990)]. Recent research proves that agents can recognize other agents' mental states, including beliefs and intentions [Tambe *et. al* (1998)]. A non-standard, and sometimes even pathological, interaction between people's mental states in developing crowd situations [Le Bon (1994); Smelser (1962)], collective delusions and hysterias got a "proper" formal interpretation just recently; see e.g. [Summers and Markusen (1999); McPhail (2001)]. However, despite the success of non-traditional approaches to researching a collective belief, a diversity of doxastic states was almost left out of consideration. Quite typically, only belief and knowledge are employed in commonly used logical or computation models. The importance of delusion, misbelief, doubt and ignorance was unfairly underestimated.

A context of the doxastic states' updating is also a missing point of modern research. Realistically, a behavior of individuals is governed by a pleiad of momentary mental states, which undoubtedly include emotions, intentions, dreams, desires and imaginations. More often than is usually expected, the mental states, and beliefs in particular, are updated irrationally or even pathologically. A reversibility of knowledge and imperfect evolution of collective beliefs is also quite a common phenomenon. Thus, for example, it was shown that a false belief may be successfully spread in a social group if supported by falsified judgements or self-fulfilling processes [Burns and Gomolinska (2001)]. Also, in situations of an emotional contagion [Hatfield *et. al* (1994)], we could possibly talk about a cognitive contagion, where one or another state of belief acts upon several individuals of a collective and, as a result, invokes complementary doxastic states. Thus third chapter uncovers and exploits the diversity of the doxastic states and particulars of space–time dynamics of locally interacting doxastic entities.

Norms are the most likely instrument for dealing with abnormal behavior. So, in the fourth chapter, we discuss how norms may influence the space–time dynamic of doxastic components of artificial crowds. A mental state of an agent is characterized by the agent's belief in some proposition and a truth value of the proposition in the agent's local vicinity. Doxastic compositions derived in the third chapter are mainly indeterministic; however, we can make them deterministic by applying norms. These norms are expressed as priority orders over doxastic states. In computer experiments with space–time evolution of well-stirred mixtures and lattices of doxatons we demonstrate how norms and initial conditions can influence the behavior of abstract collectives of simple agents. A set of findings, discussed in the fourth chapter, include controllable diffusion of doxastic states and formation of stationary patterns of doxastic states.

Conventional logics do not work in crowds because deindividuation leads to emergence of an abnormal collective mind, which becomes irrational due to cognitive and affective overload. In the fifth chapter we develop a logical basis for irrationality of crowd thinking. We "breed" logical systems which behave non-trivially when interpreted in terms of dynamical systems. We construe three-valued logical systems as pools of abstract chemical species; logical variables, involved in chemical reactions, are catalyzed by logical connectives. Then we study global and space–time dynamics of these "logical" chemical reactors. We derive a family of combinatorial systems $\langle\{T, F, *\}, \wedge\rangle$, where T, F and $*$ are truth values, $\wedge$ is a commutative binary operator and $\wedge$ acts as a Boolean conjunction on $\{T, F\}$; $* \wedge * = *$, $T \wedge * = a$ and $F \wedge * = b$, with $a, b \in \{T, F, *\}$. We look at nine combinatorial systems of the family, specified by values of a and b, and derive from each member $\langle ab \rangle$ of the family an artificial-chemical system, where interactions between reactants T, F and $*$ are governed by $\wedge$. In computational experiments with well-stirred reactors, we show that all systems but $\langle T* \rangle$ and $\langle *T \rangle$ exhibit a dull behavior and converge to their only stable points. In a reactor of the system $\langle T* \rangle$, catalyzed by $\wedge$, concentrations of reactants oscillate while a reactor of the system $\langle *T \rangle$ finishes its evolution in one of two stable points. Thus we call the models of $\langle T* \rangle$ and $\langle *T \rangle$ oscillatory and bifurcatory systems. Further, we enrich the systems with a negation connective, define additional connectives via $\neg$ and $\wedge$ and undertake a detailed study of the integral dynamic of the artificial stirred chemical reactors and of the space–time dynamic of thin-layer non-stirred chemical reactors derived from the logical connectives. We demonstrate that thin-layer reactors exhibit a rich space–time dynamic ranging from breathing patterns and mobile localizations to fractal structures. A primitive hierarchy of connectives' phenomenological complexity of non-trivially behaving logical systems is constructed therefor.

In the sixth chapter we uncover morphological consequences of irrational behavior. There we study collectives of mobile agent-automata, inhabiting a two-dimensional lattice. For every step of discrete time an agent-automaton decides if it moves at random or stays in its current node depending on a number of occupied neighboring nodes. Agents behave irrationally because they do not simply dislike to stay in neighborhoods with "density" exceeding a certain threshold but an agent moves if the number of other agent-automata in its neighborhood belongs to some specified interval or, in more complex models, a set of integer numbers. Eventually, all agent-automata find their appropriate positions and stop moving; a stationary global pattern of resting agents is finally formed. The morphology of these patterns of resting agents is studied in the sixth chapter. We define a degree of irrationality of an agent's behavior in terms of lower and upper boundaries of an action interval or a structure of an activation set; then we build a mapping between irrationality of agents' behavior and morphology of stationary patterns formed by the agents. Thus, we are making the first step towards a morphological theory of irrationality.

Natural collective phenomena, for example movement of crowds of pedestrians and the impressive nest formations of social insects, provide us with an existence proof that sophisticated constructions may be built by swarms of relatively simple artificial agents. The constructions often appear to have required impressive control and coordination — yet each agent in the collective does not appear to be provided with an internal world model or blueprint for the complete construction. These macroscopic structures emerge as the consequence of interaction of agents, carrying out simple rules based upon the local state of the world, which includes the interaction between agents and the growing structure. In the sixth chapter we characterize structures emerging in pools of irrationally behaving agents.

Considering the sixth chapter in a context of pattern formation in massive pools of discrete entities, we would like to provide several reasons for this subject to be so important. First, discrete models offer an alternative to conventional methods of numerical solutions of partial differential equations, an alternative which is so attractive because we can control parameters of behavior of each entity of the model and virtually program global behavior via local interactions of elements [Toffoli and Margolus (1991)]. Impressive results in distributed building in collectives of simple mobile agents [Bonabeau (1997)] and in design of smart matter [Hogg and Huberman (1998)] prove the viability of the discrete approach. Second, discrete models are fully scalable. They describe equally well reaction–diffusion systems [Schimansky-Geier *et. al* (1995)], externally driven granular material [Melo *et. al* (1995)] and crowds of pedestrians [Helbing (1991)]. Third, a selfishness and also irrationality, or even a state far from mental equilibrium, of an elementary entity can be accounted for during simulation. This may be particularly useful in situations when behavior of an entity, e.g. agent, violates physical laws. Thus, for instance, self-driven particles [Vicsek *et. al* (1995)] are not especially common in physics; however, they have many real biological and sociological counterparts. A fluid-like dynamic of pedestrians [Helbing (1992)] is, probably, the best example. The pedestrian dynamic together with micro-simulation of pedestrian crowds forms a new sub-discipline, at the edge of physics, computer science and sociology — *sociodynamics* [Helbing (1991)]. A concept of active Brownian particles, i.e. diffusing particles that generate a self-consistent field, offers another example [Schimansky-Geier *et. al* (1995); Ebeling *et. al* (1999); Ebeling and Schweitzer (2002)]. The concept, applied to real phenomena of cell migration, gas discharges and catalytic surfaces, where only a few particles form a stable macroscopic structure, demonstrates that a continuous description is not appropriate and the discrete nature of the phenomena must be employed. A vibrating granular material is last but not least an example in the raw of discrete models with emergent properties. It is shown that various kinds of two-dimensional patterns are formed in a vertically vibrated thin granular layer [Melo *et. al* (1995)]. A transition between different classes of patterns may be observed when the amplitude of vibration is changed while the frequency of vibration is kept fixed. Experimental and simulation studies report a wide range of patterns: hexagons, standing waves, labyrinthine patterns, stripes and localized structures [Umbanhowar *et. al* (1996); Strassburger and Rehberg (2000)].

* * *

As Marx and McAdam noted

> "The field of collective behavior is like the elephant in Kipling's fable of the blind persons and the elephant. Each person correctly identifies a separate part, but all fail to see the whole animal. The logic involves emergent group behavior in settings where cultural guidelines are non-specific, inadequate, in dispute, or lacking altogether" [Marx and McAdam (1994)].

We hope that models and paradigms developed in the book will contribute towards building of a coherent mathematics- and physics-based theory of collective mentality.