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THE STRUCTURE OF CREATIVE ACTIVITY

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Abstract. The specifics of creative activity are considered. There are three phases of such activity: discovering a new knowledge domain (subject matter) and accumulating basic knowledge, mastering the knowledge domain, and mass productive use. The life cycle of creative activity is analyzed. As shown by the analysis, creativity is concentrated in the stage of goal-setting only. A qualitative model for mastering knowledge (experience) and a graph-theoretic structural model of a knowledge domain are proposed. New models can be developed, and well-known models can be used to describe and study each phase of creative activity, including those introduced by the authors earlier: in the first phase, optimal distribution models for the researcher's efforts between the tested hypotheses and optimal scheduling models for tested hypotheses; in the second phase, mathematical models of experience; in the third phase, structural and algorithmic models and optimization models.

Keywords: creative activity, experience, creativity, knowledge domain, making and testing hypotheses.

INTRODUCTION

Activity is a dynamic interaction of a human with the reality in which he represents an actor (*subject)* purposefully influencing a *subject matter (object)* [**Ошибка! Источник ссылки не найден.**]. Activity is a form of human actions aimed at cognizing and transforming the surrounding world, humans themselves, and the conditions of their existence.

Elementary activity is understood as an activity whose goals, technologies, and result have no internal structure.[1]

In the monograph [2], an activity that is not elementary was called complex. In other words, *complex activity* (CA) is an activity with a nontrivial internal structure, multiple and (or) changing goals, actor, technology, and the subject matter's role in the goal context.

[1] In the case of elementary activity, there is no need to consider the actor and subject matter together with the activity itself: they play the role of an intuitively clear context. During such activity, only the subject matter evolves in accordance with the technology used by the actor.

The monograph [2] proposed a classification of activities and identified, in particular, regular activity and creative activity.

Regular CA is an activity performed using a known technology to obtain a priori specified results. The structure and technology of regular CA are deterministic.

Creative CA is an activity with a partially defined (incompletely known) technology at its beginning. Therefore, the technology of creative CA is developed when implementing this activity. The unknown technology is due to uncertain demand and (or) a priori uncertain specifications of the activity result.

Historically, there have been two paradigms for the definition and study of *creativity*. Within the first (activity) paradigm, creativity is treated as an activity. The most striking examples are *research activity* [3] and *artistic activity* [4].

- Creativity is a human activity that produces new material and nonmaterial values of social significance [5].
- Creativity is any practical or theoretical human activity in which new results (*knowledge*, decisions,

methods of action, or material products) arise (at least for the actor) [6].

- Creativity is an activity resulting in new material or nonmaterial values [7].

Within the second paradigm (*the psychology of creativity*), creativity is interpreted as "an interaction leading to development" [8, 9]. According to Ya.A. Ponomarev [8] and his followers, the subject must admit the influence of the object (environment) on himself; therefore, unlike activity, this interaction implies a cross-action of the object. The mechanism of this cross-action is associated with different categories: intuition, insight, cognitive unconsciousness, defocusing of attention, action's by-product, and others.

The two approaches mentioned are not contradicting but mutually complementing. Really, regardless of the position adopted, it is necessary to introduce certain assumptions to answer the following question: where does the image of a "creative product" appear in the subject's mind (an artist's intention, a researcher's hypothesis, etc.)? The psychology of creativity investigates, in particular, the reflection mechanisms of the surrounding world in the subject's mind considering the latter's experience. Within the activity approach, followed below, the assumption is the existence of a graph that objectively and adequately describes the knowledge domain's structure; see Fig. 4 in Section 5.

Creativity has become a very popular research topic in management and management psychology since the 1980s–1990s. For example, we refer to the surveys in [10–13]. There has been a significant flow of publications on this range of problems; see a scientometric analysis in the paper [14]. However, the results of creativity studies presented therein are qualitative and, at best, at the level of structural models [15].

The general model of activity, proposed in the book [16], describes the activity of subjects considering their active choice and activity in the environment. This model assesses the results of activity and mastering technologies. Moreover, it describes and examines the dynamics of knowledge, experience, and technologies using a set of admissible *structural elements of activity* (SEAs) as a function of time and previous actions, experience, activity result, subject's state, and values of *uncertainty factors* (UFs). However, the general model relations used directly yield no constructive results due to their analytical complexity.

This paper considers the specifics of creative activity and formulates its general structure in terms of the methodology of complex activity [2]. Within the life cycle model of a knowledge domain (subject matter), we identify the key phases of creative activity, showing that creativity is concentrated in the stage of goal-setting only.

The remainder of this paper is organized as follows. Section 1 introduces basic definitions. In Section 2, the life cycle of a knowledge domain is considered. In Section 3, we localize the creative aspects in the life cycle of CA. Section 4 contains a qualitative model for developing knowledge (experience); Section 5, a structural model of a knowledge domain.

1. DEFINITIONS

Based on the concepts of knowledge, experience, cognition, and skill from the dictionary [17], we will formally define knowledge and experience. Within this paper, the concepts of experience and knowledge (individual or collective) are considered equivalent. *Experience and knowledge* are defined as the result of cognizing the reality, reflected in the consciousness of an individual or a group of individuals and in the material forms available to them (documents, etc.) through beliefs, notions, judgments, inferences, theories, and skills to perform definite activities in definite conditions. *Consciousness* is understood as the process and result of creating a world's model for particular purposes [18]. In this sense, creative activity closely relates to consciousness since both involve the creation of new knowledge.

Let us define a *knowledge element* as an assertion about the properties of the external world that is confirmed to be true at some time instant (or period) by observations when executing an SEA or is verifiable by executing an SEA (a system of SEAs).

For example, a knowledge element can be a subset of the Cartesian product for the admissible ranges of environment's parameters (including the subject matter of technologies): it can determine a set of admissible values of parameters, particularly at different time instants. In other words, a knowledge element can describe the sequence of changes in the states of environment's elements or the relation between their parameters, particularly under the effect of the subjects' activities.

Activity, including the capability for independent goal-setting, the choice of states (actions), and reflection, is the basic characteristic of a human (*active element*, further also called an *agent*).

A knowledge element is said to be known to an *active system* (AS, a system containing agents) if the hypothesis on the corresponding assertion is confirmed to be true when executing one or several SEAs.

For each knowledge element, there are *preconditions*: a set of knowledge elements that must be known for the corresponding hypothesis to be tested. At each time instant, a set of knowledge elements with testable hypotheses can be determined. For such knowledge elements, the preconditions (the current "knowledge front" in Fig. 4 below) satisfy the current state of experience (knowledge).

Then each knowledge element at any time instant has one of the following states with respect to the AS:

– not available for hypothesis testing (the preconditions are not satisfied);

– available for hypothesis testing, but the hypothesis has not been tested;

– known (the hypothesis has been tested).

Let us formalize the agent's experience (knowledge) accumulated by the current time instant using a set algebra for the set of his currently known knowledge elements.

According to [2], a *technology* is a system of conditions, criteria, forms, methods, and means of consistently achieving a given goal. Following this definition, we will consider a technology consisting of two components: technological knowledge and objects (*means* of activity). In this case, technological knowledge is a subset of experience (knowledge) as a whole, and the object part of the technology (means) can be treated as an environment's component (activity resources).

As shown by historical practice, the evolution of knowledge (experience) of humankind has a "spasmodic" character: short periods (*scientific revolutions* according to T. Kuhn [19]) of forming new paradigms (new areas of knowledge) are replaced by relatively long periods of the so-called *normal development* (mastering and productive use of knowledge). This process naturally "selects" knowledge domains, i.e., subsets of sets of knowledge elements, possibly conceptually close and interconnected with each other. Let us consider their life cycles.

2. THE LIFE CYCLE OF A KNOWLEDGE DOMAIN

Based on the public-historical practice, we identify three phases[2] of the life cycle of a knowledge domain; see Figs. 1 and 2.

Phase I (*discovering a new knowledge domain and accumulating basic knowledge*). In this phase, a set of SEAs is implemented sequentially and (or) in parallel to gain knowledge: to test the hypotheses that make up knowledge (experience) elements. When implementing the SEAs for testing hypotheses, the significant conditions of the assertions are set (selected) by the subject (individual or collective). The corresponding mathematical models were considered in subsection 5.2 of the book [16].

Each such test has a binary a priori unknown (!) result. Therefore, true uncertainty is realized in each SEA [20]; the hypothesis is either rejected or confirmed depending on the result. These SEAs can be implemented in the form of activity over different objects: material (e.g., physical experiments), informational (e.g., mathematical modeling), and imaginable (thought experiments).

Assume that the first phase continues while potentially useful applications of a given knowledge domain are unknown, potentially useful goals are not formulated, and technologies for achieving them are not developed.

Each SEA and the content of this phase are intended to gain knowledge of the environment.

Thus, basic knowledge (experience) is accumulated: knowledge of the UF properties (their values and dynamic laws) and the CA technologies executed under a certain set of UF values are acquired. In the first phase, CA technologies aim to gain new knowledge (constructing a model of the surrounding reality) rather than obtain a useful result.

Phase II (*mastering the knowledge domain*) includes technology development and single productive and experimental use. A sign of the transition between phases I and II is the emerging hypotheses about a potentially useful application of knowledge (the formulation of new useful goals). In this phase, the goals of SEAs are to form technologies for obtaining useful results based on the UF model yielded by phase I. The subject does not choose the UF values: they are realized by the environment's "natural choice." In other words, some significant conditions of the assertions are determined by the UF values and are not set by the subject (unlike phase I). Note that different values of the UFs can be realized: the already known ones (new knowledge elements are not formed) or the ones not encountered before (new knowledge elements are formed). With multiple repetitions, a known technology either confirms operability (the desired productive result of CA) under all or most of the UF values or identifies new UF values. The models presented in [21, 22] adequately describe this process.

In each knowledge domain and their combination, a finite number of "reasonable," "rational," and "optimal" technologies can be created. (For example, the best electric motor, steam engine, or airplane design from the currently available materials.)

[2] The phase boundaries and the beginning of the life cycle as a whole are conditional. In most cases, we can hardly indicate a single event (the time when it occurs) corresponding to the beginning of a particular phase or the life cycle. However, this is not required to build formal models.

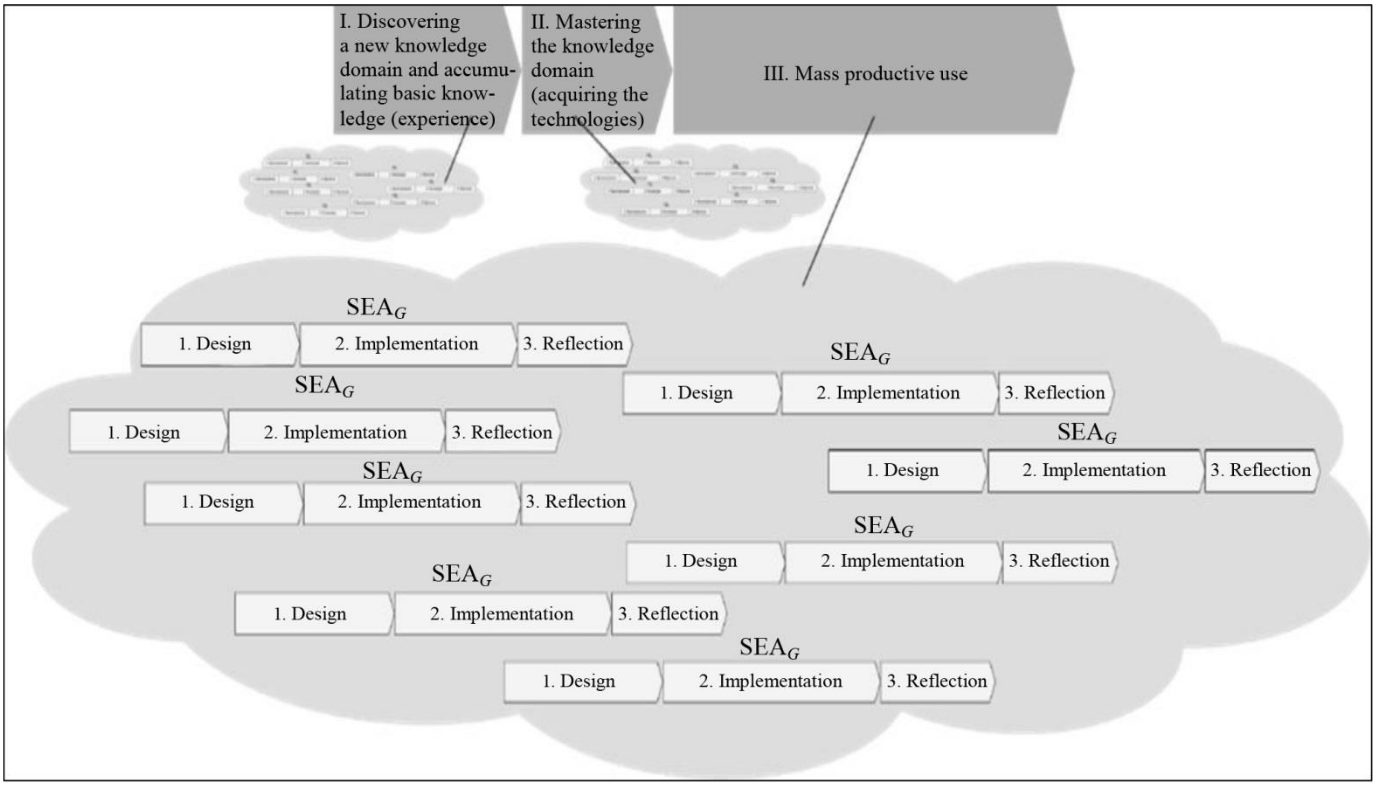

Fig. 1. The life cycle model of a knowledge domain.

Phase III (*mass productive use*). A sign of the transition between phases II and III is the massive (not single) use of known technologies. A set of SEAs with an already known technology (phase II) is being implemented to obtain a productive result (the ultimate goal of this technology). Note that different values of the UFs can be realized: the already known ones (the desired productive result is obtained) or the ones not encountered before (a new experience is formed, and the productive result can be lost). In the case of a new UF value, a return to phase I or II within the same knowledge domain occurs, or a new knowledge domain appears.

New SEAs formed in phases I and II correspond to the hypotheses about the knowledge elements; new SEAs formed in phase III, to the needs for the productive CA to obtain a useful result.

3. CREATIVE ASPECTS IN THE LIFE CYCLE OF COMPLEX ACTIVITY

Which elements (procedural, internal, or external) are "responsible" for creative activity? In other words, where is creativity concentrated? To answer these questions, we will analyze *the CA's life cycle (LC)*; see Table 10 of the monograph [2] and Table 1 below.

Stage II of the CA's life cycle (Table 1) is *goal-setting* (forming the structure of goals) and checking whether technologies exist for all subgoals. If not, the goal is the development of an appropriate technology. Note that sometimes goals—an anticipated image of a future result—can be formulated by the subject unconsciously, leading to "unexpected" results. (This is often the case for creativity; from the subject's viewpoint, goal-setting is "absent.")

According to Table 1, ***creativity is concentrated in the goal-setting stage only***! Really, technology formation and implementation (stages III, IV, and the subsequent ones in Table 1) are always (!) performed by known means and methods: we cannot assure the result without reliable means and methods (technology). In this stage, the subject sets a goal not achieved before (moreover, it is unknown whether the goal can be achieved). The corresponding CA has no technology, and the subject decomposes the goal into subgoals (this is a heuristic, creative activity) and checks the presence of a known technology for each subgoal. In the absence of an appropriate technology, he decomposes the subgoal further. This procedure continues until known technologies are found for all subgoals of the goal. Implementing a set of known technologies to achieve the obtained structure of (sub)goals is a regular CA. The subsequent phase (reflection, checking the compliance between the result and the original goal) is a regular CA as well.

Table 1

Phases, stages and steps of the life cycle of a complex activity element (A-SEA) and their content

Phase	Stage	no.	Step	Content
Design	I. Fixing demand and understanding needs	1	Fixing demand and understanding needs	A superior U-SEA or environment forms the demand for the results of CA element. The subject (actor) fixes the demand, understands the needs and decides to perform activity.
	II. Setting goals, structuring goals and tasks	2	Creating logical model	The need is structured and checked whether it is known or not (in the former case, the activity is regular). If CA is regular, this step comes to extracting information about the logical model from an information store. Otherwise, the structure of goals is formed. The goals are formulated in terms of the expected characteristics of the results of CA elements; see Section 6.1 for a detailed discussion of the result of CA. Consistency is checked/the structure of goals is modified. With each goal of A-SEA the role of the subject and technology is associated (this has been done for the result earlier); in other words, the characteristics of the subjects and technologies are specified. The result of this step is a logical model, i.e., the structure of A-SEA in the form of a set of subordinate SEAs (L-SEAs) and elementary operations (L-Op).
	III. Selecting and developing technology	3	Checking the readiness of technology and the sufficiency of resources	The presence of already known components of the A-SEA's technology is checked: the causal model of A-SEA, the technologies of all L-SEAs and the technologies of all L-Ops. The logical consistency of A-SEA and resource pools is checked: the availability and sufficiency of resources for assigning the subjects of U-SEAs and supporting the technologies of L-Ops, taking into account the use of these resources in parallel when implementing other SEAs. The result of this step is confirmation of the readiness of the technology, confirmation of the availability of necessary resources and transition to step 7, or the implementation of steps 4, 5 or 6, respectively.
		4	Creating cause-effect model	The causal relationships between the goals/results of subordinate elements (L-SEAs and L-Op) are determined and described. Possible events of uncertainty and the response rules for them are described (SEAs to be performed, or escalation to a higher level). The result of this step is the cause-effect model of A-SEA.
		5	Creating technology of lower-level elements	For an elementary operation, due to its specificity and absence of internal structure, the process of designing and describing technology elements is specific and therefore has no general description. For all subordinate L-SEAs without ready-made technologies, steps 1–6 of their life cycles are implemented recursively. The result of this step is the technologies of subordinate elementary operations (L-Ops) and the technologies of subordinate L-SEAs.
		6	Forming/modernizing resources	In the absence of necessary resources, goals responsible for their generation are set; SEAs ensuring the creation or modernization of resource pools are implemented. The result of this step is resource pools required.

Table 1 (continued)

Phase	Stage	no.	Step	Content
Design	III. Selecting and develop-ing technology	7	Calendar-network scheduling and resource planning	A calendar-network schedule is being formed. The consistency of key deadlines of needs is checked. The temporal consistency of the calendar-network schedule and resource pool is checked, taking into account the use of resources by other elements of CA. In case of inconsistency, a return to steps 2-4 is carried out or the impossibility to meet the deadlines is escalated to the subject of a upper SEA. The result of this step is a calendar-network schedule for the use of resources.
		8	Performing optimization	The dynamics of resources use is optimized, taking into account the possibility of using these resources for other CAs implemented in parallel. The result of this step is an optimal calendar-network schedule for the use of resources.
		9	Assigning actors and defining responsibilities	The responsibility matrix is fixed, which describes a correspondence between the subjects of SEAs and personnel. In fact, the assignment of subjects means the formation of demand for the results of lower SEAs and, hence, the recursive implementation of the life cycle of L-SEAs: all steps of the Design phase are carried out. The result of this step is the responsibility matrix, which together with the structure of A-SEA determines its organizational structure.
		10	Allocating resources	In accordance with the technologies of elementary operations, the resources required for the implementation of technologies are request and allocated. The result of this step is the resource allocation matrix of elementary operations.
Implementation	IV. Performing actions and obtaining results	11	Performing actions and obtaining results	In accordance with the causal model, the preconditions for the start of actions of elementary operations (L-Ops) and L-SEAs are repeatedly and constantly checked and they are launched. The elementary operations (L-Ops) are performed. The execution of subordinate L-SEAs is started. The result of this stage is the execution of actions by A-SEA and also the result of its activity.
Reflection	V. Assessing results and reflecting	12	Assessing results and reflecting	Comparison of the characteristics of the result with the required ones. Comparison of the volumes of resources with the given ones. Design of the requirements to the corrections of goals, technology, etc.

The general scheme of the life cycles of CA and a knowledge domain describes well research CA, practical CA (including engineering CA), and artistic CA.

Research CA. Nowadays, well-established paradigms and research approaches (methods of study and presentation of results) have already been developed in many branches of knowledge. Alternative approaches are perceived with a priori suspicion: researchers tend to follow the well-known (regular) technology involving SEAs for hypotheses testing, which are also regular! The exception is the periods of scientific revolutions. Some examples are provided in Table 2.

Table 2

The LC of knowledge domains: some examples of phases

LC phase	UF values	Electricity examples	Atomic energy examples
Phase I. Discovering a new knowledge domain and accumulating basic experience	Are generated or chosen by the subject and are realized in parallel	– the experiments of the ancients with amber and wool, observation of electric eels, – Gilbert's work and apparatus, – Franklin's experiments with a kite, – Galvani's and Volt's experiments and devices, – Faraday's generator, – others	– ideas and hypotheses of the ancients about the structure of matter, – Dalton's theory, Mendeleev's discovery, – X-rays, – the Bohr and Rutherford atom models, – Becquerel's observation, the research works of Curie, Flerov, and Petrzhak, – others
Phase II. Mastering the knowledge domain. The goal is to develop and master technologies	Are realized, whereas the subject fixes the new UF values	– the use of electricity for lighting, industrial drives, transport, etc., – industrial devices designed by Tesla, Edison, Dolivo–Dobrovolsky, etc.	– the Manhattan Project (the first reactor and bomb, enrichment technologies), – nuclear weapons, – the first nuclear power plants
Phase III. Mass productive use. The goal is to use the developed technologies for obtaining new results	Are realized	Batch production and mass use	

Artistic CA [4] is "arranged" in a similar way. Some examples of projects implemented by many people are:

– filming,

– setting up a theatrical performance,

– creating a monument.

Forming an idea (plot, or meaning) as *a holistic image* of a book or picture (or their elements if the subject divides the object of creativity into elements) is an elementary but creative activity. After that, the subject expresses the idea until liking the result, i.e., hypothesis testing (or rethinking of the idea) takes place as well. At the same time, the technology of applying paint, processing marble, or typing text (formulas) is regular. Such technology can also be the object of the first phase; see item C below. However, once developed, it becomes regular.

Thus, for artistic activity, we have the following:

– The idea of a work of art is a hypothesis (hypotheses) formed.

– Attempts to express the idea and checking whether the result fits the desires are tests of the hypotheses.

– Artistic technique (gouache, oil, clay, bronze, or brushstroke), which reflects the idea up to the author's individuality, is regular and "imported" from the industry.

Stages I and II (and stage V) of CA (see Table 1) are always implemented for (and in terms of) an information model of the subject matter. The other stages, III and IV, may require a CA associated with a physical object.

The goals or hypotheses of CA (stage II in Table 1) can describe any subsets of elements (their interconnections) in the body of knowledge, regardless of the representation model. In particular, hypotheses can describe new technology components.

The generalized scheme of a single creative SEA and the life cycle of a knowledge domain coincide with *the scheme of research activity*. It includes the following:

A. understanding of existing knowledge domains;

B. forming goals (in the case of creative CA, this is the hypothesis about achievable goals since at the time of goal-setting, the technology is unknown, and the possibility of achieving the goal is also unknown; in the case of research CA, the goal is to acquire new knowledge, i.e., directly test hypotheses about the laws of the researcher's environment;

C. testing the hypotheses;

D. generalizing and forming new laws (technologies);

E. passing to item A.

Items A and B correspond to goal-setting (forming the structure of goals) and checking whether technologies exist for all subgoals. We emphasize again: creativity is concentrated right here.

Hypothesis testing (item C) is always (!) performed using a known technology: we cannot assure the result without a reliable technology (means, methods, and techniques to obtain the result). If the testing technology is unknown, the hypothesis is decomposed, and the causal structure of the lower-level hypothesis testing is determined, followed by the aggregation of the intermediate results. Decomposition, formation of a causal structure, and aggregation are well-known operations: proven components of the system-wide technology for achieving complex goals (testing complex hypotheses). Decomposition is performed until a known technology is found for all goals (hypotheses). It yields a fractal set of SEAs. Next, the actions of the SEAs are executed according to the causal structures. After that, the original hypothesis is either confirmed or rejected.

Hypotheses (item B) can describe any subsets of elements (and their interconnections) in the body of knowledge, regardless of the representation model. As noted above, hypotheses can describe new technology components.

Goals are always formed to satisfy the needs of some interested parties and (or) solve their problems (equivalent). In a particular case, such an interested party is the subject itself. (In research and artistic activities, the researcher or artist himself.)

Well, the execution of complex activities is always regular: all stages after goal-setting and structuring of goals (see Table 1) are implemented using a technology known at the beginning of the action. When the goal is structured, and the structure of the SEAs is created with a verified and known technology leading to the required result, the implementation of CA becomes regular.

4. A QUALITATIVE MODEL OF KNOWLEDGE (EXPERIENCE) EVOLUTION

In any AS, agents exist and operate in the following way:

a) An active system as a complex entity “permanently” implements a set of regular SEAs.

b) Events of true uncertainty occur.

c) The agents of the AS perform reflection, comprehending the factual occurrence of these events.

d) The structure of goals is (re)formed, yielding the structure of SEAs and the structure of complex subjects.

e) For a new structure of goals, a new technology is developed or reduced by decomposition to known ones.

f) The implementation of a regular, albeit different, CA continues, and a return to item a) takes place.

The sequence a)–f) is implemented for all life cycle stages of knowledge domains; see Fig. 2.

The events of true uncertainty (b) and the events of re-forming the structures of goals (d) occur asynchronously. They are “connected” through the process of *reflection*, which has uncertain duration and result. Reforming the goals is a manifestation of the subject’s true uncertainty.

Thus, the subject’s uncertainty has two forms:

– deciding to carry out the activity (or refuse),

– forming the structure of goals.

Generally speaking, the life cycle of knowledge domains includes all three phases. In some cases, however, the development of a knowledge domain cannot lead (yet) to its productive use, and the life cycle is interrupted at the first or second phase. (The corresponding graphic images are shown at the top of Fig. 2.)

Reflection is an assessment of the existing experience and the environment, including the events of true uncertainty. On the one hand, reflection precedes goal-setting and is its source: this is how hypotheses are generated. On the other hand, reflection fixes the experience: this is how the hypotheses are confirmed or rejected.

The “general model” (see the Introduction and the book [16]) describes the evolution of knowledge (experience) using the dynamics of the sets of admissible SEAs and their dependence on the history. However, as noted above, the “general model” relations used directly yield no constructive results.

Therefore, let us concretize the “general model of ASs” [16] to investigate the development of knowledge (experience) analytically as the process of discovering new knowledge domains and accumulating “basic knowledge.” For this purpose, we will:

i. abstract from the multiplicity of agents;

ii. discard the set functions describing the SEAs in favor of another representation of the evolution process.

Consider the implementation features of the life cycle of experience (knowledge) with goals i and ii; see Table 3. For each agent, the set of admissible actions consists of SEAs attributed to one of the characteristic subsets for different phases of the life cycle of knowledge domain:

- Phase I, SEAs for testing hypotheses available at the current level of experience;
- Phase II, SEAs for acquiring and mastering technologies;
- Phase III, SEAs for productive use of mastered technologies.

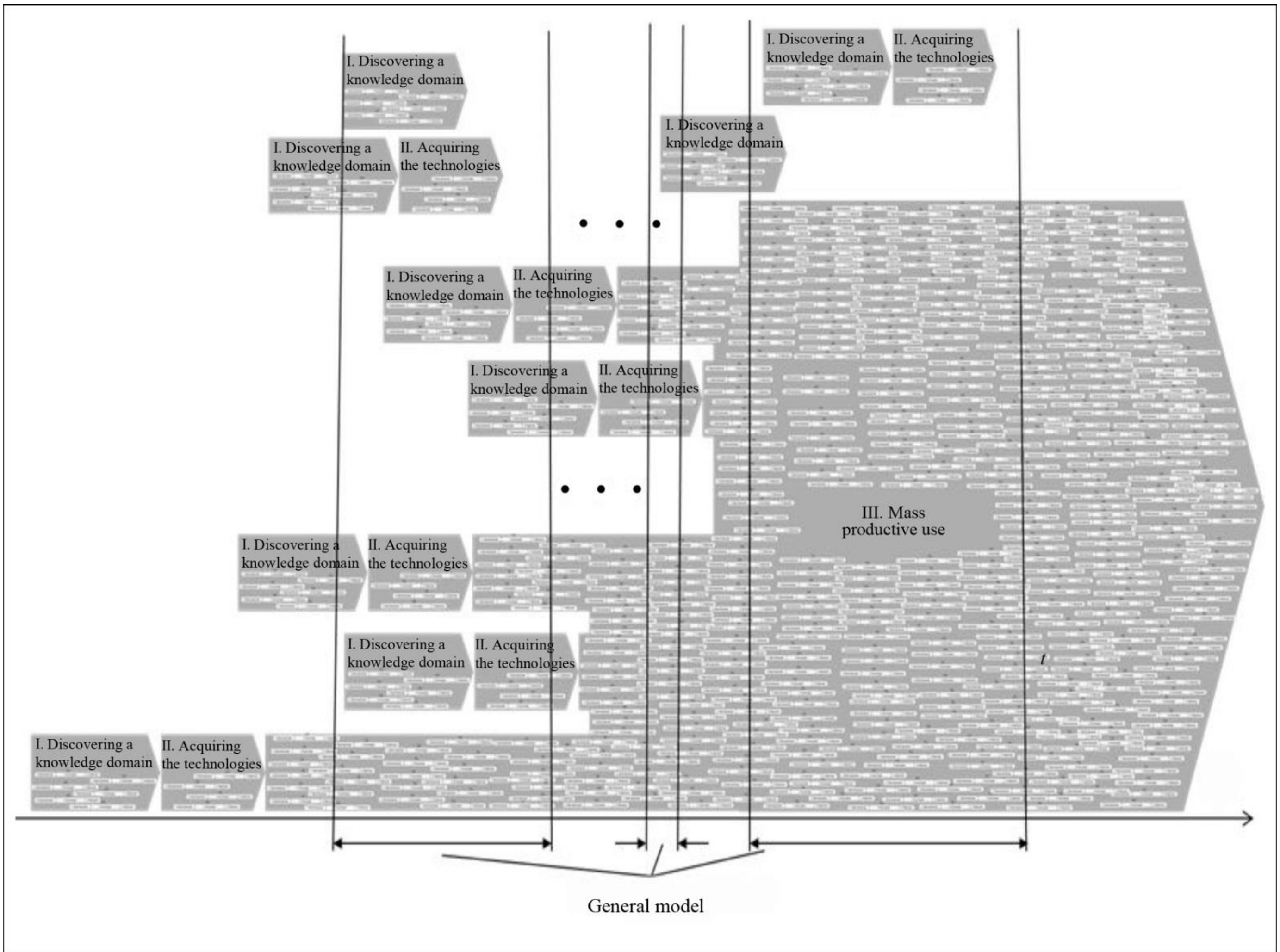

Fig. 2. The general model of knowledge (experience) evolution in an active system.

When implementing the SEAs of subset I, the agent chooses parameter values for the technology and environment, testing the hypothesis under precisely this combination of the values. True uncertainty manifests itself through the CA result, which is a priori unknown to the agent. If the environment's true uncertainty manifests itself so that the UFs take values differing from the required ones, then the CA result characterizes the test of another hypothesis not coinciding with the original one. Upon completion of the hypothesis testing, the sets of UF values and available technologies can be transformed; see Table 3 and Figs. 3 and 4.

When implementing the SEAs of subsets II and III, the agents choose the number of the CA element being executed (the technology parameters). Note that the environment's parameters (the number of the UF state) are implemented independently of the agent and are a priori uncertain for him. In this case, the CA result depends on the parameters values of the technology and the environment.

5. A STRUCTURAL MODEL OF A KNOWLEDGE DOMAIN

Consider a connected circuit-free digraph, i.e., a *network* $G = (N, E)$ with proper numbering. (No edges connect a greater-number vertex to a smaller-number one.) The network vertices correspond to knowledge domains (the sets of hypotheses and assertions), and the edge set $E \subseteq N \times N$ reflects the logical interconnections of vertices; see Fig. 4.

We denote by $N_i = \{j \in N \mid (j; i) \in E\}$ the set of immediate *predecessors* of vertex i in the network G, $i \in N$. Let the network G have a set $N_0 \subseteq N$ of *inputs* (vertices without predecessors, which reflect axioms and (or) facts of recognized common knowledge).

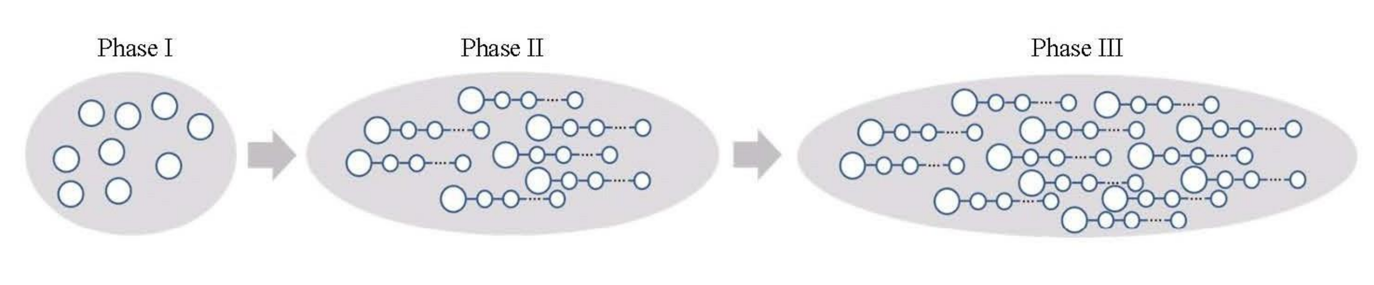

Fig. 3. The life cycle of a knowledge domain.

Table 3

The phases of creative CA

Agent's choice	UF value	Outcome	Consequence
Hypothesis testing, phase I	Coincides with the required one	The hypothesis is tested	The set of admissible technologies is transformed. Possibly, the set of UF values is transformed
	Differs from the required one	Another hypothesis is tested	
Mastering the technology, phase II	Known	The hypothesis is tested	The level of mastering remains the same
	Unknown		The level of mastering increases
Using the technology, phase III	Known	The productive SEA is executed	The expected useful result is obtained
	Unknown		The level of mastering increases, but the expected useful result may be not obtained

Assume that each vertex of the network G has a *precondition*, i.e., a Boolean predicate $\pi_i(\cdot)$ defined on the set of $|N_i| + 1$ *inputs* of two types: the initial facts $z_{N_i} = \{z_j, j \in N_i\}$ and *external conditions* $\omega_i(\cdot) \in \Omega_i$. This predicate calculates a binary *output* (new fact), i.e., a logical variable $z_i = \pi_i(z_{N_i}, \Omega_i)$, which is determinate if the output has the same value under any admissible external conditions, and is uncertain otherwise.

Consequently, a hypothesis with known initial facts is tested by finding the output value for some value(s) of the external conditions (phase I of creative CA). In phase II of creative CA, the invariability of the output value is checked for different (all admissible) values of the external conditions (UFs).

Thus, vertex i of the graph G is given by the tuple (N_i, Ω_i, $\pi_i(\cdot)$), which includes the initial facts, external conditions, and a logical predicate.

We denote by G_t a subgraph of the graph G that is reliably known to the researchers at a time instant t. (No matter how many subjects in parallel test hypotheses, exchanging their results.) For example, the graph G_t in Fig. 4 is shaded.

Within the structural model of a knowledge domain, a *hypothesis* assumes that some assertion or a combination of some assertions is true. A hypothesis is a subgraph or vertex in which the incoming arcs of all vertices are either contained in it or originate from the graph G_t.

Confirming or *rejecting a hypothesis* is testing the definiteness (truth) of a corresponding assertion under all external conditions figuring in it. In a special case, the predicate is known, and it is necessary to find the maximum set of external conditions under which its value is definite.

The hypothesis testing model was considered in subsection 5.2 of the book [16]. In particular, the following problems were posed and solved therein: the optimal distribution of the researcher's efforts between the testing of various hypotheses and the optimal scheduling of the hypotheses.

As noted, in phase I of the knowledge domain's life cycle, each knowledge element (hypothesis described by a vertex in Fig. 4) has one of the following states:

– not available for hypothesis testing (the preconditions are not satisfied; see the dotted line);

– available for hypothesis testing, but the hypothesis has not been tested (see the thin line);

– known (the hypothesis has been tested; see the thick line).

The set of known knowledge elements (the vertices indicated in Fig. 4 by thick lines) is *the current amount of knowledge*. The set of hypotheses available for testing (the vertices indicated in Fig. 4 by thin lines) is *the* *current horizon of cognition*. The current amount of knowledge and horizon of cognition form the subgraph G_t of the graph G known to the researcher at the current time instant. Each vertex indicated by a thin line represents one hypothesis or a set of independently tested hypotheses (sequentially or in parallel).

There are two types of agent's actions at each time instant: *algorithmic* and *creative*. The former actions consist in fully automatic generation and conceptual analysis of all logically possible consequences from the existing body of knowledge G_t. The result is a graph $\hat{G}_t$, conditionally called a "logical closure" of the graph G_t. The latter actions are the advancement and confirmation or rejection of hypotheses, i.e., new subgraphs G_t^h of the graph $G \setminus \hat{G}_t$. We denote by G_t^{h+} the set of confirmed hypotheses. Then $G_{t+1} = \hat{G}_t \cup G_t^{h+}$. The advancement (generation) of hypotheses is an essentially creative and non-formalized stage. Therefore, in modeling, it is advisable to describe the occurrence of hypotheses and the duration of their testing in stochastic terms.

Thus, new hypotheses can be made automatically (algorithmically) or creatively in phase I and algorithmically or creatively in response to the events of true uncertainty in phases II and III of creative CA (see arrows 6 and 7, respectively, in Fig. 4).

The hypotheses testing process (confirming or rejecting hypotheses) can be formalized using the models below.

- In phase I:

– The transition to a new horizon of cognition occurs during scientific revolutions [19]. How and why does this happen? We will not attempt to answer, simply supposing that the graph G is given. This as sumption is the essential one for the models of creative CA under consideration.

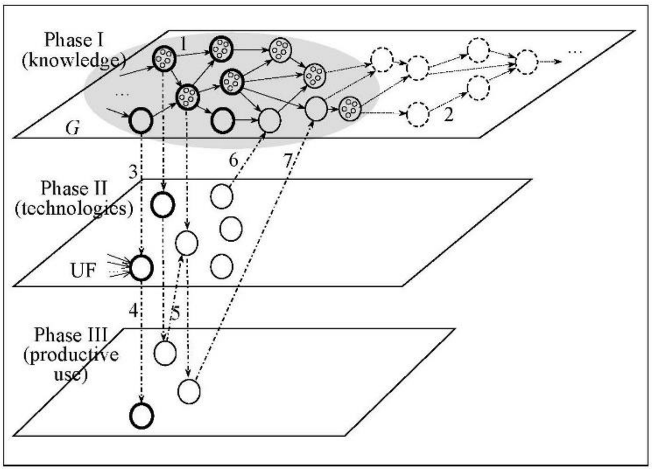

Fig. 4. The phases of creative activity (the LC of a knowledge domain).

– Hypothesis testing is described by the model given in subsection 5.2 of the book [16].

– The arrows of types 1 and 2 correspond to specifying or increasing (decreasing) the dimension (analysis and synthesis, decomposition, and generalization).

- In phase II, technology development is described by "experience models" [21, 22].
- In phase III, practical activity is described by the general schemes of CA given in the monograph [2].

The chain of arrows 3 and 4 describes the "fundamental research => technology development => production" life cycle.

Arrows 5–7 show that the problems arising in phase II or III (situations of true uncertainty) may require a return to the previous phase(s) with the advancement and confirmation of new hypotheses and (or) the development of appropriate technologies.

CONCLUSIONS

This paper has identified three phases of creative activity (the life cycle of a knowledge domain):

– phase I: discovering a new knowledge domain and accumulating basic knowledge (generating and testing hypotheses);

– phase II: developing mastering the knowledge domain;

– phase III: mass productive use.

As shown, creativity is concentrated in the stage of goal-setting only (in the case of research or artistic activity, in the generation of hypotheses). New models can be developed, and well-known models can be used to describe and study each phase of creative activity, including those introduced by the authors earlier:

– in the first phase, optimal distribution models for the researcher's efforts between the tested hypotheses and choice models for an optimal sequence of tested hypotheses [16];

– in the second phase, mathematical models of experience [21, 22];

– in the third phase, structural and algorithmic models [2] and optimization models [23].

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