Competency-based Education of Engineers-Innovators

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Abstract
The article considers general principles for the development of competency building approach in vocational education. The authors state the importance of competency building approach in engineering education at the present stage of market relations proceeding from the position of American sociologist and economist Schumpeter, according to whom innovations in mass commodity production involve constant updating of models and the range of products. From this position, it follows that dynamic innovation in production is only possible with two factors, operating simultaneously: intertwining of science and production and involvement of experts, able to carry out the transfer of scientific production into consumable products. This type of production requires analytical engineers with both formal (mathematical) and analytical (dialectical) thinking, who are able to bring together the accurate manufacturing technology and heuristics. The authors call this new type of engineers “engineer-innovators”. Sociologists agree that the high-quality training of engineers-innovators should be carried out on the basis of competency building approach, but have not been able yet to create the functional structure of the competency-based training for engineers-innovators. The results of the expert survey enabled the authors to perform a statistical factor analysis and build the optimal structure (content) of competency-based training for engineers-innovators in institutions of higher education and courses of advanced studies. Structural indicators identified by the authors through factor analysis can be used when creating textbooks for competency-based training at the engineering departments of universities and centers for professional development of specialists working in the field of innovative production.

Keywords: Competency-Based Education, Engineers-Innovators, Management of Innovative Production, Transfer of Scientific Production

1. Introduction
Economists traditionally call the increasing role of science in the production the “innovation”. This concept, introduced into scientific use by American sociologist and economist Joseph Schumpeter¹ in the early 20th century, reflects the global trend, which is an objective prerequisite for intensive rotation of the range of products as an indicator of permanent expansion of exchange relations among people. Innovation implies not only economic, but also staff preconditions which come as a result of training specialists with the analytical way of thinking. These professionals are not only able to solve production tasks autonomously, but can also make their own decisions, evaluating production risks. These people are experts in production, able to go beyond the limited range of professional skills and knowledge, constantly increasing their expertise.

In the last two decades, not only technical and technological innovations, but also product ones, have been a matter of paramount importance for the Russian economy. To accentuate the significance of the links between science and industry, the Russian authorities take many high legislative actions. However, there have been a number of problems regarding the practical implementation of the government initiatives, most of them due to delayed structural reforms in the economy, non-market distribution relations that remained from the past social policies. Besides, social and economic transformations that took place in the 1990s had a negative and destructive impact on the Russian economy. According to analysts, at present day this is primarily manifested in the following:

- Low innovation activity of a considerable part of enterprises of the Russian economy producing sector;

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• Imbalanced development and the lack of economic interaction between the elements of the innovative management and, as a result, inefficient mechanisms of transfer of scientific knowledge and new technologies into domestic and world markets;
• Low capitalization of scientific production that leads to the lack of demand for scientific organizations, insufficient investment in innovative enterprises;
• Imperfection of the economic and legal mechanisms of intellectual property transfer into production.

These problems lead to the consequences announced in the Strategy for the Development of Science and Innovation in the Russian Federation:

Russia has one of the world’s highest potentials in certain areas of fundamental science, but there are no conditions for its extensive application. This creates a high risk of degradation of national fundamental science, Russia’s losing its reputation of a scientifically developed state.

There is a gap in the innovations cycle and the transition from fundamental research through applied research to commercial technologies; low level of applied research and imperfection of innovation management in the field of advanced technologies lead to the situation when knowledge is exported overseas along with a little export of technology.

Lagging technologies dominate in the business sector, manufacturing companies’ ability to welcome innovations is still poor, a large part of the companies does not have a systematic approach to introduction of innovations. In the context of growing innovation activities, this leads to expenditures for new equipment that constitute the main part in the cost of technological innovation with low demand for scientific research and development.

In general, business sector resources are mainly focused on the purchase of imported equipment, whereas the knowledge proposed by research organizations is mostly demanded abroad. As a result, capitalization of innovative intellectual resources occurs mainly outside Russia, and large sums from businesses are excluded from the reproduction in the Russian sector of research and development.

To remedy the situation, in 2010 the Government of the Russian Federation approved Decrees No 218, 219, 220, which state the paramount importance of partnerships among industrial companies, universities and research organizations aimed at boosting innovative production, transfer of research results into innovative products, training specialists of two types: analytical engineers and innovative production managers.

Shortage of high qualified engineers-innovators is the key challenge that Russian manufacturing companies working on technological development face nowadays. It is for this reason that personnel policy in the field of science was included in the national policy of modernization of the socioeconomic life of the Russian Federation. The lack of professionals in the economies of the developed countries, particularly in intellectual activity, is aggravated by unfavorable demographic situation, the cause of which is not only a naturally declining birth rate, but also the continuing negative impact of the “demographic pit”. The unfavorable demographic situation undermines the uniform rotation of specialists not only at manufacturing companies, but also in scientific research organizations and universities. For instance, in the period from 1995 to 2012, the number of researchers in Russia decreased by 1.4 times - from 518,700 to 372,600 people. Today, the share of researchers under the age of 30 is on the average of 20%. The reason for this is not actually the migration of scientists, but a weak inflow of young specialists into the science due to low wages and lack of adequate social protection. What’s more, the average age of researchers is nowadays approaching 50 (to be more exact, it is 48), and is 63 for doctors, 52 – for candidates of science.

Along with the overall reduction in the number of researchers in institutions of various types, we can observe some mixed trends. A significant decline in the number of researchers can be registered in research organizations (for the specified period from 9,500 to 3000) and design bureaus (from 2,200 to 1,800), and their increasing number in university research institutions (from 40,000 to 53,600).

Parallel to the objective economic problems that in the 1990s led to the collapse of several schools of thought, aging and emigration of some Russian scientists, shortage of professionals with good organizing and analytical thinking skills, the situation can also be explained by ineffective vocational training at universities. What’s more, career guidance that students get while studying at university does not provide them with sufficient motivation for working in research.

The first way of familiarizing students with a career in science is their involvement in scientific work at the university. As our study showed, the proportion of those interested in research among students of Russian universities is an aver-
Postgraduate studies play an important role in staff training in the fields of science and innovative production. The authors’ analysis of the teaching staff postgraduate training allows defining the following problems:

- In Russia only an average of 26% of post-graduate and doctoral students submit the results of their research for the defense on time;
- The proportion of post-graduate students, dropping their studies without submitting the thesis is on average 38% of the enrollment.

As a result, there is a shortage of staff, which led to a decrease in the scientific institutions efficiency; however, there are other aspects to consider. Research conducted by the Center for Social Forecasting and Marketing in 2011–2014 in the Russian Federation, defined the following main reasons for low efficiency of scientific institutions (according to natural hierarchy): delayed economic modernization ⇒ insufficient financing of research ⇒ inadequate science management ⇒ shortage of highly qualified researchers ⇒ science management inability to organize the transfer of scientific products into innovative production.

At present moment, training professionals for innovative production has been made difficult, the reason being insufficient development of competency-based education. Authorities, developing the educational policy of the state, recognize the importance of competency-based education as a new stage in training professionals of innovative production; however, functional structure of this education which would guarantee its effectiveness has not been studied properly. In this article, the authors present the model of the functional structure of competency-based education, developed by them, that was formulated on the basis of the experts’ survey generalization with the application of a statistical method of factor analysis.

2. Literature Review

In the context of growing material consumption, American sociologist and economist of Austrian origin Joseph Schumpeter drew a fundamental conclusion that the further course of development of the market civilization would be based on the close interaction of consumption and production, as two opposite sides of the integral whole - human activities. The special feature of this process is it is not only production that is stimulated by consumption, but production forms consumption through the phenomenon which has become domineering in the bourgeois society – the industry of the social prestige, the use of psychological methods of advertising. The concept of innovative production drew the attention of scientists in the situation of the intensive world market development, especially in the 1960s. Innovative production issues became relevant to Russia from economic perspective as early as in the 1980–1990, but in terms of science - in the 2000s. At the same time, researchers recognized the importance of training professionals with a new way of thinking for working in the field of economy – analytical thinking, which necessitates the development of competency-based education.

Basic qualities of would-be engineers that should be formed through competency-based education have not been thoroughly discussed in recent scientific publications. This can be explained by the relative novelty of the concept and difficulties with identifying the complete structure of the competencies. The architecture of competencies comprises several components, the key of which are cognitive (information base of competencies, including knowledge of certain facts, laws, principles) and operational (ability to select and specify the correct way of actions, their sequence on technological, organizational, design planes). Assessing the results of competency-based training it is also important to take into account (define) personality traits.

In search of the best ways of transition to competency-based education, researchers have investigated the process of modernization of vocational education; changes in the logistics of university instruction through application of competency building approach; (requirements for vocational training from representatives of the innovative production. Along with
exploring the potential of competency-based education in universities, the researchers also studied how it could be applied in organizations providing courses of advanced studies for manufacturing companies personnel\textsuperscript{14}. Apart from the significance of these studies, they did not pay enough attention to the development of the system of indicators for competency-based education at engineering departments. Natural sciences form the core of instruction at these departments and require students to possess developed formal logic. This was enough for extensive, mainly assembly line production that prevailed until the 1960s. However, in the context of innovative production, when intensive rotation of the products range is required due to rapid changes in the public needs, the economy should resort to the help of science, and it needs professionals who possess, in addition to formal-logical, the analytical way of thinking. Training of such professionals, as the expert surveys carried out by the authors confirm, should be based on the principles of competency building education, which has its own specific structure. The authors designed the system of competency indicators in engineering education at a bachelor and master levels on the basis of special studies conducted in 2011-2015. The results of this research are presented in a number of scientific publications\textsuperscript{7, 15, 16}.

3. Methodology

The objective of the research is the development of the system of indicators for competency-based education at the engineering departments of universities and institutions of vocational development for innovative production professionals.

The methodology of the study involves building an electronic database of expert assessment of the maximum number of possible elements of competency-based education and aggregating raw information from the experts in complex indicators, presenting the optimal structure of competency-based education at engineering departments.

Expert assessments were collected with a questionnaire in the form of a personal interview with 200 deans of engineering departments, 600 heads of chair of core departments, 2,000 students of engineering departments at Russia’s technical universities, as well as 50 directors of professional development centers for innovation production. To ensure the selection of most stable and valid indicators that form the structure of competency-based training of engineers, the study was conducted several times at the same universities, respectively, in 2011, 2013 and 2015. In each of the three repeated studies the system of indicators was aggregated using the same method of principal factors. Only indicators with factor value exceeding 0.6 in all three studies were included in the structure of the competency-based education of engineers.

4. Results

The findings suggest that in favorable demographic conditions one of the effective ways of solving the problem of selection and training of intellectual labor professionals is the modernization of the system of vocational training in such a way which along with traditional instruction aims at developing would-be professionals’ skills of analytical thinking, scientific work. The following requires profound development of technical facilities for research in universities, which is provided by the Decree of the Government of the Russian Federation No. 219, and its functional structure is displayed in Figure 1.

In accordance with the Decree, measures to develop the technical and technological base of university research are aimed at creation of innovative environment, facilitating the cooperation between universities and industry, supporting small innovative enterprises of universities established under Paragraph 8 of Article 27 of the Federal Law “On Higher and Postgraduate Professional Education”.

![Diagram of the functional structure of state support in the development of the research facilities at universities.](image-url)
Formulated in the state policy, the principles of training 15,000 highly qualified engineers are aimed at improving energy efficiency and resource conservation, development of nuclear, space, medical and strategic information technologies, which also proves the need to change the traditional methods of vocational training and transition to lifelong learning\textsuperscript{17}. The emphasis is laid on improving the quality of vocational training of professionals in engineering and technical industries that are of strategic importance for the economic development of Russia.

Manufacturing companies’ demand for educational technologies is mainly determined by three factors: the required qualifications of employees; syllabus of vocation-related subjects; training duration. As far as the latter is concerned, the approach to it is quite clear - it is based on three levels of education: a bachelor degree, a specialist degree that is still used in Russian universities, and a master degree. The transition to competency-based education, whose system of indicators was specified by the authors through factor analysis of the expert assessments, remains relevant for all these levels. The analysis of the expert survey results showed that competency building approach to education of engineers for innovative production (engineers-innovators) is different\textsuperscript{16}.

Training of today’s engineers requires a serious correction of the goals and objectives of education and syllabus. This is especially true for Russia, where the transition to a two-level system of training engineers happened with a delay, the result being difficulties with separating into two parts the five-year engineer curriculum which had been evolving successfully over many decades in the conditions of extensive production. The findings suggest that prevailing mode of engineers training in Russian universities is still a specialist’s degree, which means that training of engineers is available in two qualifications: professional and technical engineers. According to the experts’ opinion, in future universities are planning to focus on training engineers working in the field of technology transfer (Table 1.); training of engineers-polymaths is less demanded in the present and in the future.

At present day Russian manufacturing companies often resort to engineers-polymaths, professional and technical engineers. There is a severe shortage of professional and technology transfer engineers, the latter expected to be in the highest demand in future\textsuperscript{15}.

The quality of engineering education is determined on the basis of the criteria related to competencies, largely due to the fact that the university provides professional training and building competencies of its graduates, but not professionalism, formed in the course of a long working life. Another important reason for choosing the principle of competency is that this concept allows for structuring, followed by quantitative analysis.

At present day the Ministry of Education and Science is developing educational standards of new generation, mainly within the framework of competency-building approach. Leading Russian universities have got the right to create a new training program in engineering for bachelor and master degrees independently. Experts believe that the training of engineers at bachelor and master degrees should definitely include the following competencies:

- Regarding functional and organizational competencies at the level of a bachelor degree, engineers should
be able and ready to use various skills of working with production software, to be able to apply their professional knowledge in practice and shoulder responsibility for the quality of their work. At the level of a master degree, a would-be engineer should be able and ready to analyze and synthesize the data, to organize and plan his activities, use his information management skills; be prepared to solve problems and take decisions, be able to generate new ideas and, like a bachelor, be responsible for the quality of his work;

- Regarding social and personal competencies, at the level of a bachelor degree, would-be engineers should be capable of constructive criticism and self-criticism, be prepared to work in a team, have good communication skills. At the level of a master degree, they should be able and ready for criticism and self-criticism, team work, have good communication skills, and in addition to these three major social and personal competencies, be success-oriented and self-motivated, be able and ready for life-long training, cooperation with experts from other areas of expertise, working in the multinational environment, rapid adaptation to new work situations, stick to ethical values and be able to work independently;

- Regarding professional competencies, at the level of a bachelor degree, would-be engineers should be able to use theoretical and general professional basic knowledge. An engineer with a master's degree should also possess these two competencies. In addition to that, he should be able to apply special (advanced) professional knowledge in his work and use his research skills.

By means of factor analysis of empirically aggregated expert survey the authors obtained a complete system of competency-based education for bachelors and masters (Figures 2 and 3). These systems of indicators allow us to formulate the following integral definition of a typical professional engineer who can meet the demands of an enterprise working in innovative production: an engineer-innovator is a professional with high-quality basic training in his field, dedicated to his job, able to apply professional knowledge in innovative production, self-motivated for doing the creative work at a high level, be able to apply the theoretical knowledge to solve practical problems.

Indicators of analytical thinking skills, acquired by engineers in competency-building instruction, are classified into three groups (factors) by means of factor analysis. The first factor includes 4 indicators (Factor values: 0.9–0.7) that go under the common name of “professionalism”; the second factor includes 3 indicators (Factor values: 0.9–0.6) called “initiative”; the third factor includes 3 indicators (Factor values: 0.9–0.7) under the name of “creativity” (Figure 4).

The experts - representatives of the companies that work in innovative production, - have certain general...
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requirements to competencies which should be acquired by young engineers with bachelor or master degrees. These experts’ requirements to engineers holding a master’s degree are high in terms of all competencies. Most experts see the following qualities optional for bachelors: ability to organize staff activities, using the knowledge on quality management, applying research skills, using special (advanced professional) knowledge and readiness to creative risks. Every second expert stated it is optional for engineers with a bachelor degree to have such qualities as ability to organize and plan, analyze and synthesize, and ability to generate new ideas.

Findings of the expert survey indicate that there is low demand for bachelors in industrial companies in all sectors of the economy; it is masters and graduates with a specialist’s degree who are mainly demanded (Table 2).

An efficient form of training for engineers-innovators as specialists with analytical thinking skills is doing courses of advanced studies. Career enhancement training is not only the key element of lifelong learning, but it also represents a powerful potential for economic modernization.

Studies conducted by the authors in 2011-2014 revealed a number of obstacles which hinder the adaptation of Russian engineering training to innovative production.

Firstly, at present moment two thirds of advanced training courses work primarily with three categories of students: enterprises staff; people who need additional training; people willing to do retraining to acquire qualifications for a new type of work. Dominance of the latter category of students at training courses is a natural consequence of changes in the occupational structure of the population in the years of social and economic transformation of Russia (1990-2000s), when the economy saw a decline in high-tech production and a sharp increase in services.

Secondly, public employment services began to play a big role in forming the composition of the audience at advanced vocational training. This occurs due to a phenomenon new to Russia - unemployment, when a certain part of the population does not give up and is ready to learn a new profession to find a job, while the other is content with a small dole, which does not require anything, but regular registration at training courses.

Thirdly, there is a relatively high proportion of civil servants among students of advanced training courses. To a certain extent this is a government order, a common practice of the past.

Educational opportunities of advanced vocational training organizations are actively used by Russian industrial companies, along with universities participating in the state program of scientific partnership. For these companies, advanced vocational training acts as a “filter” that allows “absorbing” engineers, professionals doing non-engineering work (programmers, genetic scientists, economists, testers, managers), capable of active and competent participation in innovative production.

Table 2. Expert assessment of the demand for professionals of different qualifications, able to successfully work in innovative production, %

<table>
<thead>
<tr>
<th>Qualification</th>
<th>Most demanded qualification</th>
<th>There is demand for qualification, but little</th>
<th>The demand for qualification is weak</th>
<th>Demand index of a professional of this qualification**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bachelor</td>
<td>18,8</td>
<td>31,9</td>
<td>46,4</td>
<td>-0,1</td>
</tr>
<tr>
<td>Specialist</td>
<td>81,2</td>
<td>14,5</td>
<td>2,9</td>
<td>+0,9</td>
</tr>
<tr>
<td>Master</td>
<td>52,2</td>
<td>40,6</td>
<td>4,3</td>
<td>+0,7</td>
</tr>
<tr>
<td>Candidate of Sciences</td>
<td>46,4</td>
<td>34,8</td>
<td>13,0</td>
<td>+0,5</td>
</tr>
<tr>
<td>Doctor of Sciences</td>
<td>34,8</td>
<td>27,5</td>
<td>31,9</td>
<td>+0,2</td>
</tr>
</tbody>
</table>

* Adding the sum of the numbers in rows in the first three cells up to 100% is an indicator of the lack of need for employees with this qualification.

** Computed using the formula of statistical average: \( I = \frac{a + 0,5b - c}{a + b + c} \), with component values: \( a = +1 \), \( b = 0,5 \), \( c = -1 \).

Values: “+1” – maximum demand for an employee, “-1” – no demand for an employee.

Figure 4. Indicators of an analytical engineer.
Manufacturing companies lay special emphasis on improving skills of their engineers, being the largest group of their professionals. The composition of engineering staff doing an advanced training course within the affiliate research program of manufacturing companies and universities according to their field is as follows (Figure 5).

Engineers of manufacturing companies cooperating with universities in the state scientific programs, who did an advanced training course within a competency-building approach, consider developed communication skills and ethical values to be the most for their work.

If leaving aside two fully autonomous competencies (ability to generate new ideas and ability to apply research skills), the importance of the remaining 25 competencies, which, according to the surveyed engineers, are to be formed in the educational competency-building programs at advanced training courses may be classified into 4 groups by factor analysis (Figure 6).

5. Discussion

A number of scientists hold to the opinion that vocational education aims to equipping engineering students with two basic skills: knowledge of procedures, standards and measuring means of the quality of production processes performed. Others give a more functional definition, according to which the content of engineering education is the techniques and methods of instruction that can be quickly modified in the context of information society, the emergence of modern electronic means and fast changes in the pace and forms of communication. According to this position, up-to-date educational technology is a complex of three interconnected components:

- Modern teaching methods: active teaching, emphasizing the interaction between students and the teacher, that is, when a student is not a passive ‘object’, but an active participant of the educational process;
- Relevant content of the subject, which is transmitted to students in the form of knowledge and involves not only memorizing information, but mainly formation of competencies allowing engineers to feel confident in the innovative production;
- Modern training equipment, including information and communication infrastructure, multimedia, the use of distance learning techniques.

According to the authors, there is a somewhat different approach to the technology of competency-building education in sociology. Acknowledging the overall significance of didactics and educational methods regarding learning and management of the professional information, sociology considers the education technology from the perspective of the end customer - a university student as a would-be engineer in innovative production. At the present stage, the key idea of Russian vocational training
modernization is the development of such quality criteria, which would allow improving the learning outcomes so that they meet the expectations of employers in innovative production.

Therefore, the most appropriate definition, according to the authors’ opinion, is the one adopted by UNESCO: “Educational technology is a systematic approach to creation, application and designing of the integral process of teaching and learning through the use of technical and human resources and their interaction that aims at the optimization of education”. The functional structure of this definition is represented as follows (Figure 7).

Figure 7 shows the level of education technology which can be used by representatives of manufacturing companies to describe their requirements to engineers’ professional training.

The implementation of education quality improvement programs approved by universities for engineers working in high-tech industries involves the participation of manufacturing companies regarding the improvement of training programs and plans, participation of their employees in teaching, the development of practical training and internships for students, post-graduates and teachers in innovative production, the development of lifelong education for the company staff.

As the experience of developed countries shows, education design that aims at forming a high qualified and creative person can only be based on such technologies which include, along with traditional professional knowledge, a wide range of competencies. This is not about a knowledgeable student, but the one seeking knowledge, not imitating, but a creative engineer – that is about the engineer-innovator.

Such training may be achieved through a competency model, in other words, a complete set of competencies and indicators of an engineer’s activities. Any model of competences, prior to its practical application, should be evaluated by experts for ranking the competencies, matching them with various types of behavior. In the following study, the authors discuss building of a competency model, which is required for successful research and innovation work in the full-cycle: development of scientific products → transfer of scientific products in production → bringing innovative products to the end consumer. To solve this practical problem, the authors used the factor analysis of the experts’ survey and created the classification of features of would-be engineers-innovators enrolled at bachelor and master programs.

6. Conclusion

At present moment there are serious problems in the organization of competency-building training of engineers with analytical thinking. Assessing the impact that the changes in the system of university education in the 2000s had on the development of science and innovation in Russian economy, the experts pointed out the difficulties in transition to a two level education system, adaptation of bachelor and master degrees to traditional engineering courses. This resulted in a number of problems:

- Nowadays there are some inconsistencies in the training of engineers for the whole economy and certain fields and the overall situation of uncertainty; there is a search for and introduction of new organizational forms of education – bachelor and master degrees; manufacturing companies demand a fast transition of engineering departments to the two-level high-quality education, this form of vocational training including the design of bachelor courses through transformation of technical colleges;
There are certain challenges in the work of organizations, providing retraining and advanced vocational courses for engineers of innovative production, these difficulties include delayed awareness of enterprises of the need for lifelong education of their engineers; this problem can be solved through more convincing demonstration by universities the significance of master’s training for enterprises as the main form of advanced training of engineers-innovators;

• Technical and technological development of the enterprises are mainly facilitated by the engineers capable of generating ideas on the development of modern technologies and manufacturing of new products; thus, technical universities should pay special attention to training engineers-polymaths and technology transfer engineers;

• To promote the universities cooperation with manufacturing companies regarding the transfer of scientific products into innovative production, universities created small innovative enterprises, universities management encourages the participation of teachers and students of engineering departments in research and innovative production; however, there is a weak innovation support from municipal authorities, which hinders the state scientific programs of “enterprise – university” cooperation;

• There is a slow growth of private and corporate investment in education, private manufacturing companies, providing hardly any support to engineering education, opt for target corporate training; private and corporate investments in engineering education are minor, also due to the low profitability of enterprises and the lack of available funds; that is why, training of engineers-innovators requires financial support from the state and preserving the sufficient number of state-funded places at engineering departments of universities;

• Integration of small university enterprises in scientific innovative production requires the establishment of zones with modern technologies (industrial parks) in the universities that would provide favorable conditions for the commercial production of small enterprises, actively involving students and post-graduates of engineering departments.

Upgrading of engineer-innovators training requires limiting the range of traditional methods of vocational education and the transition to lifelong education presented in the competency-building model of education. This position corresponds with the educational policy of the state.

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