Fourth-Generation R&D: From Linear Models to Flexible Innovation

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The management of research and development has evolved through four different phases. The first two ones involved linear flows of knowledge. From its beginnings in the mid-nineteenth century to the 1950s, it was based on serendipity and somehow isolated from the other functions of the firm. In the 1950s and 1960s, it adopted the basic routines of project management. In the 1970s and early 1980s, business development groups appeared within the firm, to coordinate different functions and assure a multi-directional flow of information. In the late 1980s and 1990s, technological alliances with users, suppliers and competitors increase the non-linear flows by incorporating information generated outside the firm. J BUSN RES 1999. 45.111–117. *© 1999 Elsevier Science Inc. All rights reserved.*

Research and development (R&D) is one of the preferred means by which companies (and other organizations, including societies) increase their stock of knowledge. R&D is conducted in three main types of units: company laboratories, government research centers, and university laboratories. In-house corporate R&D is a German organizational innovation, developed in the chemical industry in the second half of the nineteenth century and originally intended to create new synthetic dyes for the textile industries (Freeman, 1982). This organizational novelty spread to other industries, including the electrical and the emerging car industry and spread to the United States in the late nineteenth and early twentieth centuries, when General Electric, AT&T, and Du Pont, among a few other corporations, created their first R&D laboratories. The mission of corporate R&D was the development of competitive advantages through new and exclusive products and processes. Corporate R&D is thus, most often, commercially applied R&D.

Similarly, in the nineteenth century, government R&D started in Western Europe and North America. The first public laboratories were created to help industries like agriculture, fisheries, and mining, in which the average size of the firms was usually too small to justify research infrastructures. The goal of the first investments in public R&D was to prevent market failure: left to themselves, at least some private industries tend to underinvest in R&D. Also, technical knowledge is, partially, a public good: it is socially optimal to produce it only once and to diffuse it among producers (for example, new varieties of cereals among thousands of farms). Later, governments started R&D in other areas for "mission" purposes in order to attain social goals, like defense, communications, health, and environmental improvement. University R&D started in the late nineteenth and early twentieth centuries in North America, again using the German university system as a model. The faculties of engineering, medicine, and natural sciences were the first to develop graduate programs and research centers.

In these three types of organizations, R&D passed through several stages (Roussel et al., 1991). The first two may be characterized as two phases of the linear model of R&D. The first phase predominated up to the 1950s and early 1960s. R&D was then an isolated activity conducted in some area of the corporation, and handing over, from time to time, its results to manufacturing. The second stage featured the spread of project management methods in the control of R&D projects, mostly in corporate labs. Corporations developed this management innovation in the 1960s. The linear model remained everywhere present, especially in government and university laboratories, though under more advanced management techniques within the corporation.

Evolution toward a radically different new stage occurred in the early 1970s and early 1980s. Again, corporate labs initiated the new trend: R&D ceased to be the exclusive responsibility of R&D managers and became more and more linked to other areas in the company, like marketing, manufacturing, and finance. Business development groups appeared in the firm, together with concurrent engineering, an organizational innovation breaking the isolation of the R&D departments. R&D included marketing, manufacturing, and financial expertise in order to increase the number of projects

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yielding commercially successful results. At this stage, information feedback loops took place within the corporation. In the mid-eighties, a fourth stage in R&D organization emerged, characterized by cooperative R&D and systematic links between independent research agents: technological alliances between corporate users and producers became widespread. Government laboratories and universities increased enormously their links to industry. Informational loops are now interorganizational. Corporations devised new management methods and evaluation routines to cope with a different environment.

From Linear to Flexible R&D

R&D emerged as an activity characterized by a high degree of uncertainty and serendipity. Within the corporation, scientists and engineers in the research lab studied materials, products, and processes and, sometimes, arrived to produce novelty that companies could introduce into production. This process was linear or sequential within the corporation: R&D tended results to manufacturing, some of which would become products, that were then submitted to the marketing and financial functions. Within the macro-economy, the process was equally sequential. Universities produced fundamental knowledge that was expected to be, through some unspecified channel, adopted and used by government laboratories conducting mostly applied research, the results of which were handed over, again by some transfer process, to companies conducting commercial R&D. Evaluation methods were basically internal to the research unit: these included peer review, output/input ratios (i.e., patent/cost ratios or patents per researcher), and the proportion of projects leading to commercially successful products.

The arrival of project management to R&D in the postwar period (second generation or stage in R&D management) did not destroy this linearity: it only introduced some order, reduced some uncertainty, and increased cost and time controls and accountability into the corporate R&D lab. PERT and GANTT charts made their appearance in R&D management (Bergen, 1990). University and government laboratories were mostly unchanged by the spread of R&D management techniques in the larger corporate research units. Cooperation among business enterprises or between business and public laboratories was not an issue in management (Heyel, 1963).

In the late 1960s and 1970s, third-generation management introduced in-house feedback and the integration of R&D within corporate strategy: the selection and management of projects became, at least partially, a responsibility of the upper management of the corporation and/or interdepartmental business development groups. Companies became capable of conducting R&D in areas where they had some manufacturing and marketing competency or in new and promising areas in which they had strategically decided to build competencies. Knowledge from other areas of the corporation was systematically introduced in the design of the projects to ensure that R&D results would be useful to the corporation. External market knowledge was captured periodically through market research (mainly in mass market products) and/or through informal company-to-company communications (Allen, 1977).

In the late 1980s and 1990s, fourth-generation R&D introduces the knowledge of the users and the suppliers, and even competitors and other companies with complementary competencies. Knowledge produced in university and government laboratories is now systematically tapped. Feedback is now more formal and inclusive and more complex to manage, with the development of technological alliances. The frontiers of the corporation become more porous, as intellectual property resulting from technical alliances is partially shared with external agents. Traditional R&D management methods become partially obsolete and new routines emerge to cope with new activities, new flows of knowledge, and new types of employees. In the new business environment, flexibility is the key characteristic of the emerging model of R&D.

The new alliances belong to the realm of strategic behavior. Through strategic alliances, corporations look for key complementary assets (technology, marketing knowledge, financing) that outside partners may possess or that can be produced through the combination of internal and external resources (Hamel and Prahalad, 1994).

Why the New Model Emerges

Fourth-generation R&D has existed as an organized activity, though marginally, since the very beginnings of industrial research. There is anecdotal evidence of cooperative R&D among industrial corporations or between government and university laboratories and business since the nineteenth century. Aircraft manufacturing is one industry in which technological collaboration between aircraft assemblers and engine manufacturers was documented since the early twentieth century (Mowery, 1987). What is new in the late 1980s and 1990s is that these cooperative forms have now become widespread across the industrial spectrum. The evolution of R&D bears some resemblance to some characteristics of change in the biological world: in the era of dinosaurs, between 225 and 65 million years ago, mammals existed, though in limited ecological niches. Only later they became dominant, after the disappearance of dinosaurs, when they proved better adapted to a new and rapidly changed environment.

The business conditions of the 1980s and 1990s are also entirely new and highly disruptive when compared with the quiet economic situation that prevailed from the second industrial revolution to the 1980s. The present economic and technological environment is characterized by several new features:

- New industrial countries and new industrial competitors have arrived in the global marketplace. In the previous era, competition occurred among a few North American and Western European corporations. Industrial hierarchies and leaders were stable: GM, Ford, and Chrysler dominated the North American car industry, whereas Volkswagen, Fiat, Peugeot, and Renault dominated the European auto industry. The computer industry recognized one undisputed leader, namely IBM. The manufacturing subsidiaries of AT&T and IT&T dominated the world telecommunication equipment industry. GE, Westinghouse, and Allis-Chalmers were the leaders of the electric equipment industry. In the 1980s and 1990s, however, Japan, Korea, and the new competitors from South East Asia have disrupted all existing hierarchies and entered all industrial markets. In 1994, Korea became the fifth world largest investor—following Japan, the United States, Germany, and France, and preceding Italy and the United Kingdom—measured by the number of patents granted to domestic inventors (World Intellectual Property Organization, 1995).

In this new context, long-term R&D projects have become much more uncertain and risky. Any newcomer may arrive first to commercially successful results and seize a large share of the global market before older, established firms can achieve results in their competing R&D projects. In this environment, corporations prefer to develop technological partnerships in order to reduce risk and uncertainty and better monitor other competitors' technological development.

- In the post war period, the development of science-based industries, like information technologies, biotechnology, and advanced materials, had two different kinds of effects. For one, this trend increased the level of complexity of any R&D project. It became more difficult for any single company, even the largest, to pretend to be knowledgeable in all the dimensions of a complex research project. Companies develop partnerships with other corporations with complementary knowledge, including users and suppliers. Capturing the knowledge of the users became essential to the success of major projects (von Hippel, 1988; Rosenberg, 1982). Also, universities and government laboratories can provide essential insights in the characterization of new materials, proteins and micro-organisms, and lasers and optical devices. Many R&D projects became multi-agent and tapped the competencies of previously unsolicited organizations.

The technological frontier advances much more rapidly and the stock of knowledge of any organization becomes obsolete quickly. Simultaneously, the life cycle of products shrank, and the race to innovate further accelerated its pace. In order to achieve results within shorter periods of time, companies collaborate to reduce lead time and bring products to market as quickly as possible.

- The information content of all products soars, and with it there are increasing returns to scale (Arthur, 1994). Information has a particular characteristic when it is embodied into products: users have to be educated, and they invest increasing amounts of time and capital in becoming acquainted with the new products. Therefore, they tend to stick to the products they have learned to use; this is particularly true in the case of telecommunication equipment, software programs, computers, and numerically controlled machines, but also occurs in scientific and medical equipment, transportation equipment, and other products. Being first may thus allow the product leader to capture the market for a long period of time. The producer that arrives first to the market may gain a competitive edge that could create a knowledge barrier to future products. Cooperation between innovative agents may reduce the lead time and gain this competitive edge.
- In all advanced countries, the government funds, directly or indirectly, a high proportion of R&D expenditures both in business and in the public sector. But in the 1980s and 1990s, governments are also committed to deficit reduction and are increasingly solicited by other constituencies. In all industrialized countries, public funds available for R&D are in shorter supply. Companies learn to cooperate to obtain public money. Simultaneously, governments tend increasingly to allocate their R&D funds to groups of companies or to industry-university research centers to better diffuse technical knowledge and to reduce costs. Also, governments push government research centers to cooperate with private business both to improve technology diffusion and to reduce the financial burden of the public labs.
- New management techniques, mostly originating in Japan, tend to emphasize collaboration and not only competition. Vertical collaboration between assemblers and suppliers permits the spread of quality control, just-in-time, and cooperative research to improve products and reduce production and R&D costs in all partners. Horizontal collaboration between competitors increases the chance of arriving at results and reduces R&D costs and lead time.

Thus, the new environment tends to curtail the efficiency of linear models of R&D and increase the usefulness of the feedback models based on collaboration and flexibility.

New Environment, Strategies, and Routines

These deep changes in business environments have brought major changes in R&D strategies and accompanying changes in established routines in the research laboratories. Nelson and Winter (1982) have defined routines as ways of doing things, regularities in the behavior of economic agents that they use to cope with uncertainty and risk. Routines emerge and evolve mainly as adaptive responses to environmental disruption. They are trial-and-error essays to cope with disruptive external pressures.

Three sets of routines may serve to illustrate the new management methods. These three sets are intellectual property, project management, and evaluation routines.

Handling Intellectual Property

In linear models, as well as in the first (internal) feedback model, intellectual property (IP) is entirely bestowed in the R&D-active corporation. Technological development is conducted within the frontiers of the corporation and consequently, the firm captures the first results of its own investments in R&D before knowledge leaks to other parties and social returns overcome private benefits.

In the fourth generation, or flexible model, IP may be shared from the start by research partners. We found four major different new routines for the management of IP:

- IP may belong equally to all technical partners. This is the case in those alliances in which the goal of the collaboration is the production of basic or fundamental knowledge. This type of collaborative research yields results that are far from commercial products. This type of knowledge is leaky and difficult to keep secret. Universities and public laboratories often participate in these kind of collaborative ventures, which usually produce articles in scientific and technical journals and seldom yield patents or prototypes.
- Partners distribute IP on the basis of their differential contributions to the common project. Parallam, a new material produced by three very different corporations, and 3TC, a new drug against AIDS are cases in point.
- One major partner may entirely appropriate IP. Smaller partners may obtain other results. In vertical collaborations, smaller corporations may become the suppliers of large assemblers for a specified part or component in the development of which they have participated. University partners may obtain the right to publish some of the more fundamental results after submitting the future publication for the approval of the major ally.
- IP may belong to one partner (i.e., a public laboratory, and industry-university research center, a cooperative research center) under the proviso that other, usually industrial, partners obtain a first right to license from the owner.

These solutions to the IP dilemma sometimes result in conflicts and disagreements about the proper handling of the results. Bellcore, the large cooperative research center in the United States, supposedly suffers from these type of disputes. In an extensive study on Canadian technological alliances, the sharing of IP appeared as the most widespread difficulty affecting R&D partnerships (Niosi, 1995).

Project Management

In the linear models, R&D managers are responsible for the definition and supervision of the research project. In the first feedback model, some difficulties may arise as the responsibility of the day-to-day management of research projects may be allocated either to R&D managers, to corporate managers, or to interdepartmental teams (Smith, 1982).

In the fourth-generation model, project management may be solved in a variety of different ways:

- Managers delegated by the different organizations may also run collaborative R&D projects. Corporations use this solution where the contributions of the different partners are roughly equivalent and/or when they envisage the collective ownership of results.
- The leading partners may also run collective projects. These are usually larger assemblers or the final users of the research results. The participation of smaller partners in the project management committee will then vary according to the different technological and/or financial contributions of the partners.
- Finally, the partners may set up permanent collective management R&D structures, like R&D joint ventures, cooperative industrial research centers (cases of Bellcore and MCC in the United States), or industry-university R&D centers (like the Canadian Microelectronics Corporation at Queen's University). The participation of the allies to the collective management structures varies widely according to the financial and technological contribution of the partners.

Evaluation of Results

Ex-post evaluation of results also adopts entirely new forms and characteristics in the feedback model. In the linear models, particularly when corporations have introduced project management methods, the upper hierarchy of the corporation periodically conducts internal evaluations of the efficiency of the R&D laboratories, sometimes with the help of external consultants. Issues at stake typically include identifying the proportion of projects that have successfully attained commercial products, the contribution of R&D to cost reduction in the corporation through new or improved processes, the new materials that have been incorporated into products reaching the market, and the percentage of the corporate revenue stream that is attributable to internal R&D results.

In the fourth-generation model, the relevant questions are: how important are the results of the cooperative projects to the commercial products of the corporation? What are the opportunity costs of collaborative research when compared to the potential costs of conducting purely internal R&D? What are the transaction costs of these intercorporate structures?

Evaluation of R&D efficiency is conducted through surveys among partners and among users of public R&D, following alliances in which government laboratories have been involved.

Case Studies

Sharing Intellectual Property

Under the new R&D model, corporations have developed new routines to share IP. They include dividing the results among partners on the basis either of differential contributions or on a geographical basis. The following examples illustrate both types of division of results.

The Case of Parallam

Between the early 1970s and 1991, MacMillan Bloedel (MacBlo), the largest Canadian forest products company, conducted a long-term, costly (C$150 million) R&D project, aiming at creating valuable new goods that would be exclusive to the corporation. More specifically, the goal of the R&D project was to develop a wood-based composite material that uses wood chips left over from the plywood process to be used in the manufacturing of high-resistant beams for the construction industry. MacBlo set up a technological alliance with a Canadian chemical company and a German manufacturer of mechanical presses. Under the terms of the alliance, the chemical partner developed a new powerful glue that was able to hold together the wood fibers, and it kept the IP of the adhesive. The German manufacturer developed a numerically controlled press that used microwave energy to cure the glue and became the sole owner of the new machine designs. MacBlo kept the IP of the new material. MacBlo erected two large new plants to manufacture the engineered composite at a total cost of $100 million, one in Colbert (GA, USA) and the other New Westminster (B.C., Canada). Parallam, the new building material, is now a major contributor to MacBlo's net revenues.

Developing and Sharing 3TC

In 1986, a group of university researchers founded BioChem Pharma in Montreal, as a spin-off of the Institute Armand-Frappier, a constituent of the Université du Québec. The goal of the new biotechnology company was to develop a few vaccines and diagnostic tests, mostly aimed at AIDS and cancer, on the basis of previous research conducted in the Institute. By 1990, BioChem had developed a new drug against AIDS, called 3TC, which could potentially replace ATZ. That year, facing the huge costs and complexities of the preclinical and clinical trials of the drug, BioChem signed an alliance with Glaxo Plc, the British multinational pharmaceutical corporation, for collaboration in the last phases in R&D and the marketing of the new drug. Glaxo put its research, manufacturing, and marketing expertise in the alliance, together with the sums required to conduct the last phases of the development of 3TC. BioChem contributed with the new patented drug to the alliance. The partners shared IP on a geographical basis: BioChem would become its sole manufacturer in the United States and Canada, and Glaxo would keep the rest of the world. The partners have manufactured the drug since 1995, and it became an instant success; according to some observers, this is the second most important Canadian contribution to pharmaceuticals since Nobel Prize winners Banting and Best developed insulin on the basis of the research they had conducted in the 1930s at the University of Toronto.

Managing Alliances

The most usual type of alliance is a company-to-company agreement supervised by a committee integrated by R&D managers of both partners. However, corporations have developed several other managing structures in order to run collaborative structures. They include permanent private and nonprofit cooperative research centers, R&D joint ventures, and industry-university corporations. Joint management of collaborative research allows for permanent information loops from partners to R&D performers.

R&D on Third-Generation Robots

In 1988, a group of Canadian firms collaborated with the cooperation of McGill University Center for Intelligent Machines to conduct precompetitive research on advanced robots. The alliance was formed within a larger consortium, called PRECARN (PRE-competitive Canadian Research Network). The robotics consortium included companies with capabilities in the production of this advanced equipment (of which CAE Inc., the developer of the robotics arm of the U.S. shuttle and a world leader in flight simulators, and MPB Technologies, another Canadian contractor in the U.S. space program) and users of this type of equipment (including Hydro-Quebec, the second largest Canadian electrical producer). The alliance had a 5-year horizon and was managed by a team under the direction of MPB, one of the technical leaders. The C$10 million project resulted in new knowledge that became property of both industrial users and producers. Users and producers are linking with universities and government laboratories all across Western Europe, Canada, and the United States. The Microelectronics and Computer Technology Corporation, incorporated in the United States in 1982 is a similar consortium, one of the first in the United States, associating suppliers and customers of microelectronics parts and components in order to avoid duplication of R&D efforts, accelerate the development of products, and reduce time to market.

Evaluating Results

Corporations no longer evaluate R&D performance solely on the basis of counting patents, publications, or successful new products on the market, or even through sophisticated ratios of profits form new products on internal research expenditures. Results are increasingly evaluated through the performance of products and services used by customers, thus evaluating the performance of R&D with the help of users. This practice occurs both in business firms and public and cooperative research centers.

Evaluating the Performance of a Government Research Center: CRIQ

The Quebec Industrial Research Center (CRIQ) is the second largest provincial research organization in Canada. Its original mission is to support the province industrial enterprises, with an emphasis on small and medium-sized firms without R&D capabilities. Founded in 1969, it has an operating budget of some C$35 million, of which the Quebec government funds one-third and the industrial partners contribute the remaining two-thirds. The CRIQ conducts R&D in cooperation with industrial firms and offers them technical service in the areas of standardization, advanced technical managerial practices like concurrent engineering, and provides technical information and technology transfer. Areas in which CRIQ has built an expertise are manufacturing automation in the forest and transportation equipment industries.

When in 1993, the CRIQ requested an evaluation of its performance, we organized two major studies. We conducted by mail a postal survey; we sent a questionnaire to nearly 1,000 occasional and potential customers. We conducted the second study through in-depth interviews with some 50 regular industrial sponsors and clients. The goals of both evaluations were to measure the satisfaction of the industrial users (with different levels of acquaintance) with CRIQ's services, together with the business impacts of those services. Our evaluation concluded that nearly 25% of Quebec's industrial enterprises considered CRIQ the first organization they would choose to conduct technical development. However, nearly 75% of the province industrial firms did not even know of the existence of CRIQ or were not acquainted with its competencies. As expected, regular customers displayed a very high level of satisfaction. We concluded that there existed a high technical quality to CRIQ's services and a fair effort of marketing promotion of its activities.

Evaluating the Performance of Cooperative Non-Profit Research Center: CRIM

The Computer Research Institute of Montreal was formed in 1986. It is a non-profit organization, with a total budget close to C$15 million, financed by its corporate and governmental members. A joint effort of government, university, and private industry, by the end of 1994 it had 72 members, including 55 enterprises (35 SMEs and 20 large firms), 10 universities, and a few government research centers and departments. It conducts high-level R&D in the area of both precompetitive R&D of information technologies, and it transfers its results to industrial users. Areas of strength are software engineering, voice recognition, and other specific niches in the software industry. By the end of 1994, CRIM had completed nearly 50 R&D projects, most of them with industrial partners. It also gives technical training support to its corporate members. A 16-person board manages CRIM; the board is composed by half of its corporate sponsors, the other half coming from its university and government members.

In 1994–95, we conducted an evaluation of CRIM's activities through a survey of its industrial and university clients. The outside evaluation accompanied a series of more traditional internal performance indicators. The exercise was supposed to give the management feedback on the efficiency of its collaborative R&D, its technology transfer, and its training activities. We conducted the survey on a representative sample of its sponsors, which are its most frequent associates and customers for all of CRIM's activities. The goal of the exercise, implemented through personal interviews with top-level executives of corporations and universities, was to identify strengths and weaknesses in CRIM's activities. More specifically, the objective was to measure the contribution of CRIM to the learning processes, market competitiveness, profitability, and job creation of its sponsors. Whereas the general evaluation was highly positive, we discovered a few areas in which there was room for improvement; CRIM was able to learn from its customers and became more efficient and effective through several changes in its operating routines.

Conclusion

In the highly dynamic business environment of the 1980s and 1990s, with the development of new industrial competitors, an unfolding triple technological revolution and the development of science-based industries, freer markets, and reduced government support, companies (together with public and university laboratories) are abandoning the linear models of innovation and developing entirely new routines, both internal and external, based on flexibility. The goal of these routines is to reduce lead time, minimize the number of unsuccessful R&D projects, and cut research costs. Corporations attain these goals through the development of feedback mechanisms to ensure that complementary, technical, and nontechnical (i.e., market) knowledge both from within the corporation and from external users and customers enters the R&D process. The era in which companies spent their R&D budgets and expected results on the basis of pure serendipity (or even informal or periodical market analysis) is definitely involved.

Similarly, public laboratories and university research centers, in their need to compete with other agencies within the public sector, are rapidly linking themselves to industrial customers and ensuring that some of their research results find a market outside government. Again, the new environment is one of reduced public expenditures, and one in which each public agency must justify its contribution to economic growth, competitiveness, and social welfare.

Under these constraints, entirely new collaborative strategies and routines develop to handle the production, distribution, and continuous evaluation of R&D results. These new routines are developing and spreading very fast, first within high-tech companies, then within the public and quasi-public sector, and even in low and medium-tech business firms. These routines emphasize flexibility. Collaborating with customers brings rapid evaluation of performance of products and processes. Cooperation with both competitors and users reduces costs and lead time. Absorbing new, complementary knowledge from allies is much less costly and cumbersome than taking them over, which often requires managing unwanted assets.

The new generation of R&D is a new evolutionary stage in the development of the corporation. As such, it brings permanent additions to the repertoire of routines of the firm. The first generation brought the corporate R&D laboratory. The second generation adapted project management methods to R&D. The third brought internal collaboration between different functions in the firm. The fourth adds routines designed to make more flexible the conduct of R&D function through the incorporation of the knowledge of users and competitors.

Flexible innovation incorporates many of the effective methods of previous stages, like project management techniques and business development groups. It also has many other advantages: it is less costly than alternatives like mergers and acquisitions; it reduces uncertainty and risk; it accelerates innovation (a key advantage in a world with reduced life cycle of products); it reduces duplication of efforts; it increases and improves user-supplier collaboration; it permits a better targeting of markets through the involvement of major users in R&D projects for future products; and last but not least, it allows firms to concentrate on core competencies.

The development of fourth-generation R&D can be understood using both evolutionary and resource-based theories of the firm. Through this fast-spreading routine, corporations aim at the development and acquisition of strategic resources, produced by other firms or in partnership with external allies. Strategy used to be confined to the borders of the firm. Increasingly, strategy is only understandable with a view to changing and dynamic networks of independent firms.

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