Technology Diffusion

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Abstract

Technology diffusion is the process by which new technologies are adopted for use across individual firms or households in a given market, and across different markets. The most salient facts about this process are that it always plays out over time, and the time before adoption is widespread varies greatly across technologies. The dominant explanations for gradual adoption are the time needed for information about the technology to diffuse, and heterogeneity among adopters, such that those for whom the benefits of the new technologies adopt first, while those for whom the benefits are less wait until the technology has improved and/or its cost has fallen. Research has focused on the nature of the information diffusion process, and the attributes of firms and households that affect their adoption decisions. Promising areas for new research include the application of insights ad methods from behavioral economics, the linking of formal models to empirical research, the diffusion of technology to less developed countries and its role in economic development, and public policy issues related to technology diffusion in important sectors such as health care and global climate change.

INTRODUCTION

What is it and Why Does it Matter

Josef Schumpeter described the process of technological progress as consisting of three stages: "invention"—the first technical implementation of an idea; "innovation"—the first commercial introduction of a new product or business method; and "diffusion"—the gradual adoption of a new way of doing things by multiple actors (Schumpeter, 1942). Thus it is through the process of diffusion that the benefits of a new technology come to be widely enjoyed.

The process of technology diffusion has been the subject of extensive study by historians, economists, sociologists and other social scientists. When we look back in time at the diffusion of technologies that are now widely used,

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the initial approach is often one of puzzlement: why did it take so long for this superior way of doing things to become widely accepted? Sometimes, we find ourselves in the mirror-image position. We see a technology (e.g., mosquito nets to prevent malaria, or energy-efficiency investments) that seems to offer transparently clear benefit at no or low cost, and we puzzle over why it is so hard to get everyone to use it. Needless to say, the source of puzzlement is fundamentally the same in both cases. New, intrinsically superior technologies often take a long time to diffuse widely. Further, there is tremendous variability in the diffusion rate. For example, it took about 40 years for the clothes washer to go from being present in one quarter of households to being present in three-quarters of all households, while the color television achieved this amount of diffusion in less than 10 years (Hall, 2005). The economics of technology diffusion explores the reasons why diffusion is not instantaneous, and tries to model and measure the factors that affect its pace.

KEY ASPECTS OF THE DIFFUSION PROCESS

Different researchers and different studies have emphasized different aspects of the diffusion phenomenon. Taken together there are three broad categories of considerations that seem to be important:

Economic Incentives. On the demand side (potential adopters), firms and individuals respond to the economic benefits of the new technology relative to its alternatives. On the supply side, firms respond to the profitability of selling the new product.

Information and Information Processing. Adoption decisions are determined by what potential adopters know or do not know about the new technology, and by their ability to process that information. Further, the act of adoption and subsequent use by one actor thereby creates a source of information about the new technology for other actors. This means that the spread of information about the technology is endogenous to the diffusion process itself.

History/Culture/Institutions. The openness to a new technology will be determined by the particular context in which it is introduced. Social and cultural norms and habits affect people decisions. In addition, an existing technology may be embedded in institutions and physical infrastructure in ways that advantage it over the new technology, so that these advantages then have to be overcome for new technology adoption to occur.

Which of these factors is most important varies from technology to technology, and disciplinary inclination also affects which factors are emphasized by particular researchers.

FOUNDATIONAL RESEARCH

Diffusion Curves and the Epidemic Model

It has been long observed that the pattern of diffusion of a new technology can typically be described by an S-shaped function as illustrated in Figure 1. Initially, only a few early adopters try a new technology. At this early stage, both the fraction of potential users who are using the new technology and the rate of increase of that fraction are low. Gradually, both the extent of use and the rate of increase of that extent rise, leading to a take-off phase in which diffusion accelerates significantly. At some point, the extent of use becomes high and the rate of increase of that extent falls, leading to a leveling off or saturation. Depending on the technology, saturation may occur at 100% of potential users or close to it, or at some lower level.

An easy way to generate a diffusion process that will follow an S-shaped evolution over time is to model it as analogous to an epidemic. For an infectious disease, any one person's chance of catching the disease is proportional to the number of people who already have the disease. For a population, the number of new cases in a given period will be proportional to this probability for a single person, multiplied times the number of potential disease victims. And this number of potential victims in any period is equal to the

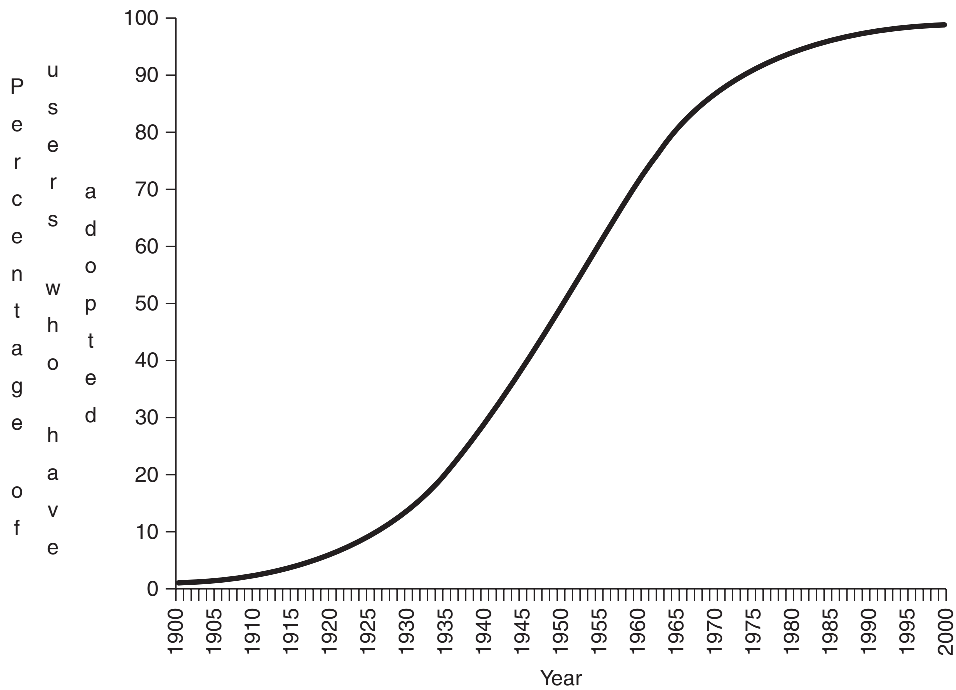

Figure 1 Typical S-shaped diffusion curve.

initial potentially susceptible population, minus the number of people who already have the disease and hence cannot be newly infected in the current period. That is:

$$\text{Number of new cases} = A \times (\text{number of infected people}) \times [P - (\text{number of infected people})]$$

where A is a parameter that is larger for more infectious diseases, and P is the initial potentially infected population. One can see that this equation implies few new cases when very few people have been infected, and also few new cases when almost everyone has been infected. The number of new cases will be greatest when half of the potential population is infected.

If this equation is expressed in terms of the time derivative of the stock of infected people, it is a differential equation whose solution is a logistic function with the characteristic shape of Figure 1. Mechanically, we can think of technology as spreading as a disease, with each adopter potentially infecting other potential users with the new technology bug. More concretely, we can think of the epidemic model as capturing the essence of the importance of information in the diffusion of technology. People have many sources of information about a new technology, but one of the most important sources is seeing the technology in use by others. This means that having a lot of people around me use a technology increases the chance that I will learn about it, and hence increases the chances that I will adopt it. While this story is simplistic, it does capture an important aspect of the process, and it is sufficient to generate the typically observed S-shaped diffusion pattern.

Information Transmission and Marketing

The rate at which diseases spread is affected by hygiene and public health practices; the spread of technologies is affected by marketing and other aspects of information transmission. In marketing there is a literature going back to Bass (1969) that studies which modes of information transmission are most effective, and how the importance of different modes varies as diffusion progresses. It is frequently presumed that mass media play an important role in disseminating information about new technologies, but Rogers (1995) argues that interpersonal communication is more important than mass media in determining the rate of diffusion.

The important role played by others' adoption in providing information about new technologies has potentially important normative policy implications. At a general level, markets for information are imperfect, so when one firm or household acts to provide information to others they create a social benefit for which they are imperfectly compensated. In economic jargon, they are generating a positive externality. Since the act of technology adoption typically generates information for others, it is characterized by such a positive externality. At a theoretical level, the government can increase social welfare by subsidizing activities that generate positive externalities. There is thus at least a theoretical justification for policies (e.g., tax credits for hybrid cars) that subsidize the adoption of new technologies, over and above any broader social good that is generated by the particular technology (Jaffe & Stavins, 1994).

Market-Wide Economic Factors

The rate at which diseases spread is affected by hygiene and public health; the rate at which a *specific* disease spreads is also affected by its intrinsic contagiousness. Analogously, the rate of technology diffusion is affected in general by modes and mechanisms of information transmission, and the rate of diffusion for a particular technology will be affected by its benefits and costs relative to existing alternatives for that population. Better or less expensive technologies will be more "contagious," spreading faster, and achieving effective saturation sooner.

Griliches' classic study of hybrid corn showed that differences in the rate of diffusion of hybrid corn varieties across different states could be explained by differences in the net economic gain for farmers generated by the new varieties, related to factors such as farm size (Griliches, 1957). Of course, it is the attractiveness of the new technology *relative* to the status quo that matters. The radio diffused faster than the washing machine, perhaps because the latter was evaluated relative to the alternative of hand washing, whereas the former performed functions not otherwise available from existing technologies.

Individual Economic Factors: The Heterogeneous Adopters Model

The discussion so far treated everyone as equally susceptible to the disease or new technology. In this conception, the only reason not everyone adopts a new technology right away is that information about it spreads only gradually, and that learning is mostly generated by the diffusion process itself. An important complementary perspective on gradual diffusion starts with the insight that potential adopters are, in fact, heterogeneous with respect to the net benefits generated for them by the new technology. If we combine the reality of heterogeneous potential adopters with the observation that the new technology itself typically improves and falls in cost as it diffuses, we can generate an S-shaped diffusion curve even if information were perfectly available.

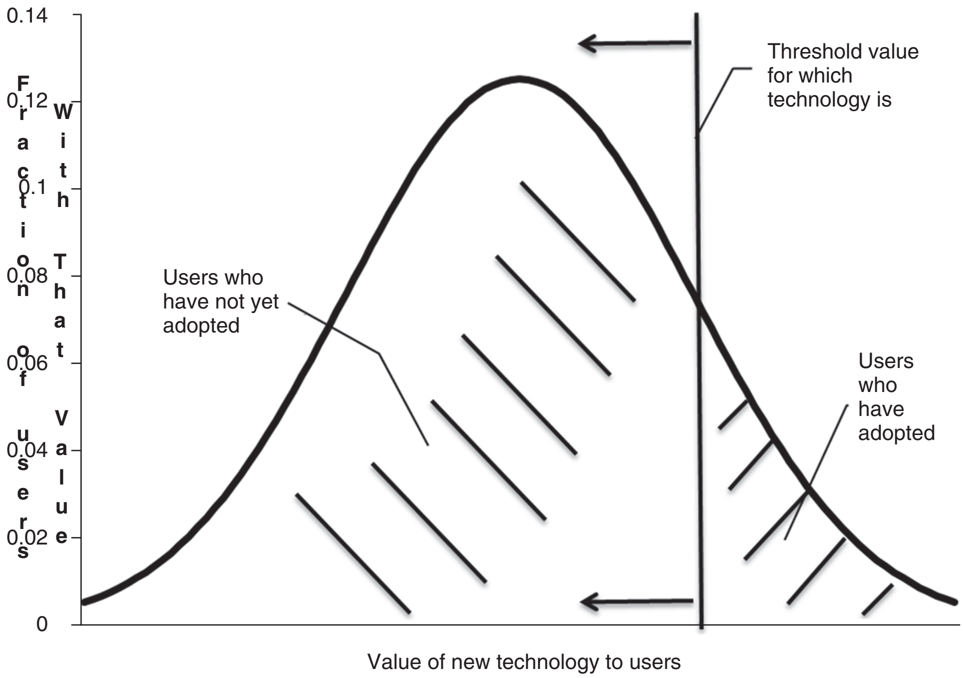

Figure 2 Distribution of heterogeneous adopters and diffusion over time.

Suppose, for illustration, that the gross benefit from the new technology (e.g., lower operating cost or higher quality output) is distributed across firms with a typical unimodal distribution as illustrated in Figure 2. There are many firms for which the benefit is near the average benefit, and smaller numbers for which the benefits are significantly greater or significantly less than the mean. At a moment in time, we assume that all firms for which the benefit exceeds the cost will adopt if they have not done so before. This means that there will be a threshold benefit level, such that all of the firms for whom the benefit exceeds this level will adopt, and all firms for whom the benefit is below this level will not. As shown in Figure 2, the cost will be relatively high initially, which means that the threshold benefit level will be high. Only the few firms in the tail of the distribution to the right of this threshold will have adopted. But over time, the cost will fall. This makes the threshold benefit level fall. With every cost decline, more firms find the new technology attractive. If the cost falls continuously and relatively smoothly, this gradual fall will sweep out the distribution of benefits and generate an S-shaped diffusion curve.

Figure 2 represents the situation as the benefits of adoption being heterogeneous, while the (uniform) adoption cost falls over time. What matters, of course, is the relative benefits and costs; both the heterogeneity and the improvement over time can be on either side of the equation. An important source of heterogeneity is, in fact, on the cost side, because the cost of adopting a new technology is not limited to the purchase price of the new good. It includes also all of the costs that the user must bear in learning how to use it, and adapting existing processes and practices to it. Brynjolfsson (2000) has studied extensively the costs that firms bear in adopting new computer information systems, and shown that the internal adaptation costs greatly exceed the purchase cost of the hardware and software.

David (1975) is a pioneering implementation of the heterogeneous adopters approach. The mechanical reaper was an important nineteenth century invention that greatly improved farm productivity. But it was a costly piece of equipment; the trade-off between its productivity benefit and this cost was more favorable for larger farms. As a result, larger farms adopted first, and smaller firms adopted later after the cost fell and the reaper itself improved.

Many new technologies share with the mechanical reaper the feature that they reduce production costs or improve product quality but require a significant initial fixed investment. Firms that can balance this initial investment against productivity benefits on a larger volume of output will then find the investment more attractive. As a result, it is frequently observed that the largest operators will be the first to adopt a new producer-goods innovation. As the cost of the new equipment falls over time, it becomes profitable for smaller and smaller firms and this progression generates gradual diffusion.

Note that the learning/epidemic model and the heterogeneous adopters model can each generate S-shaped curves by themselves. In reality, both phenomena are typically at work, and the diffusion pattern we observe is generated by the combined effect of information spread and improvement in the technology making it attractive to more potential users over time.

Interaction of Diffusion and Innovation

The previous section simply took as given that the cost of new technologies falls and their quality rises over time. There are at least two reasons why this is, in fact, the typical pattern. First, learning-by-doing in the manufacture of new products typically leads their production cost to fall as cumulative production grows. In addition, diffusion and the resulting use of a new technology by multiple, diverse parties lead to improvements that feed back and improve the technology. Indeed, such user-driven innovation—which is inherently bound up with the diffusion process—frequently accounts for a major share of the overall performance advantage that a mature technology has over its predecessors. There is therefore an additional positive externality generated by the early adopters of a new technology: their feedback improves the technology, and the benefits of such improvements are captured to some extent by the technology seller and by later technology adopters (von Hippel, 2010).

NETWORK EFFECTS AND TECHNOLOGY "LOCK IN"

The diffusion pattern for some new technologies is affected by what economists call "network effects." Network effects exist when the value of a particular product to one user is affected by the extent to which that product is used by others. The network effect can operate directly, as in the case of technologies that communicate with each other. Having a telephone was not very useful until a significant number of other people also had telephones. Network effects can also operate indirectly, through the impact on investment in supporting or related technologies. The value of a computer depends, to some extent, on the nature and diversity of software that is available for the computer; an increase in the number of people that use a computer increases the market for such software and therefore likely increases the amount of software available.

Both direct and indirect network effects can operate at the level of a category of products, or at the level of a specific technology type. If you have a telephone, you can call any other type of telephone, so the value to you of the telephone network is independent of what variety of telephone other people have, because all telephones are mutually *compatible*. In contrast, in the early days of the personal computer, Apple computers were *incompatible* with IBM PC-based computers. The value of either type to a user depended mostly on the number of users of computers of the same type, because they could exchange files with such users, and because that determined the extent and variety of software available for that computer type.

Because of the compatibility issue, the early days of technology diffusion for a class of products can affect long-term technology evolution. If network effects are significant and technology types are incompatible, the type that gets to the market first or otherwise builds an initial lead in user adoption has a self-reinforcing marketplace advantage. The fact that it is more widely used makes it more desirable, which leads to more adoption and an increase in the network-size advantage. Theoretically, one type may achieve an insurmountable advantage, even if it is inherently inferior to another type for some or all users (Arthur, 1989).

This phenomenon of "technology lock-in" has been much discussed, although its actual relevance to the market success of particular technology types such as the "QWERTY" typewriter keyboard, the internal combustion engine, AC versus DC electricity, the VHS videotape, and the IBM PC and its clones is much debated. As discussed further below, it is also a topic of concern for policy when a new technology with widespread public benefits (e.g., electric cars) must overcome the network advantages of an existing technology (e.g., fossil-fuel-consuming cars for which the existing network of filling stations is in place).

For many technologies, compatibility of competing product varieties is achieved through the establishment of standards. Standard-setting organizations provide a forum in which maker of related technologies meet and frequently agree on technical specifications that ensure the compatibility of different products. Compliance with standards is typically voluntary for manufacturers, so a seller who desires incompatibility may always choose to have its products operate outside the standard, but if all competing products are mutually compatible, that is a risky strategy.

Market Structure

Market structure and technology diffusion are mutually endogenous. Market structure affects the rate of technology diffusion. As noted, larger firms generally adopt new technologies faster than smaller firms. Controlling for firm size, firms in more competitive industries also adopt faster, all else equal (Mansfield, 1961).

At the same time, technology diffusion affects market structure. Klepper and his associates have shown that the typical evolution of a new industry involves initial growth in the number of producers, with a peak and subsequent decline as the market for the technology becomes saturated and the technology itself matures (Klepper, 1996).

CUTTING EDGE RESEARCH

Combining Information Spread and Heterogeneous Adopters

As noted above, the two primary explanations for gradual diffusion are gradual diffusion of information about the new technology, and heterogeneous adopters who each adopt when the technology has improved or become inexpensive enough to be optimal for them. There has been relatively little work combining these two approaches. The primary empirical challenge to such combination is the identification of empirical strategies that distinguish them. The thrust of the information story is that the probability of adoption for a given actor depends on the extent of previous adoption in an information neighborhood. For some products, the information neighborhood would be geographically defined, but for others it might not be. The thrust of the heterogeneous adopters story is that the first adopters will be those who have particular attributes that makes the new technology particularly valuable to them. To the extent that potential adopters in a given group share attributes affecting the desirability of the technology, this could lead to adoption patterns very similar to what would be expected from the information story.

Cultural and Social Factors

Social norms and traditions have powerful influences on human behavior, including the decision to try something new. Within a market, variations in the social and cultural context can be a dimension of heterogeneity that would provide additional explanation for why some firms or households adopt before others. Across different countries, widespread differences in norms and traditions are a source of different overall diffusion rates. Tellis, Stremersch, and Yin (2003) added variables related to gender, culture, social attitudes towards risk, and religion to models based on economic factors in predicting technology adoption rates across European countries.

International Diffusion and Technology Transfer

The above discussion considered the diffusion of a new technology within a given market. A somewhat distinct topic is the international spread of a new technology. Comin and Hobjin created the Historical Cross Country Technology Adoption Dataset (HCCCTAD), which documents the historical diffusion of dozens of important industrial technologies around the globe (Comin, Hobjin, & Rovito, 2006). The striking empirical regularity in these data is that there is tremendous variation, even for a given technology, in the rapidity of its adoption, even among countries at similar stages of economic development, although the disparities are smaller for more recent technologies than for those of the nineteenth and early twentieth centuries. Thus the issues of information diffusion and heterogeneity of potential adopters that govern gradual diffusion within a market, also operate on a global scale.

The diffusion of new technologies from developed countries to the less developed world is of particular interest because of its implications for economic development. This process of "technology transfer" occurs through multiple mechanisms, including importation, imitation, and foreign direct investment. An important issue with respect to technology transfer is whether less developed countries' policies with respect to protection of intellectual property ("IP") have an impact on the willingness of multinational companies to transfer technology to them. Empirical evidence does suggest that foreign direct investment is influenced by IP policy for high and middle income countries, but not for the least developed (Hall & Helmers, 2010).

Another technology transfer issue is absorptive capacity. Some advanced technologies require skills and infrastructure to use and/or to adapt to local conditions. This means that the least developed countries may not be able to benefit from these technologies, creating an unfortunate feedback in which the countries are poor in part because of low utilization of the highest-productivity technologies, and their poverty prevents them from creating the indigenous human capital and infrastructure that would support those technologies.

Sectors of Particular Interest

Much current empirical research on technology diffusion is focused not on general modeling or results about the diffusion process, but rather on understanding the forces affecting diffusion of particular technologies that are significant because of their effect on the economy or public policy objectives. Widespread diffusion of the personal computer has generated a significant body of research on how this new technology is incorporated into business systems, and the resulting impact on productivity or consumer satisfaction. The role of new medical and pharmaceutical technologies in both health outcomes and the cost of health care is a topic of significant economic and public policy interest. This has led to a large body of research on the diffusion of medical practices, both in terms of measuring what affects the choices of health care providers and patients, and also in terms of measuring whether and to what extent new methods actually improve outcomes and are cost-effective. The problem of global climate change, and the resulting policy motivation to reduce fossil fuel emissions, has led to a renewed interest in the "paradox" of the slow diffusion of technologies that reduce energy use.

RESEARCH ISSUES GOING FORWARD

Insights from Behavioral Economics

The last 2 decades have seen major growth within economics of research that attempts to incorporate limitations on agents' cognitive abilities into explicit models of economic decisions. Work in this area has looked at decisions in financial markets and health care, among others. Since the decision to adopt a new technology is imbued with important considerations of information processing and decision-making under uncertainty, it is a natural area for the further application of ideas from behavioral economics. It would seem fruitful to explore the impact on adoption decisions of behavioral issues such as:

- Framing bias (how a decision is described or presented affects people's choices independent of the underlying benefit/cost trade-offs);
- Difficulty assessing the significance of low-probability events;

- Salience bias (people give too much weight to events that they have witnessed personally and/or recently); and
- Loss aversion (people give more weight to having something and losing it than to missing an opportunity to gain something).

These and other limitations on economic agents' cognitive abilities likely have important implications for the decision to adopt a new technology.

Linking Formal Modeling and Econometrics

Much of the empirical work on technology diffusion has been descriptive, or based on correlations of diffusion rates with observed attributes across different contexts. There has been some work modeling the adoption decision, but relatively attempt to implement such models empirically. Such models predict that the probability of adoption for any agent, at a point in time are a function of certain observable and unobservable characteristics, and so in principle should be estimable as some kind of hazard function. It would be particularly attractive if availability of information, determined endogenously by previous diffusion, could also be incorporated into such models.

Appropriate Technology, Technology Transfer and, IP Regimes

As noted above, access to advanced technology is a crucial issue for economic development. There is a literature looking at the country level at the factors that correlate with foreign direct investment and other indicators of multinational activity in a country. There is much less on the efficacy of specific mechanisms of technology transfer, or on the ways in which the technology transfer process differs for countries in different circumstances and at different development stages. A crucial issue is the adaptation of foreign technology to be most useful and cost-effective in a given country. Finally, while the developed world has pressed less-developed countries to adopt developed-world IP policies so that developed-world inventions are protected from imitation, it is not at all clear that such policies benefit the less developed countries. Research is needed on the tailoring of IP policies to specific country circumstances to try to achieve the best overall balance of incentives for technology transfer, indigenous innovation, and investment in adaptation of foreign technology to local conditions.

Diffusion Policy in Particular Sectors

Public policy is increasingly concerned with the diffusion of new technology in particular sectors. As the internet and computer literacy are increasingly seen as necessary for success in today's economy, the diffusion of these technologies across households becomes a matter affecting income inequality and employment. New health care technologies are simultaneously sought, and also feared as a source of the growth in health care expenditures. Mitigation of global climate change impacts will require the diffusion of an entirely new energy infrastructure, and adaptation to the changes in climate that are likely unavoidable poses its own technology challenges. In each of these areas, there is a great need for deeper understanding of how the generic processes of technology diffusion play out in the relevant specific contexts.

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