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Long Waves of Technological Innovations

This article is a sequel to my article in Studia Politica Slovaca 1/2009. There I found waves of technological innovations during the period of the modern economy (after 1600 AD). Each wave started with an innovative phase (a technological revolution), continued with an application phase (a boom) and terminated with a crisis.

I this article I defined five pre-modern waves of technological innovations in the period roughly from 1900 BC to 1600 AD. These waves are comparable with the modern waves (post-1600). In this more distant past I found 5 technological revolutions which initiated long economic waves: Indo-European technological revolution (1900-1100 BC), Celtic and Greek technological revolution (700-200 BC), Germanic and Slavic technological revolution (300-700 AD), Medieval technological revolution (930-1200) and Renaissance technological revolution (1340-1470).

Key words: technological revolution; economic long waves; Kondratiev cycle; history of Europe; economic development; technological and social innovation

Introduction

In 2009 the journal Studia Politica Slovaca (issue 1/2009) published my article "The waves of the technological innovations of the modern age and the present crisis"[1].

My theory presented in that article was based on the thesis that the main technological innovations are introduced in society and the economy not continually but in specific waves, and the time spans of these waves is shortening due to technological progress. I also asserted that technological revolutions are the main engine of economic development, and hence long-term economic cycles are dependent on these waves of technological innovation.

This is quite logical, because in conditions of stable natural and human resources and their full-scale utilization on the level of the given technologies, the new growth of value being gained from nature can be reached only by enhancement of the efficiency of work and its organization, i.e. only by introduction of new innovations.

A period of technological revolution (an innovation phase) is associated with economic revival. When new but also already-proven and reliable technologies are available, the interest in new technological development temporary declines and investments are diverted from research to their maximal practical utilization. This period we can designate as an application phase. It is also associated with economic growth and perhaps even an economic boom. However, at a

[1] Daniel Šmihula: The waves of the technological innovations of the modern age and the present crisis, *Studia Politica Slovaca*, issue: 1 / 2009, http://www.ceeol.com/aspx/issuedetails.aspx?issueid=0877948e-72f8-48ee-9e03-0987d5e1d-26d&articleId=3827075e-0e06-4447-8d1c-f99c78126ba2

certain moment profitability from new innovations and new sectors declines to the level acquired from older traditional sectors. Markets are saturated by technological products (everybody has a mobile phone, every small town has a railway station) and new capital investment in this originally new sector will not bring any above-average profit (e.g. the first railways connected the biggest cities with many potential passengers, later ones had ever smaller and smaller customer potential, and the level of profit from each new railway was therefore lower than from the previous one). At this moment economic stagnation and crisis begin – but a will to risk and to try something new emerges. The stagnation and crisis are therefore overcome by a new technological revolution with new innovations which will revitalize the economy. And this new technological revolution is the beginning of a new wave.

The internal structure of each long wave of technological innovations with economic implications is as follows: innovation phase – technological revolution (an economic revival after the crisis from the end of a previous wave) application phase (an economic boom) saturation of economy and society with innovations, impossibility of further extensive growth (an economic crisis)

I proposed a theory that during the modern age in society **six waves of technological innovations begun by technological revolutions** can be identified (one of them is a hypothetical revolution in the near future):

	Economic wave based on technological revolution	**Technological revolution**	**Period of technological revolution**	**Length of the whole wave of technological innovations**	**The leading sectors**
1.	1600-1780	Financial-agricultural revolution	1600–1740	180 years	finance agriculture, trade
2.	1780-1880	Industrial revolution	1780–1840	100 years	textile, iron, coal, railways, channels
3.	1880-1940	Technical revolution	1880–1920	60 years	chemistry electrotechnical industry, machinery
4.	1940-1985	Scientific-technical revolution	1940–1970	45 years	air-industry, nuclear industry astronautics synthetic materials, oil industry cybernetics
5.	1985-2015 (?)	Information and telecommunications revolution	1985–2000	30 years	telecommunications cybernetics informatics internet
6.	2015-2035 (?)	Post-information technological revolution (hypothetical)	2015-2025 ?	20 years?	biomedicine, nanotechnology, alternative fuel systems (hydrogen?)

Obviously, the years given are for guidance purposes only.

Thus defined, technological waves and technological revolutions fit fairly well into the system of Kondratiev long economic cycles[2]. My theory has even provided a potential explanation of such cycles or waves. (It is better to talk about waves than cycles because the word "a cycle" invokes an idea of a return to an original state, which is not correct. The starting point of each new wave is on a higher level than the starting point of the previous one.) Long-term economic growth has always been initiated by new technological innovations and lasted until the effect from them leveled out. The stagnation which then arose had to be overcome by a new technological revolution.

Reactions to the theory of waves of technological innovations

The article had a surprisingly wide response, probably because of the fact that Studia Politica Slovaca also has an internet version. It was quoted even in Brazil and New Zealand[3] and in contexts which were not at all anticipated, e.g. in an article on sub-atomic Physics[4]. In Netherlands my hypothesis became a part of one question for leaving examinations in Mathematics for local high schools in 2011[5]. This is an excellent proof of the extent of globalization and the importance which the internet has today. The internet currently is a mighty tool of democratization in the scientific and academic community. Only 15 years ago the importance of articles published in Studia Politica Slovaca would not have extended beyond the borders of one small Central European country, i.e. Slovakia. Somebody who was then writing about long economic cycles would have been restricted, in terms of the texts accessible for use, to a couple of the most prestigious journals from big and important countries (which are subscribed by most University libraries). Now, every scientist and journalist with the help of google can get plenty of materials placed on the internet all over the world. From this point of view, my article was an excellent example of how the internet (a technology of the last technological revolution!) has changed social, political and economic conditions.

It was interesting also to observe how my hypothesis has begun to live its own independent life and my original ideas have been creatively developed by other scientists and authors. Sometimes I had the feeling that my original ideas were over-interpreted.

In the first place, attempts were made to fit my theory absolutely mechanically to the Kondratiev economic cycles[6]. I am not sure that this is possible.

Also, a very bold hypothesis emerged that the potential post-informational technological revolution predicted by me would inevitably start in Asia[7] –which is something I did not say, although

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2 Freeman, C., L.: *As Time Goes By*, Oxford, Oxford University Press, 2001, p. 141

3 See: Ivan Barbosa da Cunha: Relatório e parecer prévio das contas anuais do governo do Estado do Pará, Tribunal de Contas do Estado do Pará, Belém – Pará, ISSN 2179-4618, júl 2010, http://www.tce.pa.gov.br/contas_governo_do_estado_2009/ACG2009.relatorio_e_parecer_previo.pdf a Enrico Tronchin: Disruptive innovation for sustained economic growth, Why New Zealand's innovation system should be open, distributed and inclusive of innovative users (2011), in The RaD Amplifier http://www.rndamplifier.co.nz/home/Tronchin%202011%20Disruptive%20innovation.pdf

4 Simon Berkovich: Obtaining inexhaustible clean energy by parametric resonance under nonlocality clocking (2010), http://www.chronos.msu.ru/RREPORTS/berkovich_prime_energy.pdf

5 Voorbeeldexamen vwo A, www.cve.nl/document/vwo_a_voorbeeldexamen

6 Ivan Barbosa da Cunha: Relatório e parecer prévio das contas anuais do governo do Estado do Pará, Tribunal de Contas do Estado do Pará, Belém – Pará, ISSN 2179-4618, júl 2010

7 *Dr. Prashant Wasankar: Riding the Bull,* http://webcache.googleusercontent.com/search?hl=sk&q=cache:klDlZK_Ez8UJ:http://wi.accordfintech.com/resume/930_Riding%20the%20Bull.pdf

I do not exclude it. Others did not understand the difference between invention and innovation. The invention is a making-up of something new which did not exist before. But as such, it may finish at the bottom of a drawer. Only an invention which is applied in practical life can be a real innovation. The source of such innovations may be not only inventions but also imitations taken, for example, from some other society. The economic and social consequences of innovations – regardless of their origin - are the same. From the 17th century, European society was the most developed world society and therefore all new inventions arose in Europe. In the more distant past this had not been true and many European innovations were in reality imitations of Arabic and Chinese inventions[8].

Several specialists tried to find some internal mathematical regularity in a process whereby the waves of technological innovations became shorter. The Dutch Ministry of Education in its examination question specified that each new wave has two-thirds the length of the previous one. A.A. Davydov from the Russian Sociological Association believes that the lengths of these waves can be derived from the Fibonacci sequence[9]. Personally, I have not seen any necessary relation between the waves and any exact mathematical formula, although on the other hand I do not exclude it. But I cannot as yet find any internal causality for it.

From this discussion I have taken inspiration to attempt to prolong a chain of the wave of technological revolutions further into the more distant past. Here I had already made the first step: as one of the few, probably, I had tried to take into consideration also development before the industrial revolution, with a description of the so called Financial - Agricultural revolution in 1600-1740 AD.

Attempt to find waves of technological innovations in pre-modern Europe

An attempt to identify waves of technological innovations in pre-modern Europe is an extremely demanding and risky task. As the first step, it requires us to dispense with the idea that technological innovations and cyclical fluctuations are typical only of the capitalistic economy. Here we must be aware that any attempt to analyze economic development and technological changes in pre-modern ages is confronted with a deficit of reliable information. There was no global economy and therefore it is not easy to recognize which economic and technological event was only "local" and which "global". What is more, economic dynamism was very slow and it is not easy to distinguish periods of economic growth or decline. There were no exact statistics. And if there were, the potential growth of GDP was usually on the level of a fraction of one percent. (In medieval agrarian economics a growth of 1% a year is regarded as rapid.)

The greater part of GDP was being produced in agriculture, i.e. in a sector for which a simple renewal of performance from the last year was typical. Trade and handicrafts (sectors with potentially higher dynamism) were marginal. It is not easy to define even a potential crisis and decline. The society was poor and its surplus production was only slightly over the level needed for biological survival. Even a small and temporary fluctuation could have dramatic consequences. From this point of view, the importance of external factors (crop failure, war, plague, earthquake etc.) could have been higher than internal economic and social processes.

[8] For the imporatnce of imitations, see: Shenkar, Oded: Copycats, Harvard Business School Publishing Corporation, 2010

[9] А.А.Давыдов: ВОЛНЫ ИННОВАЦИЙ И ЧИСЛА ФИБОНАЧЧИ: ОЦЕНКА ПЕРСПЕКТИВНОСТИ ГИПОТЕЗЫ http://www.ssa-rss.ru/files/File/KomitetyROS/SystemSociology/Fibonacci_Numbers.pdf

For agrarian societies, probably the best way to monitor technological progress and the economic growth dependent on it is to monitor their population growth and territorial expansion, although these come with a time lapse as a delayed reaction to significant technological and economic success.

The causality chain which we shall follow is not:
Technological innovations → economic growth,
But:
Technological innovations → economic growth → population growth → (potential) territorial expansion.

This makes our task even more challenging and the result uncertain. Population growth should follow an economic revival with some delay - perhaps of one generation. The sign of crisis might be a population decline and a collapse of political structures. As the main sector with about 90% of the labor force, even a small improvement in agricultural methods can have a significant result in all other sectors. For example, if productivity in agriculture grows by 10%, it releases about 8.2% of the labor force from agriculture. The difference seems to be very slight; however, it means a growth of the percentage of the labor force in non-agrarian sectors (handicrafts, trade, army, public service, intellectual professions) from 10% to 18.2%.

In spite of all obstacles, we can try to find technological and economic waves analogous to the waves in the modern economy even in times before 1600 AD.

The beginning of each wave should be related to some technological revolution, a revolution in the field of knowledge and in the organization of society, and its end with a protracted crisis.

Methodologically, the best solution is to concentrate on the territory of Europe and mainly on its most developed regions in the given time period. For example, during the greater part of the Middle Ages this meant western Europe (France, Germany, Italy, south England) and the nearby regions of Northern and Central Europe, i.e. the areas that in the 16th-19th centuries were the nucleus of our contemporary global civilization (and the global economy). If there is any continuity, it must be observable in this region, despite the fact that prior to the 18th – 19th centuries all technological and economic waves in Europe must have had mostly a regional character. Theoretically, for the period before the 12th century probably the most decisive and leading area was the Mediterranean.

Renaissance and Medieval technological revolutions

In the era before 1600 AD in pre-modern Europe two periods of specific and relatively quick technological changes can be identified rather easily:

the period of humanism and renaissance (c.1340- 1470 AD), which can be labeled "the Renaissance technological revolution" a period of changes (930-1200 AD) which is a completion of the periods designated as "Ottonian renaissance", "Phenomena of Europe of the year 1000 AD" and "Renaissance of the 12th century". The term "Medieval technological revolution" for this period is perfectly adequate.

Innovations introduced into society in these periods initiated economic and population growth. At the moment when the innovations became exhausted, or more precisely when they became

universal and it was no longer possible to obtain higher production by their ongoing diffusion (but only by a new level of intensification), the period of crisis occurred.

The Renaissance technological revolution and its long wave

This last pre-modern wave began precisely in the famous period of humanism and renaissance. That was a period when innovations were introduced in all sectors. The 14th century in Italy was characterized by an accentuated interest in classical wisdom and sciences as such. But the renaissance was not a simple return to antiquity, rather it was a new way of thinking and feeling[10]. The most practical innovations[11] were: eyeglasses, fire-arms, spinning wheel, clock (horologe), Hindu-Arabic numerals, perspective and oil-painting in art, etc. The water mills were significantly improved[12]. The Renaissance was probably the first period in which scholars perceived and hailed technological progress.

Progress was visible also during the first two-thirds of the 15th century. Improvement was achieved in the sectors of metallurgy (rolling of metal plates, blast furnaces using charcoal), mining (a conversion to a complexly managed deep mining), transport (introduction of four-wheeled carts instead of the previous two-wheeled carts) and in the contemporary "information sector" (letterpress, transportable watches with watch-springs, mathematical methods of navigation using an astrolabe, a compass and a quadrant).The most perceptible signs were the high towers of city halls and cupolas of cathedrals and large sails with three or four masts capable of enduring long transoceanic voyages.

We can locate this Renaissance technological revolution in the period 1340-1470 AD. Despite the technological progress, a boost in economic growth did not occur concurrently. The long and profound crisis, known as the Crisis of the 14th Century, lasted until the end of that century. But the causes of this prolongation were mainly extra-economic and extra-technological: the epidemic of plague in 1347-52 and its following waves, and also the beginning of the Little Ice Age. Europe needed a longer time to manifest new positive changes.

The real economic boost in Western, Central and Northern Europe came after 1420, and a population growth came after 1470[13]. (The Europeans probably needed to develop a resistance against plague.)

This period was terminated by the crisis of the second half of the 16th century, which was caused by the first inflation, religious wars and uprising. The crisis virtually drained Portugal and Spain, destroyed Italy, and exposed Central Europe to attacks from contemporary non-European powers: the Ottoman Empire and Muscovite Russia. Transoceanic voyages and colonization, originally very profitable "technologies", were in many aspects an actual disaster for Spain and Portugal….

[10] Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p.339

[11] See: Jílek, František, Kuba, Jozef, Jílková, Jaroslava: Světové vynálezy v datech, Praha: Mladá fronta, 1977, p. 47-50

[12] Landes, David S.: Bohatství a bída národů, Praha: B/B art, 2004, p. 65-68

[13] Grosse illustrierte Weltgeschichte, Parkland Verlag, Stuttgart, 1990, p.173

The wave of the medieval technological revolution

The period of 930-1200 AD also represented a specific revolution in technology and consequently in the economy. Traditionally, we know it as the Ottonian renaissance and the Revolution of the 12th century. Later, the intensive economic development and population growth of the 11th-13th centuries were replaced by the already-mentioned Crisis of the 14th century, when Europe was sorely afflicted by famine, epidemic, the schism in the Christian church, an escalation of conflict between nobility and burgesses, invasion of the Balkan peninsula by the Turks, and the Hundred Years' War, etc. This crisis continued even after the start of a new wave (the Renaissance technological revolution) in Italy, because there were external reasons for stagnation. Moreover, any time specification is only approximate, and geographical distances and obstacles together with insufficient transport connections, prevented a synchronization of economic development in all European countries. At the time when a new development started in Italy, the crisis could continue in France and Germany.

The medieval technological revolution took place approximately in the period 930-1200 AD[14]. It was an innovation phase of the economic wave which lasted until the 14th century. It started with the already mentioned Ottonian renaissance (936-1002) – a period of development of arts, culture and knowledge together with a growth of literacy among the higher classes, technical skills, stone architecture north of the Alps and production of books (manuscript). In Western Europe and the Byzantine empire, philosophy and logic, the basic instruments for recognition and analysis of the word, revived.

The 11th -12th centuries were extraordinarily rich in technological innovations[15]: the use of horse-collar and horse-shoes were being extended across Europe[16], water and wind mills were introduced. The great innovation was the introduction of paper-production… In the 12th century the use of building machines and siege engines became universal[17]. Many of these innovations were not inventions of Western and Central Europe in the 11th or 12th centuries (paper came from the Arabic lands and China and the water mill had been known even by the Romans), but only their massive application in practice made them real innovations.

There was also an agrarian revolution which ran its course in Western Europe during the second half of the 10th century: beans and other pulses and further types of vegetables began to be cultivated, dung began to be used for fertilization, and hereditary transfer of feudal fiefs in the possession of knights meant that they began to have an interest in further improvement of agricultural production[18].

In the military sector the phenomena of a heavily armored cavalry (knights) and also the crossbow (the first weapon with "machine" features) emerged. These innovations are proof of progress in metallurgy and technical skills. Italian sea navigation took its first steps (maritime republics such as Pisa, Naples, Amalfi, Venice), which resulted from improvements in ship building (new types of sail and crossbows). In 962 the western Roman Empire was reconstituted[19].

[14] See: Jílek, František, Kuba, Jozef, Jílková, Jaroslava: Světové vynálezy v datech, Praha: Mladá fronta, 1977, p. 40-44
[15] Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p. 202
[16] Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p. 216
[17] Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p. 208
[18] Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p. 71-73 and 213
[19] Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p. 64

During the 11th and 12th centuries medieval towns, as specific centers of trade and handicrafts with guilds and merchant associations, were developing from older marketplaces[20]. In the 12th century the Gothic architectural style with its specific novelties was spreading through Europe.

About the year 1000 AD and thereafter, we can observe the first self-evident signs of a modest economic prosperity and population growth. (We traditionally speak of the "Phenomena of Europe in the year 1000 AD" [21]). This population growth in Western Europe resulted in so-called internal colonization and the crusades[22]. In the 13th century this colonization movement also rolled through Central Europe. It was a result of improvements in agricultural production, above all the introduction of fertilizing and a three-field crop rotation. The agents of internal colonization were frequently the monasteries, which then had the best agricultural "know-how". Monasteries also played the role of centers of education and banking. The castle, as the centre of social secular life in the countryside, and the first universities, as institutional centers of knowledge and learned recognition (Bologne in 1119, Oxford in 1167[23]), were also established in this period. The universities furthermore produced scholastic philosophy. (Therefore we tend to describe this period as the "Renaissance of the 12th century").

An autonomous medieval city, a castle, a university (also independent and autonomous) and economicly important monasteries were specific "inventions" of the 12th century, which to some extent have lasted until the present day…. This innovation phase created an intellectual and technological basis for the entire civilization of the Middle Ages. The cliché of the "dark Middle-Ages", at least as regards practical technical skills, is not founded in fact[24].

For the 13th century and the beginning of the 14th century, what is typical is the development of practical applications of previous innovations rather than new inventions.

As noted above, the end of this wave (930-1340) was characterized by the cruel "Crisis of the 14th Century" [25], the beginning of which in Western Europe is associated with the "Great famine" in 1315-1317 AD. Overpopulation used to be seen as the cause of this, and apparently this is correct. But the notion of "overpopulation" is to be interpreted in the sense that the given territory could not provide a living for its inhabitants with existing technological facilities. That was precisely the case in the early 14th century, when existing technologies and methods did not provide more opportunities for an extensive growth (enlargement of field area), because the success of the internal colonization from the previous period meant that no more free soil was available. As grain was being cultivated even in less suitable localities, it is obvious that average crops started to decline[26]. The existing model of economic development was already exhausted by about 1300 AD[27]. If during the 12th and 13th centuries there had existed opportunities of emigration to the Outremer, Iberian peninsula and Central Europe, now it was no longer possible… A new increase

[20] Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p. 90

[21] Grosse illustrierte Weltgeschichte, Parkland Verlag, Stuttgart, 1990, p. 141 and Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p.71

[22] Horská, Pavla, Kučera, Milan, Maur, Eduard, Stloukal, Milan: Dětství, rodina a stáří v dějinách Evropy, Praha: Panorama, 1990, p.159-161

[23] Folta, Jaroslav, Nový, Luboš: Dejiny prírodných vied v dátach, Bratislava: Smena, 1981, s.55

[24] Landes, David S.: Bohatství a bída národů, Praha: B/B art, 2004, s.65

[25] http://en.wikipedia.org/wiki/Crisis_of_the_Late_Middle_Ages

[26] Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, s. 215

[27] Horská, Pavla, Kučera, Milan, Maur, Eduard, Stloukal, Milan: Dětství, rodina a stáří v dějinách Evropy, Praha: Panorama, 1990, s. 175

of agricultural production was possible only by means of further new methods and technologies. After 1310 AD the standard of living declined[28]. The plague of the "Black death" therefore affected populations which were already weakened. The crisis was so deep that it touched even the next innovation phase (the Renaissance technological revolution).

Older waves of technological innovations

These two pre-modern waves can be perfectly ranked with the 5 modern waves after 1600 AD. Thereby they create a chronologically continuous chain of European and later world-wide technological and economic development since the 10th century. Their indicative time-spans (260 and 410 years) seem to confirm the hypothesis that each new long economic wave based on some technological revolution lasted about 2/3 as long as the previous wave – or, the length of each previous wave was 1.5 times that of the following one.

It is interesting, while seemingly irrelevant, that the number 1.5 is relatively very close to the number 1.618 which represents the so called golden ratio (*sectio aurea*). And the golden ratio has a strong relation to the Fibonacci sequence:

$$\lim_{n\to\infty} \frac{F(n+1)}{F(n)} = \varphi.$$

Perhaps the regularity in a process of shortening of the long waves of technological innovations really has something in common with the Fibonacci sequence, as Davydov suggested[29] - simply because it has some relation to the growth of wealth in society, and the growth of wealth or productivity (an acceleration of economic growth) theoretically could have some relation to the Fibonacci sequence. It could express, for example, some principles in the process of accumulation of capital and knowledge….

By means of the supposed ratio 1:1.5 it is possible to create the following table, if we start from the wave of the financial-agricultural technological revolutions (1600-1780 AD):

	Period of economic wave based on technological revolution	Length of the whole wave of technological innovations
E	1330-1600 AD	270 years
D	925- 1330 AD	405 years
C	315-925 AD	610
B	600 BC – 315 AD	915
A	1915-600 BC	1370

[28] Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, s. 121-123

[29] А.А.Давыдов: ВОЛНЫ ИННОВАЦИЙ И ЧИСЛА ФИБОНАЧЧИ: ОЦЕНКА ПЕРСПЕКТИВНОСТИ ГИПОТЕЗЫ http://www.ssa-rss.ru/files/File/KomitetyROS/SystemSociology/Fibonacci_Numbers.pdf

The result is surprising and shocking. Only a superficial knowledge of European history is enough to show that these waves constructed on a sheet of paper rather well fit in a real framework of the historical development of Europe! Waves E and D are indubitable: they represent the already described waves of the Renaissance and medieval technological revolutions.

However, even waves C and B, and probably even wave A, can be incorporated into the timeline of European history.

Wave C

Wave C is not as clearly defined as waves E and D. Unlike the later waves, a traditional interpretation of history does not identify it with "progress", in the sense of a progressive technological and mental revolution. The period of 400-1000 AD is, as traditionally viewed, almost automatically associated with "Dark Ages". With the exception of professional historians, the public believes that it was a period of decline and barbarism. But such a picture is false.

The European continent in this period went through a complex and diversified development. Our contemporary ethnic and political map of Europe is to a significant extent a product of this period. The perception of the period of 400 -1000 AD as a time of darkness is already obsolete[30].

It is generally accepted that European society was afflicted by a severe crisis at the end of wave C, i.e. in the period 830-930/950 (the definitions of periods are not firm, and again we see a diffusion of the crisis into the next innovation phase).

During this crisis the central authority (represented by the Frankish empire) declined[31], and Europe was exposed to naval attacks by Arabians and Vikings and land invasions by Hungarian tribes, which it could only scarcely resist. (Only the improvement of heavy cavalry in the following period afforded protection.) In comparison to the Carolingian period, a general decline could be observed[32]. The crisis was overcome only about 1000 AD.

It seems to be more difficult to identify a potential period of innovation at the beginning of wave C, with a potential application phase (a boom) sometime in the middle of it. Nonetheless these existed, and the Dark Ages were not so black as they are painted…. We should not uncritically accept the judgments of Roman and Italian Renaissance scholars from the past.

Looking only at the Roman state, we can see that about 300-315 AD Romans succeeded to some extent in managing the so called "Crisis of the 3rd century" which threatened the integrity of the Roman empire. But on the other hand, this crisis and the way in which it was managed brought the real end of the antique style of life. The Romans introduced three important social innovations. The first one is known universally: it is Christianity, which represents an ideology and a life style in many aspects radically distinct from the traditional Roman life. Christianity also had consequences for economic and family life (pro-work and pro-natal). The second change was an expansion of noblemen's country estates. It is traditionally described as a decline of cities and city life, but in reality it must have been an economically effective adaptation. The third (political) change was a change of political regime: the Roman Empire introduced a new style of rule- the dominate- and became administrated by its net of bureaucratic structures, and

30 See: Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991

31 Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p. 67

32 Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p. 63

all fictions about political continuity with a small city republic were dissolved. Christianity, the rural lifestyle, monarchy, and a nostalgia for the late Roman empire, were elements of European culture during the whole of the Middle Ages. But these Roman reforms did not prove to be effective and a transformation to smaller and more flexible political units followed. These new barbarian kingdoms were characterized by lower expenses and a smaller tax burden[33].

While the cultural transformation was realized within the borders of the Roman Empire, in Central, Eastern and Northern Europe an important revolution in material technologies took place outside of the empire's limits [34]. It is interesting that while the majority of European cultural innovations traditionally came from South Europe (literature, religion, philosophy, law, mathematics), Central, Western and Northern Europe were traditional places of material technological inventions and practical skills, even in periods which, under the influence of Greek and Roman written sources, we tend to regard as barbarian…. Perhaps this resulted from the distribution of raw material resources (iron ore, coal, copper) in Europe…

During the period 300-700 AD these "barbarians" invented several improvements in iron metallurgy, damaskieren, new methods in the processing of gold and leather… Goths and other Germanic people started to use long iron swords.

The Germans in Gaul introduced a heavy plough with wheels, an earth-board, a coulter and a mouldboard. (Romans would plough with a simple wooden ploughshare!) Now it was possible to cultivate even heavy soils, which were ignored by Romans and Celts. It seems that the number of inhabitants of Frankish Gaul was doubled in comparison the Roman period. An economic revival due to settlements of barbarians was noticed even by Roman authors sometime at the beginning of the 5th century (Chlorus)[35]. In Northern Europe the first technical conditions for the future Viking navigation were established (a new type of ship: a longboat suitable for oceanic voyages). In Europe horse stirrups were introduced from the East. During the 7th century in Western Europe a net of monasteries emerged as centers of production, culture and education. A very interesting civilization arose also in Ireland and Anglo-Saxon Britain during this period (again, in comparison with the Mediterranean they did not represent "progress", but in the conditions of Northern Europe they did, and very dramatically).

In the 6th century Ostrogothic Italy, Visigothic Spain and Frankish Gaul manifested several signs of a revival and perhaps also prosperity. The downfall of the Roman state in many aspects meant economic relief for the Western provinces[36]. However, the potential positive impacts of this technological revolution were overshadowed by the Byzantine-Germanic and Byzantine-Slavic wars, the Moslem invasion in the 7th century, a deterioration of climate between 500 and 900 AD (a cold and wet period) and a cyclic epidemic of plague which had its onset in 541 and lasted up to about 800 AD[37]. Probably the main economic and demographic success of new technological innovations was in preventing the situation from becoming even worse. This was the reason why positive economic and technological changes from the period are not generally known. But the 6th, the 8th and perhaps the first half of the 9th century were periods of demo-

33 Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p. 46

34 See: Jílek, František, Kuba, Jozef, Jílková, Jaroslava: Světové vynálezy v datech, Praha: Mladá fronta, 1977, p. 38-42

35 Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p.34

36 Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p. 47

37 Horská, Pavla, Kučera, Milan, Maur, Eduard, Stloukal, Milan: Dětství, rodina a stáří v dějinách Evropy, Praha: Panorama, 1990, p.145

graphic growth in Gaul, Spain and other European regions, which would not have been possible without some kind of economic prosperity[38].

What is more, we should perhaps change our perception of the Migration Period and the collapse of the Western Roman Empire. Most modern European nations are not ethnically and politically successors of the Romans but rather descendants of Germanic tribes, Slavs and Celts who had lived behind the *Limes Romanus*. Even states like Spain, Italy and France arose politically from the barbarian kingdoms of Visigoths, Longobards and Franks from the "Dark Ages"! But in spite of this, we traditionally lament the fate of the Roman Empire and do not celebrate the victories of our forefathers over the Romans…

Therefore we should try to find signs of technological revolutions in 300-700 AD, above all in the world of the Germanic peoples and Slavs: the technological revolutions that helped them to defeat the Romans. Such an attitude is logical even from the point of view of methodology, because all technological revolutions and their economic waves described above were associated with the territory of Western Europe and the nearby regions of Central and Northern Europe.

Some inventions of European "barbarians" have already been mentioned. Nevertheless, the real scope of the changes which emerged in the societies of Germans and Slavs in the 4th-7th centuries is surprising. The change was so striking that historians have called the 4th century a "Germanic revolution" [39]. In this century, in the Central European and East Europe territories of the Germanic people and their Slavic neighbors, important changes in technologies and social organization occurred. Weapons and armors were improved, agrarian production was increased, and new political units arose. There was now a clearly defined group of professional warriors in the society. Agriculture in Central and Northern Europe in this period abandoned the extensive system of "Celtic fields" with a short period of cultivation and a long period of fallow land, and went over to the system of two-field crop rotation combined with fertilizing and stock-raising. (Slavs experienced the same process one or two centuries later than Germans.) Glass-making was also significantly improved. Most Germanic tribes in the 4th century adopted a new ideology (Christianity) and a new writing type (runes)[40]. Perhaps none of these novelties were really the Germans' or Slavs' own inventions, but their introduction into Germanic and Slavic areas had the character of social and technological innovations. (The hypothetical center of these technological and social changes could be theoretically identified with the area of Chernyakhov archeological culture in present-day Ukraine.)

The Germanic peoples and Slavs fell behind the Greeks and Romans from the point of view of political organization and theoretical and literary erudition. However, that was not necessarily true in the area of practical skills and technologies. Worse climate conditions undoubtedly made them work at technological improvements. They were also able to utilize inspirations not only from the Greek-Roman world but even from Iran and the steppe areas inhabited by nomads. These changes enabled the Germanic peoples in the 5th century and the Slavs in the 6th- 7th centuries to gain control of practically the entire European part of the Roman empire (Germans: Britain, Gaul, Spain, Italy, Slavs: Noricum, Pannonia, Ilyria, and other Balkan provinces including Greece). The development of the Slavs during "Dark Ages", as compared with the Germans,

[38] Horská, Pavla, Kučera, Milan, Maur, Eduard, Stloukal, Milan: Dětství, rodina a stáří v dějinách Evropy, Praha: Panorama, 1990, p.154-156

[39] Heather, Peter: Gótové, Praha: Nakladatelství Lidové noviny, 2002, p.73-103

[40] Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p.35

has been less adequately described, but in the period 400-600 AD they must have gone through dramatic changes which enabled an originally small population to settle the whole of Central and Eastern Europe. Probably they, like the Germans before them, started to use a new model of plough and new methods of agriculture[41]. During the Migration period the Slavs in written records were overshadowed by the Germanic tribes and groups, but it was precisely the Slavs (together with the Anglo-Saxons) whose territorial gains have proved to be stable. They are, even today, the most numerous language group in Europe and live on 55% of the continent. It is clear that in the conditions of Central and Eastern Europe they must have had some advantages which helped them to be successful in a brutal competition.

From the point of view of technologies we could describe the collapse of the Roman empire and the events of the Migration period as a situation where a civilization with a high cultural level succumbed to societies which were not so cultured, but on the other hand had better material technologies (barbarian long sword versus Roman short sword; an iron plough; better processing of iron) [42] and for the given conditions a more effective (and simpler and cheaper) model of social organization. The end of the Roman empire might have been a decline from the cultural point of view, but from the point of view of material technologies it was progress.

Roman authors (Salvianus) themselves emphasized the fact that the establishment of Visigothic and Frankish kingdoms was welcomed by local inhabitants, because it meant a reduction of the tax burden and elimination of the corrupt Roman bureaucratic state machinery….[43]

This technological revolution could be named "the Germano-Slavic technological revolution". The application phase of its wave was in the 8th and at the beginning of the 9th century (the rule of Charlemagne). The crisis came approximately in the second half of the 9th century…..

Wave B

Wave B should be placed in the period bounded by the years 600 BC and 315 AD. Fascinatingly, it fits into the era of both Greek and Roman classical civilization in the Mediterranean and a less well-known but also important development in Central and Western Europe.

We can locate the innovation phase of this wave in the period 700-200 BC, and for the area of the Mediterranean this needs no further commentary. All of the wonders of classical and Hellenistic civilization (including technical innovations) were invented at this time[44]

Notable development proceeded also in areas outside of the Greek world. The Etruscan civilization in the 8th-7th century dramatically increased iron production. However, probably the most radical change was located north of the Alps. In 700-200 BC Celts living originally in south Germany, Bohemia, Austria started to use iron, which from the point of view of archeology is documented as the beginning of a new Hallstatt culture[45]. The Celts were inventors of numerous

41 Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p.202

42 Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p.33

43 Heather, Peter: Gótové, Praha: Nakladatelství Lidové noviny, 2002, p. 191-199 a Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p. 33-35

44 Folta, Jaroslav, Nový, Luboš: Dejiny prírodných vied v dátach, Bratislava: Smena, 1981, p. 36-38

45 Grosse illustrierte Weltgeschichte, Parkland Verlag, Stuttgart, 1990, p.60 a 78

iron tools (used practically without changes until now: scissors, saw, hammer, tongs, etc.)[46] and spread them throughout Europe. This change affected Central a Western Europe and had more immediate impact on the economy than the works of classical philosophers.

This innovation wave in which the main role was played by Celtic iron smiths and Greek philosophers might be called the Celtic and Greek technological revolution.

After the period of Hellenism the innovation capacity of the classical civilization dramatically declined[47]. When the Roman Empire reached the limits of the area in which the agricultural methods developed in the Mediterranean could be applied, further expansion was no longer possible, and the empire had no further opportunities to obtain new natural resources (which meant that the extensive mode of economic development was reduced). As a result of this situation, a crisis and an internal struggle followed (180-300 AD). This crisis is known also as the Crisis of the Third Century (211-284)[48] and afflicted the Western provinces above all. The traditional classical form of social life (the classical city) was never again regenerated. In the period 150-400 AD the population also declined in the Roman empire. The general sign of depopulation was abandoned fields (*agri deserti*)[49]. This decline was overcome precisely by the technologies which barbarians brought with them. From the point of view of "barbaric" Western and Central Europe, the crisis should be seen in the penetration of Romans and Germanic peoples from the north and a virtual collapse of the Celtic civilization in 60 BC- 200 AD.

Wave A and the hypothetical prehistoric waves

It is not easy to define the wave that theoretically should have run its course within the broad limits 1900-600 BC. This wave was probably initiated by a technological revolution which was a result of infiltration of Indo-Europeans from the Don and Volga steppes. The consequent technological revolution (1900-1100 BC) introduced in Europe horse-breeding, chariots and later the use of iron[50]. With the help of these, in 1600-1000 BC they conquered Europe and Iran and started to infiltrate into India and the Middle East. This technological revolution "of horse and iron" could be called the Indo-European technological revolution.

As for preceding waves in the past: the potential waves from 4000-1900 BC and 7000-4000 are only hypothetical. We cannot exclude the possibility that they could be harmonized with some real historical progress in agriculture, bornze metallurgy, handicrafts etc, but unclear dating and the slow diffusion of innovations practically eliminate the possibility of "tracing" clearly defined periods of technological revolutions, economic booms and crisis. This is a question for archaeologists….

46 Holodňák, Peter: Keltové zahájili „technickou revoluci", In: Historie, Praha, VII-VIII/2011

47 Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p. 29

48 Grosse illustrierte Weltgeschichte, Parkland Verlag, Stuttgart, 1990, p. 100 and Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991. p. 29

49 Le Goff, Jacques: Kultura středověké Evropy, Praha: Odeon, 1991, p. 44

50 See: Cotterell, Arthur: Vozataj, Praha: BB/art s.r.o., 2006

Mathematical relations in the duration of economic waves based on technological revolution

It seems that a stable mathematic relation in the duration of modern and pre-modern economic waves based on technological revolutions can be found.

The duration of every wave represents approximately 2/3 (or 1/1.618) of the previous wave's duration. It is not easy to find a real principle or economic relations behind this regularity.

The first possible assumption might be that it has something to do with a growth of GDP and an accumulation of capital and knowledge.

A table of approximate values of GDP per capita in terms of purchasing power parity for Western Europe and Great Britain (one of the most innovative and developed economies in 1340-2000) at the beginning of the technological revolutions looks like this[51]:

	Year	Western Europe GDP (PPP) per capita	Ratio to the value from the previous cycle	United Kingdom	Ratio to the value from the previous cycle GDP (PPP) per capita
D.	930	420		400	
E.	1340	600	1.43	680	1.70
1.	1600	889	1.48	974	1.43
2.	1780	1 100	1.23	1400	1.43
3.	1880	2 000	1.81	3500	2.50
4.	1940	4 000	2.00	6000	1.70
5.	1985	14 000	3.50	16 000	2.60
6.	2015(?)	23 000	1.60	26 000	1.65
Average ratio:			1.86		1.85

(Values of GDP per capita in terms of purchasing power parity and identifications of the crucial years are merely approximate.)

We can create a very similar table for other European countries.

It is not easy to specify what these values tell us. On a very hypothetical level, we could perhaps guess that a new technological revolution and a new long economic wave start when GDP per capita in terms of purchasing power parity reaches the level of 1.4-2.5 times the GDP per capita (PPP) from the beginning of the cycle. The average value of this ratio is 1.85. (But, of course, it is an exact number based on imprecise values.) In 11 out of 14 values this ratio is in a much narrower framework of numbers ranging from 1.23 to 2.00. The average value of this ratio calculated for these 11 values is 1.59 for Western Europe and 1.58 for UK. It is interesting that these values are very close to the so-called golden ratio (1.618). Does it predicate anything on principles of accumulation of capital required for the start-up of a new technological revolution? On the basis of existing research, it is not possible to give a definite answer… We can see that the periods of 1780-1880 (the wave of Industrial technological revolution) and 1940-1985

[51] Datas are from: http://en.wikipedia.org/wiki/List_of_regions_by_past_GDP_(PPP)_per_capita#cite_note-0, based on Maddison, Angus: Countours of the World Economy, Oxford University Press, 2007

(the wave of the Scientific-technical revolution) are exceptions. Perhaps these two technological revolutions represented much bigger changes than the other usual technological revolutions? If they provided better (more efficient) new technologies than usual, why did these waves not last a shorter time? The potential explanation is that, more than on a growth of production, the economic wave depends on the speed of saturation with new technologies. In this case, even in the periods 1780-1880 and 1940-1985 it was necessary to wait until the market was saturated (at its own pace, independent of the quality of technology) and only then could the new revolution start. However, the technologies of these two technological revolutions were so radical that they provided the opportunity for extraordinary economic booms.

Does the regularity in shortening of long economic cycles depend more on a potential regularity in acceleration of the speed of saturation with new technologies than on the accumulation of capital or knowledge and the productivity of technologies? It is hard to decide….

It is possible to divide the given groups of cycles into two subgroups: the era of agrarian society and the era of industrial (modern?) society, with different "rhythms" of technological and economic development. In Europe until 1780 the ratio between values of GDP (PPP) per capita at the start of each wave was about 1.38-1.52, while in industrial modern societies this ratio is on average 2.1-2.2. Again, it is not easy to say why. Does it mean that an industrial society needs to be "richer" than an agrarian society to be able to start the "engine" of a new technological revolution? Perhaps as in conditions of an industrial modern society new technologies do require much higher capital investments?

Even if we cannot as yet find rational grounds for mathematical regularity in the process of shortening of long economic waves, this is not an argument for denying its existence. We know several more mathematical regularities in various different scientific fields which are based only on empirical statistics and not on rational explanations. For example: the well-known Moore's law describes a long-term trend in the history of computing hardware. It says that the number of transistors that can be placed inexpensively on an integrated circuit doubles approximately every two years. The similar Kryder's Law says the same for the capacity of hard disks. Moore's law is confirmed empirically by developments in 1971-2010. Both laws might express some unknown internal dynamism in the development of computer technologies. In the field of astronomy we know the Titius–Bode law (a hypothesis that planets in the solar system orbit at semi-major axes, the lengths of which are functions of planetary sequence), but here too we do not know its physical explanation.

Conclusion

We can regard it as a confirmed fact that technological innovations do not come continually but that they have a higher concentration in certain periods (technological revolutions).

These technological revolutions are the starting triggers of long waves of economic growth, which terminate with crisis.

The theory of technological revolutions and long economic waves can be applied even to pre-modern European societies.

Each new wave is shorter than the previous one, due to an acceleration of technological and economic progress.

From empirical data it is possible to formulate a hypothesis that there is a certain regularity in this process of shortening: the duration of each new wave is about 2/3 of the previous one. (This ratio may also be coincidental.) It is not possible to identify the rational causal relation.

There is also a regular correlation in the duration of the innovative phase (technological revolution). The length of the innovative phase represents about 50-65% of the duration of the whole wave.

Pre-modern and modern waves can be ranked in the two following tables. They mostly concern Western and Central Europe and the so-called western islands. From the time when the whole world was integrated into the political and economic system which arose in Europe (19th century), they have been applicable universally. (Unlike the theoretical calculations, time periods here are rounded):

Pre-modern technological waves:

	Economic wave based on technological revolution	**Technological revolution**	**Period of technological revolution/ (fraction of the duration of the whole wave)**	**Length of the whole wave of technological innovations/ (a ratio of durations of given and previous revolutions)**	**The most important innovations**
	7000-4000 BC	hypothetical		3000 years	agriculture?
	4000-1900 BC	hypothetical		2100 years	bronze metallurgy?
A.	1900-700 BC	Indo-European technological revolution	1900-1100 BC (0,56)	1200 years	horse-breeding, chariots, iron
B.	700 BC- 300 AD	Celtic and Greek technological revolution	700-200 BC (0,50)	1000 years (0,83)	iron tools and weapons, Greek classical civilization
C.	300-930 AD	Germano-Slavic technological revolution	300-700 (0,63)	630 years (0,63)	two-field crop rotation, improvements in iron metallurgy heavy plough, longboat, horse stirrups
D.	930-1340 AD	Medieval technological revolution	930-1200 (0,66)	410 years (0,65)	horse-collar, horseshoes, water and wind mills, paper, beans, fertilization, heavy cavalry, crossbow, three-field crop rotation, university
E.	1340- 1600 AD	Renaissance technological revolution	1340-1470 (0,50)	260 years (0,63)	eyeglasses, firearms, spinning wheel, Hindu-Arabic numerals, blast furnace, letterpress, watch, astrolabe, compass, oceanic sails

Modern technological waves :

	Economic wave based on technological revolution	Technological revolution	Period of technological revolution/ (fraction of the duration of the whole wave)	Length of the whole wave of technological innovations/a ratio of durations of given and previous revolutions)	The leading sectors
1.	1600-1780	Financial-agricultural revolution	1600–1740 (0,77)	180 years (0,69)	finance agriculture, trade
2.	1780-1880	Industrial revolution	1780–1840 (0,60)	100 years (0,55)	textile, iron, coal, railways, channels
3.	1880-1940	Technical revolution	1880–1920 (0,66)	60 years (0,60)	chemistry electrotechnical industry, machinery
4.	1940-1985	Scientific-technical revolution	1940–1970 (0,66)	45 years (0,75)	air-industry, nuclear industry astronautics synthetic materials, oil industry cybernetics
5.	1985-2015 (?)	Information and telecommunications revolution	1985–2000 (0,5)	30 years (0,66)	telecommunications cybernetics informaticsinternet
6.	2015-2035 (?)	post-information technological revolution (hypothetical)	2015-2025 ?	20 years?	Biomedicine, nanotechnology, alternative fuel systems (hydrogen?)
7.	2035- 2048 (?)	(hypotetical)		13 years (?)	

It is interesting that wars did not have an impact on long-term trends of economic and technological development. The reason probably is that, on the one hand, wars destroy human lives and material values, but on the other hand they stimulate the introduction of technological innovations and political reforms. From the long-term perspective, they are also a catalyst of social progress, because wars are mostly won by societies with a more effective model of organization and with a better level of utilization of material and human resources. Probably epidemics and climatic changes have a greater impact in terms of modifying internal economic processes.

The second, third and fourth long waves of the modern age were rather well described by modern economists as “long economic cycles” as conceived by Kondratiev, Schumpeter and Freeman.

The theory of long economic waves presented in this article can be applied with surprising exactness to the economic development of Western and Central Europe and the western offshoots (Australia, etc.) after the 10th century AD. And with some speculation, also to a more distant past.

From the 18th century, what was originally only a European regional political and economic system has been extended to the whole world in a process of colonization and globalization, and local regional systems have been suppressed. We can say that the contemporary world is

economically, politically and ideologically[52] an enlargement of this European system. Therefore the new world system follows the "rhythm" of waves which had been limited only to Europe in the past. From this point of view, even the Indians, Japanese and Chinese have become "Western Europeans". (For Americans, Brazilians, Russian, Australians etc. this is not disputable: they represent only an enlargement of the European civilization.) The originally regional waves became universal, because the civilization in which they took place became global.

If Europeans had not been successful in the 16th-19th centuries, we might have lived in accordance with "Chinese" or "Indian" long economic waves. A new technological revolution genuinely may (but also may not) start in India or China, but simply because these countries are now parts of the "Western world" in the broadest meaning of this phrase: they have adopted Western technologies, science, economic principles, political ideas, hobbies, styles of life and dress…

[52] Both Chinese states: People Republic of China and the republic of Chinja on Tawain are ruled by European („Western") ideologies: the communism and liberal democracy.