Why is that Europeans Ended Up Conquering the Rest of the Globe? Prices, the Military Revolution, and Western Europe's Comparative Advantage in Violence

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Abstract

Preliminary data from England and France show that the relative price of artillery, handguns, and gunpowder declined between the fourteenth century and the eighteenth century. Prices fell relative to the cost of factors of production, and the price decline suggests that the military sector of western European economies experienced sustained technical change before the Industrial Revolution–a claim in accord with qualitative evidence from research on the late medieval and early modern military revolution. The price data shed new light on this revolution and point to a potential explanation for why western Europe developed a comparative advantage in violence over the rest of the world.

In recent years, historians, economists, and other social scientists have energetically debated when Western Europe first forged ahead of other parts of the world–in particular, advanced parts of Asia–in the race toward economic development. Was it only after 1800, with the Industrial Revolution well underway, that Western European per-capita incomes, labor productivity, or technology diverged (Pomeranz, Goldstone, Bin Wong)? Or was it earlier, before the Industrial Revolution (Van Zanden, Broadberry)? And what was the cause of the divergence? Was it beneficial institutions, which encouraged investment and the accumulation of human and physical capital (North and Thomas; North and Weingast; Acemoglu, Johnson, and Robinson)? The Scientific Revolution and the Enlightenment, which spread useful knowledge and political reform (Mokyr)? Or was it simply an accident that the Industrial Revolution started in England and then quickly spread through Western Europe (Clark)?

In this debate, one area in which Western Europe possessed an undeniable comparative advantage well before 1800 seems to have been overlooked–namely, violence. The states of Western Europe were simply better at making and using artillery, firearms, fortifications, and naval warfare than other advanced parts of the world and they had this advantage long before 1800. By 1800, Europeans had conquered some 35 percent of the globe, and they controlled lucrative trade routes as far away as Asia (Parker, 5). Some of the land they subjugated had come into their hands because of new diseases that they introduced into vulnerable populations, and in these instances–in the Americas in particular–their advantage was not military, but biological (Diamond). But other inhabitants of densely populated parts of Eurasia would have had the same biological edge. Why was it therefore the Western Europeans who took over the Americas, and not the Chinese?

That is not the only evidence for Western Europe's military advantage before 1800. States in other parts of the world–the Ottoman Empire, for instance–certainly possessed firearms and ships equipped with artillery, but by the late seventeenth century, if not beforehand, nearly all of them had fallen behind.[1] In 1572, cannon founders in Venice found that guns captured from the Ottomans during the naval battle at Lepanto could not be reused. They had to be melted down–and new metal had to be added to the mixture–because, in their words "the material is of such poor quality." (Mallett and Hale, 400). For an economist, that amounts to strong evidence from revealed preference about how much better Western European weapons had become; records of the export trade point in the same direction. By the seventeenth century, Western Europeans were shipping actual weapons to Ottomans, despite a papal ban on military trade with the Muslims (Parry). And from renegade European gun founders in the sixteenth century to Napoleonic officers the early 1800s, experts from Western Europe were hired in Asia to provide needed expertise in gun making, tactics, and military organization. In seventeenth-century China, even Jesuit missionary were pressed into service to help the Chinese Emperor make better cannons. The evidence for Western Europe's military prowess is strong enough to have convinced some of the historians who argue against any divergence between Western Europe and advanced areas of China before 1800. Although they would argue that Western Europe was not wealthier or more developed than rich areas of China, they would acknowledge that its military technology was more advanced (Bin Wong, 89-90; Pomeranz, 199-200).

At first glance, at least, it is surprising that western Europe had eked out a military advantage before the Industrial Revolution. Firearms and gunpowder originated in China and spread throughout Eurasia. States outside Western Europe had the new weapons and could become, for a while at least, proficient at manufacturing or exploiting the new military technology. The Ottomans, for instance, made high quality artillery as late as the 1500s, and the Japanese independently discovered, at about the same time as Western Europeans, the key tactical innovation (volley fire) that allowed infantry soldiers with slow loading muskets to maintain a nearly continuous round of fire.[2] Yet by the late seventeenth century, if not before, Chinese, Japanese, and even Ottoman military technology and tactics lagged far behind what one found in western Europe.

Apart from Carlo Cipolla pioneering effort some 40 years ago, economist historians (and social scientists in general) have not paid much attention to western Europe's growing comparative advantage in violence before the Industrial Revolution and the concomitant advances in military tactics and technology. The subject has attracted a number of talented military historians and historians of technology, but their work, on what they call the "military revolution" tends to leave out the economics. What happens if we look at the price data and ask what they tell us about western Europe's military growing military strength?

The price data, it turns out, offer some novel insights into the debates military and technological historians have had over the nature of the military revolution. They also point to a possible explanation for Western Europe's comparative advantage in violence. Even more important, however–at least for economic historians–the price data suggest that in the military sector of western European economies it was possible to sustain technical change for centuries–a feat virtually unknown elsewhere in pre-industrial economies.

The Evidence from Prices

Suppose that we confine ourselves to examining the cost of producing the new weapons that played a key role in military revolution–artillery, handguns, and gunpowder. The question would be whether the cost curves for producing these military goods are declining, once we take into account changes in other prices. If the cost curves are shifting down, then the production functions for the weapons are moving out, and the firms producing them are undergoing technical change.

This sort of exercise certainly has its limits. To begin with, it likely to underestimate the magnitude of the military revolution. Ideally, we should be measuring the cost of attaining a given level of military effectiveness, but we are instead simply gauging the cost of producing certain military products, and only doing that once the products are available for sale in sufficient numbers to leave a historical record. Restricting our attention to the products leaves out tactical innovations, better training, and improvements in provisioning armies and navies and in raising money to pay for military operations. And by omitting advances in ship construction and naval strategy, it glosses over a great deal of naval warfare, where western Europe's comparative advantage was probably greatest. Similarly, waiting until prices appear in the historical records is likely to omit the initial drop in the cost of producing the weapons right after they were first introduced but before sales and cost estimates left much of trace in the archives.

In an ideal world, we could put together a long, homogenous series of prices for artillery, handguns, and gunpowder in countries across the world. Unfortunately, we are not at that stage yet, in large part because prices for military goods–guns in particular–are hard to come by.[3] For the moment at least, we have to make do with somewhat fragmentary price data from two European countries only, France and England.

What then do the price data for artillery, handguns, and gunpowder from France and England tell us? Let us begin by assuming that each of these goods is each produced by cost minimizing firms that, at any fixed time t, have identical constant returns production functions for each one of the goods; this seems reasonable in a world that was by and large without large scale manufacturing firms. Let us suppose too that the factor and product markets were competitive. The latter assumption could cause some concern, because state could conceivably act as a monopsonist or regulate the markets for weapons and for the factors of production used in making them. But it is probably not too unreasonable, at least in France and England. There were many buyers of arms and gunpowder besides the state: military contractors bought them, as did privateers merchants, city governments, and even colleges. Production was for the most part in the hands of a large number of contractors and independent craftsmen who competed with one another, and what regulation existed was probably not effective.[4]

If we accept these assumptions, then the cost of producing a quantity y of one of our military goods at time t is then $y\,c(w, t)$, where $c(w, t)$ is the cost of producing one unit of our military good and w is the vector of factor prices. The function $c(w, t)$ depends on time to allow for the possibility of technical change; if there is technical change, then $c(w, t)$ will be a decreasing function of t for any given w.

Since the price p of the good produced will be the marginal cost, or $c(w, t)$, we could (at least in theory, and provided that our assumptions hold) test for technical change by regressing the price of each of our military goods on w and t. All we would have to do is to choose a suitable functional form for $c(w, t)$. Ideally, we might want to use some flexible functional form, but lack of enough price observations would probably limit us to using a Cobb-Douglas function, which would at least be a first order approximation to $c(w, t)$. If we adopt the Cobb-Douglas functional form, and if the technology changes at a constant rate and is Hicks-neutral, then

$$\ln (p) = \ln (c(w, t)) = a - bt + s_0 \ln (w_0) + \ldots + s_n \ln (w_n) + u \qquad (1)$$

where a is a constant, $b > 0$ is the rate of technical change, u is an error term, and s_i and w_i are the factor share and price of the i-th factor of production. Equation 1 is equivalent to assuming that the good's production function is Cobb-Douglas with a multiplicative constant that grows at rate b. Because the factor shares have to add up to one under our assumption of constant returns to scale, we can single out one of the factor prices (say w_0) and actually estimate the following equation:

$$\ln (p/w_0) = a - bt + s_1 \ln (w_1/w_0) + \ldots + s_n \ln (w_n/w_0) + u \qquad (2)$$

where the only restrictions on the s_i are then that they lie between zero and one.

Unfortunately, we do not yet have enough data to do that, although it may become possible in the future as more prices become available. We can, however, try comparing the price of our military good with that of a similar civilian commodity that involved a similar production process. If the civilian commodity was made with similar factors of production and similar factor shares, and if the same economic assumption held for it too (constant returns to scale, competitive factor and product markets), then equation 2 would apply to its price q too, and the logarithm of p/q would be:

$$ln\ (p/q) = c - dt + e_1\ ln\ (w_1/w_0) + \ldots + e_n\ ln\ (w_n/w_0) + v \qquad (3)$$

Here c is a constant, d is the rate of technical change for the military good minus that for the non military good, v is an error term, and the e_i's are differences in the factor shares for the two goods. If the factor shares for the two goods are nearly equal, then the e_i's will be close to zero, and

$$ln\ (p/q)\ -\ c - dt \qquad (4)$$

We could then regress *ln (p/q)* on time and come up with an estimate for d, the rate of technical change for our non military good less that for our non military good. The estimate will be biased because the variables $ln\ (w_i/w_0)$ will be omitted from the regression, but because the e_i's are small, the bias will be small too and may be either positive or negative.[5] If production of the non-military good does not experience any technical change, then d will be close to the rate of technical change b for the military good. If there is technical change in production of the military good, the d we get from equation (4) is likely to underestimate the rate at which the cost is declining. The key, of course, will be finding non-military goods with factor shares similar to those of the military goods–ideally, non-military goods whose production functions did not change.

This we can actually do, although suitable prices of military goods are rare enough to make regressing *ln (p/q)* on time seem like overkill. The number of observations involved is so small that it is probably better just to tabulate *ln (p/q)* versus time and see whether it drops. That may seem overly simple given the long build up, but it is good to know what assumptions lie behind such a rudimentary procedure, and equations 3 and 4 make all the assumptions clear. And we will run the regressions too, but with a small number of observations, the estimated standard coefficient errors will be meaningless.

Tables 1 and 2 show what happened to the prices of French and English handguns, artillery, and gunpowder for a small number of observations scattered between the fourteenth century and the late 1700s. The English prices are expressed relative to the Phelps-Brown and Hopkins consumer price index and also relative to a non-military good that presumably had a similar production function. For English handguns (muskets and pistols, done separately), that good is wheelbarrows, which, like handguns, were made of wood and metal. Technical change in the production of wheelbarrows was probably small in the period of interest (1620-78), and wheelbarrows had the additional advantage of offering repeated price observations and yet at the same time having relatively little price variation. For English artillery, the non-military good was nails; they seemed a better match for the cannons in the table, at least some of which were made out of wrought iron.[6] Nail making did experience some technical change in late eighteenth century and perhaps as early as the seventeenth century, but that was well after the price observations for English artillery.[7]

For French artillery, handguns, and gunpowder, prices are displayed in grams of silver and relative to the price of lathing nails. Although the price of something like wheelbarrows might have been a better non-military yardstick for handguns, it proved impossible to find wheelbarrow prices or prices of any other good made out of both wood and metal. Lathing nails, however, are not a bad choice. Like the fabrication of handguns, the making of nails required metal and skilled labor and it also consumed wood for heating the furnaces. Lathing nails also served as the non-military good for artillery. For French gunpowder, I experimented with both lathing nails and the unskilled wage, since description of the production process suggest it was labor intensive. Because the technology of nail making may have changed beginning as early as the seventeenth century, all of the comparisons between the price of nails and the price of artillery, handguns, and gunpowder may underestimate technical change for the military goods.

Like the prices of arms and gunpowder, the prices of the various non-military used as yardsticks were fragmentary and not available for the same years for which prices of arms and gunpowder could be found.[8] To solve this problem, I took 50-year averages of the arms and gunpowder prices in France, and of the lathing nails that served as the non-military yardstick. In England, prices were a bit more abundant, and the price of the non military goods were averages of available data for wheelbarrows and horseshoes within plus or minus 4 years of the dates for which I had arms prices.

With the exception of pistols in England, all of the weapons prices trend down over time: for artillery, handguns, and gunpowder, in both in England and France (Tables 1 and 2). The downward trend is apparent whether we measure the prices in silver in France, relative to the consumer price index in England, or relative to non-military goods. The periods covered are different, but they stretch from the fourteenth century to the end of the eighteenth century. And when the price of the military goods relative to the non military goods are regressed on time, the regression coefficients are all negative, even for English pistols (Table 3). The downward trend fits what Greg Clark has discovered about the price of gunpowder in England, which does not appear in Table 2. It too drops sharply relative to wages between the fourteenth century and the nineteenth century, and Clark's data show that price of gunpowder also fell (though by a smaller amount) relative to cutting tools (Clark, 2004).

All of the regressions point to technical change, at rates that vary from 0.1 percent per year to 1.6 percent per year (Table 3). If we add Clark's figures for the price of gunpowder relative to the wages to the table, we get a rate of technical change of 0.4 percent per year (Clark, 2004) and an overall median rate of 0.3 percent per year. These numbers compare favorably with rates of long run total factor productivity growth elsewhere in the preindustrial world, which usually did not exceed 0.1 percent per year (Clark, 2003). There were some exceptions to this rule–English agriculture, for instance, which seems to have sustained long term total factor productivity growth rates of 0.2 to 0.3 percent per year–but in most sectors of the preindustrial economy, faster growth could simply not be sustained.[9] Even during the Industrial Revolution, total factor productivity growth in Britain seems to have hovered between 0.1 percent per year and 0.35 percent per year.[10] How could the defense industry do so well over such long periods of time, and in two economies–France and England–that were largely pre-industrial?

Perhaps one should simply not believe the data. After all, the figures are fragmentary and the number of observations is minuscule. The raw price data for French handguns in particular is particularly noisy, and one could certainly worry that quality differences and omitted prices for factors of production would make all of the tables and regression results purely random. Suppose, however, that the negative coefficients in the regressions were purely random. How often would we expect to get that many negative coefficients if we were simply drawing from a Bernoulli distribution with a probability of getting a negative regression coefficient exactly half of the time? We have 7 regressions coefficients in Table 3, but to stack the case against finding anything but a chance result, let us assume that the regressions that use the same non-military good as a yardstick are not independent. Under these harsh assumptions, Table 3 has only 4 independent draws, and Clark's finding about the trend of English gunpowder prices relative to wages would be a fifth that would also be negative. The odds of drawing 5 negative numbers are 1 in 32, or roughly 0.03.[11]

Perhaps the regressions and tables are therefore telling us something. Perhaps the figures they contain are not as unreliable as it might seem at first glance. After all, careful reading of the sources (and in particular, sensitivity to changes of vocabulary) can help guard against unsuspected changes in quality, and I have in any case put the data together in a way that is likely to underestimate technical change.[12] And there are a number of other reasons why the rates of technical change are likely to biased downward as well. Price figures for a new weapon, as we noted above, may not appear in historical records until well after it is first invented, and that means after the period when costs of production are likely to be falling most rapidly thanks to learning by doing (Lucas). This was probably what cut the rate of technical change for pistols: they were introduced in the sixteenth century, but for the moment we only have useable prices from much later.[13] Similarly, if the non military goods have also experienced technical change, then the relative prices will suffer some downward bias, and they will of course also underestimate advances in military tactics and organization that have nothing to do with technology and gloss over naval warfare, where western Europe's progress and comparative advantage were probably greatest.

Implications for Military History and Economic History

To assert that military production experienced surprising technical change in late medieval and early modern Europe would of course fit what military historians claim when they write about the military revolution (Black, Parker). More evidence would of course be useful; I am currently gathering it in printed and archival sources. But perhaps it is not too early to speculate a bit about what the price trends imply, both for the military revolution and western Europe's comparative advantage in violence, and for more general issues in economic history.

For economic history, the big surprise is the evidence of sustained technical change over perhaps four centuries before the Industrial Revolution. If further data bear out this conclusion and demonstrate that the rates of technical change were substantially higher than the 0.1 percent or less that characterized most preindustrial economies, then we will have something to explain. What could possibly account for such unusual sustained growth before the nineteenth century?

One possibility would be the competition among European states, which fought practically incessantly between the late Middle Ages and the end of the Napoleonic Wars. Until the French Revolution, the states' rulers (typically kings or prices) had every incentive to fight: they bore little of the cost of a military buildup, and they were rarely deposed or killed in case of defeat. The political incentives and military competition gave rents to victors (control of lucrative trade routes, for instance), and those rents would conceivably encourage military innovation, both in the realm of military technology and in tactics and military organization. One could imagine a model in which the military competition among the states would raise the gap between the rents going to the victor and the meager lot accorded to the losers; the victor would get a temporary monopoly, while the others would earn a competitive return near zero.[14] Via this difference in rents, the military competition would foster high rates of military innovation. So too might the practice of exchanging information about military advances, by hiring away mercenary soldiers and skilled craftsmen such as gun founders. Yet because warfare interfered with trade and destroyed capital elsewhere in the economy, all the progress in the military realm would fail to ignite economic growth overall.[15]

What do the price trends say about the military revolution? Military historians have debated whether the revolution revolved around a particular technology and set of tactics in which western Europe had a comparative advantage. The influential historian Geoffrey Parker has claimed that the key technology and associated tactics appeared at the end of the fifteenth century and then spread throughout much of western Europe over the next two hundred years, giving Europeans an advantage that allowed them to dominate the rest of the world. The technology consisted of artillery and handguns, thick earthwork fortifications that could resist bombardment (the so called trace italienne), infantry soldiers trained to fire their muskets in volleys, and sailing ships armed with cannons. Other historians disagree about the timing or the nature of the technology. They argue that the military revolution spread out over a longer period or that western Europe experienced repeated revolutions in tactics and technology between the end of the Middle Ages and the early nineteenth century, beginning in the fourteenth century, when knights on horseback were supplanted by archers and infantry troops with pikes (Parker, Black, Rogers).

The price data cannot speak to the question of tactics, but evidence for sustained technical change does support the historians who believe that the improvements in military technology were spread over a longer period or that there were repeated military revolutions. And if competition between states was the driving force behind the ongoing technical change in military production, it would provide a theoretical explanation for what one military historian has called "punctuated" equilibria: repeated improvements in technology and tactics that gave one state an advantage and then were imitated, leaving a new status quo (Rogers). The reason is that other states would eventually imitate successful military innovations, and when they did so, there would be a new equilibrium that would last until another state discovered better tactics or technology. The Dutch, for instance, invented volley fire in 1594 and put it into practice beginning in 1599. The new tactic was described in print as early as 1603, and books explaining it quickly appeared in several languages. It was also spread by foreigners who served in the Dutch army and by Dutch military instructors who taught the tactic to states allied with the Dutch.[16] Other western European states then adopted volley fire, reducing the military advantage the Dutch had.

If the price data point to competition between states as the driving force behind technical change, then this competition could also be considered as the cause of western Europe's comparative advantage in violence. If this argument turns out to be correct, then western Europe's early dominance of the world would result from competition between states for the rents earned by conquest. The military competition actually destroyed resources, but it was made possible by the nature of political regimes in early modern Europe, and by the fact that the continent was not part of any Empire, but was instead fragmented in to perpetually warring states.

This may seem to pushing the argument too far (particularly since the evidence is so thin) but does seem to fit what we know about certain other parts of the world. In China, for example, it was clear to both Chinese and western observers in the 1500's and 1600s that China's military technology lagged behind Europe's (Chase, 142). Yet China had been quite inventive earlier;

indeed, it was the birthplace of both gunpowder and firearms. What marks China's innovations, though, was that they came during periods when the Chinese Empire was fragmented or non existent. As the military historian Kenneth Chase has noted, the Chinese discovered crossbows and trebuchets before the Empire was unified in 221 BC. They began to use heavy cavalry during a second period of disunity between 220 and 589, and two subsequent periods of fragmentation (756 to 960 and 1127-1276) witnessed the invention of gunpowder and firearms (Chase, 32-33). But some three quarters of the two millennia between 221 BC and the nineteenth century, the Chinese Empire was intact, which may have lessened the incentive to create new military technology. Western Europe, by contrast, spent much more time fragmented into warring states. After the fall of the Roman Empire, western Europe knew only two short lived empires (the Carolingian and the Napoleonic), and it thus lived through a millennium and a half of nearly uninterrupted disunity.

There is an alternative explanation for Europe's comparative advantage–geography. Kenneth Chase maintains that China had no reason to develop firearms because its enemies were typically horse riding nomads from the steppes of Asia, who fought with bows and arrows and depended on their mobility, rather than any advanced technology. The steppe nomads had no fortified cities to attack with artillery, and firearms were useless against them, for they had to be pursued on horseback and it was impossible for a rider to shoot early hand guns (apart from pistols, which had a very short range) with any effectiveness. A similar argument wold apply elsewhere as well. Eastern Europeans, for instance, faced similar enemies from further East along with more heavily armed western Europeans, and so they too had less of an incentive to develop firearms. The same would hold for the Ottomans (Chase).

If we pursue this geographic explanation a bit further, though, we can perhaps get it to complement the argument about competition. The reason is that the geography is not merely a matter of climate, density of population, and agricultural endowments, which are what Chase stresses. It is also a matter of politics. If the Chinese Empire had disintegrated into separate states, then the ones away from the interior would have faced enemies who were not steppe nomads, but warriors who could have developed very different military technologies. Similarly, if western and eastern Europe had been unified into an Empire, then their common enemy might have been steppe nomads, or powers like the Ottomans, who had to had to spend at least some of their resources fighting nomads. In that case, the western Europeans might never have developed their formidable military technology. The big question then would be what held China together and what kept western Europe from coalescing into a cohesive Empire. That is the question we may have to answer if the conclusions from the meager price data hold true.

Table 1

Prices of English Artillery and Handguns

Date	Price and Units	Price/CPI (Index)	Price/Price of Nonmilitary Good (Index)	Number of Price Observations
Artillery (Cannons)				
	Pence per Pound		Price/Price of Horseshoes	
1382-88	3.94	100	100	5
1428	2.30	70	37	2
1430-39	3.00	72	53	reported average
Muskets				
	Pounds per Musket		Price/Price of Wheelbarrows	
1620	0.70	100	100	1
1621	0.68	101	96	1
1659	0.80	79	76	Estimate for Equiping Force of 26,000 Men
1674	0.60	64	64	1
1678	0.67	73	77	1
Pistols				
	Pounds per Pistol		Price/Price of Wheelbarrows	
1650	0.41	100	100	3
1652	0.45	141	107	1
1654	0.50	187	100	2
1659	0.45	131	82	1
1674	0.30	94	61	1
1706	0.50	174	104	1

Source: Tout (artillery in 1382-88); Clifford Rogers (artillery in other years); and Thorold Rogers (Muskets and Pistols).

Note: The table omits some sixteenth prices for pistols cited in Hall that would have yield a much higher rate of technical change. They will be included when it is clear that they are all actually pistols and not other sorts of handguns. The figures from Tout are taken from the documents he publishes for 1382-88, and not from the averages he reports. When there is more than one price available for a given date or period, the available prices are averaged; for artillery, the averages are weighted by cannon weight.

Table 2
Part 1:
Prices of French Artillery and Handguns

Date	Price in Grams of Silver and Units	Index of Silver Price	Price/Price of Nonmilitary Good (Index)	Number of Price Observations
Artillery (Cannons)				
	Grams Silver per Kilogram		Price/Price of Lathing Nails	
1476	6.08	100	100	1
1524	6.75	111	92	1
1622	3.69	61	83	1
1647	2.48	41	56	1
1690	2.52	41		1
Handguns				
	Grams Silver per Gun		Price/Price of Lathing Nails	
1450-99	87.16	100	100	5
1500-49	49.14	56	47	3
1550-99	83.87	96	119	4
1600-49	80.87	93	126	12
1650-99	38.32	44		2
1700-49	34.41	39	79	3
1750-99	67.22	77	46	4

Source: d'Avenel, vol 6.

Note: Artillery included canons, couleuvrines, serpentines, and pieces de canon. I used only those prices for which d'Avenel had converted the prices to francs per kilogram in order avoid problems with different units of weights. The lathing nail prices for artillery were averages for the 50 year period including each data: 1450-99 for 1476, 1500-49 for 1524, etc. There were no lathing nail prices available for 1650-99. Handguns included arquebuzes, fusils, and mousquets; if the context made it clear that the mousquets or arquebuzes were large caliber, they were excluded. As explained in the text, the flintlock fusils, which appeared in the late seventeenth century, represent a qualitative improvement; including them in the table will therefore underestimate technical change. Handgun prices were averaged over 50 year periods, and lathing nail prices were again averages for the same periods.

Table 2
Part 2:
Price of French Gunpowder

Period	Price in Grams of Silver per Kilogram	Index of Price in Days of Unskilled Labor	Price/Price of Lathing Nails (Index)	Number of Price Observations
1350-99	55.76		100	2
1400-49	20.44		31	16
1450-99	10.79		16	3
1500-49	8.01	100	10	5
1550-99	17.95	94	32	19
1600-49	17.30	89	34	15
1650-99	13.11	63		3
1700-49	12.75	83	37	7
1750-99	8.28	53	7	1

Source: d'Avenel, vol. 6; Baulant.

Note: Prices of gunpowder, lathing nails, and wages were all averaged over 50-year periods. Wages are for unskilled building workers in Paris; eventually I will extend these back before 1500. The price of gunpowder was clearly influenced by warfare; the table does not take that into account.

Table 3

Coefficients of Time in Regression of *ln(p/q)* on a Constant and *t*

Military Good with Price *p*	Non-Military Good with Price *q*	Period	Coefficient of Time *t* in Percent Per Year	Number of Observations
France				
Artillery	Lathing Nails	1476-1647	-0.3	4
Handguns	Lathing Nails	1450-1799	-0.1	6
Gunpowder	Lathing Nails	1350-1799	-0.3	8
Gunpowder	Unskilled Wage	1350-1799	-0.2	6
England				
Artillery	Horseshoes	1382-1439	-1.6	3
Muskets	Wheelbarrows	1620-78	-0.6	5
Pistols	Wheelbarrows	1650-1706	-0.1	6

Source: See text.

Note: See text for explanation of regressions; the negative coefficients are a sign of technical change. For all French military goods except artillery, an observation was a 50-year average for *ln(p/q)*, not an individual price reading. The observations for English artillery are averages over shorter periods.

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[1] (Inalcik; Chase 2, 97-98; Heywood 2002ab; Parker 87-89, 126-29, 173-75) Chase considers the Ottomans a military threat to Europe until the late seventeenth century, and he quotes a 1644 Chinese opinion that Ottoman guns were better than European ones. But he also acknowledges that the Ottomans were not at the frontier of military technology and that they often depended on Christian "renegades" for help.

[2] With volley fire, infantrymen were trained to line up in long rows. The first row would fire their muskets, and while they were reloading, the rows behind them would advance to the front and take their place on the firing line (Parker, 18-19).

[3] Accounting records in national and local archives in France contain more data on weapons' prices. The same is likely true for other European countries too, and similar data may be available for other parts of the world as well.

[4] See, for example, the description of the Ordnance Board and the development of cast iron naval guns in sixteenth-century England (N. A. M. Rodger 213-15, 225-226, 233).

[5] The bias in the estimate for d will be RE, where E is the n by 1 matrix formed by the coefficients e_i and R is the 1 by n matrix of coefficients we get by regressing $ln\ (w_i/w_0)$ on a constant and time and taking the resulting n coefficients of t.

[6] At least two of the pieces of artillery from the years 1382-88 were made of copper or an alloy such as bronze, according to the documents printed by Tout.

[7] See the Encyclopédie, s.v. "Clous"3: 548; Encyclopedia Britannica, 11th edition, s. v. "nails".

[8] Prices for French artillery were the most fragmentary. So far, I have collected only 5 useable prices for French artillery, for the years 1476, 1524, 1622, 1647, and 1690. Here useable prices are ones that are quoted in currency per unit of weight, with known units of weight and no

obvious misprints or quality differences from other the other pieces of artillery. Lathing nail prices are available for only 4 of these years, even if we take fifty-year averages.

[9] Mokyr; Clark, 2003, table 1; Hoffman, especially tables 4.8 and 4.9; and, for English agriculture, Allen.

[10] Crafts and Harley estimate total factor productivity growth during the English Industrial Revolution at 0.1 percent per year between 1760 and 1801 and 0.35 percent per year between 1801 and 1831.

[11] A tougher question is to ask whether the regression coefficients in Table 3 would be likely to arise if we were drawing them randomly from a population with median of –0.l, or, in other words, from a population presumably typical of the sort of slow technical change one would find in a pre-industrial society. If we treat all 7 regressions and Clark's relative price of English gunpowder and wages as 8 independent observations, and make no assumptions about the distribution we are drawing from, then the probability of getting as many regression coefficients as we did that are below -0.1 by chance is approximately 0.25.

[12] As Europeans experimented with different types of handguns, they coined a wide variety of words to distinguish different calibers and firing mechanisms. The lists of handguns in d'Avenel and Rogers use this wide vocabulary, and also seem to distinguish atypical firearms that were specially crafted for wealthy purchasers. One does have to watch, though, for changes in meaning: a <u>mousquet</u> (musket) started out as a large caliber weapon in the early seventeenth century, but by the middle of the century it had become nearly synonymous with the smaller caliber <u>arquebuse</u> (arquebus). The price data for these very firearms provides one example of how the data likely underestimate technical change. The French firearms prices for the late seventeenth and eighteenth centuries are prices for flintlock handguns, which replaced the older matchlock muskets and arquebuses. Firing a flintlock was much easier, for the soldier no longer

had to go through some 28 steps while holding a lighted cord in his fingers and keeping it from igniting the powder he was carrying. Instead, he simply pulled a trigger. The advantage of the flintlock should have pushed its relative price up, and with more data, I could have perhaps corrected for the improvement by adjusting the price of the flintlock downward to make it comparable to the older muskets. Because I did not do so, the firearm data underestimate the rate of technical change. For details on matchlocks and firearms, see Clark, p. 25; Hall; and Lynn. Another problem with the data is that it includes some estimates for wholesale purchases alongside what primarily prices for smaller quantities; see, for example, the price of muskets in England in Table 1. I have included these even though one might presume they would involve some sort of volume discount.

[13] For pistols, see Hall, 190-98. Hall quotes some earlier figures which suggest that the relative price of pistols in the middle of the sixteenth century was twice or more what it was in 1650. If he is correct, then pistols too experienced rapid technical change. Even though these figures would reinforce my argument, I have not added them to Table 1 until I can be sure that they all are really are for pistols, and not for other sorts of handguns.

[14] For a model of this sort in the endogenous growth literature, see Aghion et al.

[15] For examples of how warfare destroyed capital and interfered with trade, see Hoffman.

[16] My account of the origins and spread of volley fire is borrowed from Parker, 20-21.