

Why Is It 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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January 8, 2005

Abstract

Preliminary data from England, France, and Germany show that the relative price of artillery, handguns, and gunpowder declined between the fourteenth century and the eighteenth century. Most of these prices fell relative to the cost of factors of production, and the price decline suggests that the military sector of western European economies experienced rapid and 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 (Wong 1997; Pomeranz 2000; Goldstone forthcoming)? Or was it earlier, before the Industrial Revolution (van Zanden 2003 ; Allen 2005; Broadberry and Gupta 2005)? 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 1973; North and Weingast 1989; Acemoglu, Johnson et al. 2002)? The Scientific Revolution and the Enlightenment, which spread useful knowledge and political reform (Jacob and Jacob 1997; Mokyr 2002)? Or was it simply an accident that the Industrial Revolution started in England and then quickly spread through Western Europe (Clark 2003)?

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 1996 , 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 1997). 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 1984, 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 1970). 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 missionaries 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 (Wong 1997, 89-90; Pomeranz 2000, 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. 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's 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.³ 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, even though they acknowledge that the cost of weapons fell.⁴ What happens if we examine the political economy of the military revolution and look in particular at prices of military goods? What do 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.⁵ For

the moment at least, we have to make do with somewhat fragmentary price data from several western European countries only—in particular, 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 are small relative to the size of the market they sell in and that entry into these product markets is open. Let us also assume that markets for the factors of production are competitive and that the firms have U-shaped short run average cost curves.⁶

These are not unreasonable assumptions for England and France. (They seem reasonable for Germany too for that matter.) Factor markets were competitive, and weapons production in these countries was, for the most part, in the hands of a large number of small scale contractors and independent craftsmen. Furthermore, entry into the weapons business did seem to be open, at least in the long run. Craftsmen and contractors moved their production from city to city and even migrated from country to country. While there were some signs of fleeting collusion or high prices granted when a country wanted to nurture its own arms industry, they seem to have been temporary, because major weapons buyers would go elsewhere if they thought prices were high.⁷

Under these assumptions, it will be difficult for weapons producers to collude, and free entry will drive them to produce at minimum average cost. The long run industry supply curve will then be flat, and the cost of producing a quantity y of our military good at time t will be turn out to be $y c(w, t)$, where $c(w, t)$ is the minimum average cost of producing the good and w is the vector of factor prices. The function $c(w, t)$, which is also a firm's marginal cost, will be independent of y but will depend 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 , and the partial derivative of its logarithm will give the rate of technical change. (For technical details here and in what follows, see the appendix.)

Because collusion will be difficult, the price p of the good produced will be the marginal cost, or $c(w, t)$. Provided that all of our assumptions held, we could therefore 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 deriving it from a Cobb-Douglas cost function, which would at least be a first order approximation to $c(w, t)$. The Cobb-Douglas technology will have to constant returns to scale since the marginal cost is independent of output. If we adopt the Cobb-Douglas functional form, and if the technology changes at a constant rate and is cost neutral, then

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

where a is a constant, $b > 0$ is the rate of technical change, u is an error term, s_i and w_i are the factor share and price of the i -th factor of production, and the factor shares have to add up to one. 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 add up to one, we can single out one of the factor prices (say w_0) and actually estimate the following equation:

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

where the only restrictions on the s_i now are that they and their sum 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.⁸ But if we let w_0 be the price of skilled labor (an essential input into weapons production), then we can at least calculate p/w_0 and compare how it changes with the variation in the relative prices w_i/w_0 through w_n/w_0 . If p/w_0 , the relative price of military goods relative to skilled labor, falls more rapidly than the relative prices of the other factors of production, then we have evidence for technical change in the military sector, and we can estimate how large the rate of technical change must have been.

If Figures 1 through 5 can be trusted, the price of military goods seems to have fallen relative to the cost of skilled labor and relative to the cost of major factors of production used in producing weapons in both England and France. Prices dropped for artillery, muskets, and pistols, and they did so as early as late Middle Ages. Of course, one might want to add a rental price of capital to the figures, but if we make reasonable guess at depreciation and suppose that the sales price of capital goods was proportional to skilled wages, then the rental price of capital declines only slightly in the figures, and if the capital is building space, its rental price may have actually risen sharply, at least in some locations (Figures 6 and 7). What the figures suggest, therefore, is that the military sector of the economy witnessed sustained technical change over a long period of time before the Industrial Revolution.

We can get a sense of how large the technical change must have been if we take our earliest and latest price observations for each military good and use equation (2) to estimate an upper bound for how much of the change in the price can be accounted for by shifts in the costs of the factors of production. We know how much $\ln(p/w_0)$ changed between the first and last observation, and we know how much the terms $\ln(w_i/w_0)$ changed too, at least for the factors of production listed in Table 1. Our coefficient b will therefore equal

$$(-\Delta \ln (p/w_0) + s_1 \Delta \ln (w_1/w_0) + \dots + s_n \Delta \ln (w_n/w_0) + \Delta u)/\Delta t$$

where Δ denotes the difference in each term between the initial and final period. This expression will be greater than or equal to

$$(-\Delta \ln (p/w_0) + (1 - s_0) \Delta \ln (w_i/w_0) + \Delta u)/\Delta t$$

where s_0 is the factor share of labor and $\Delta \ln (w_i/w_0)$ is the smallest of the terms $\Delta \ln (w_1/w_0)$, \dots , $\Delta \ln (w_n/w_0)$. If we take expectations (to make the Δu disappear) and assume that the changes in the prices of the factors of production are all at least as large as smallest one we can derive from Table 1, then we can calculate a lower bound for the expected value of b simply by guessing at s_0 .

If we perform this calculation with a labor share of 0.5 (other reasonable labor shares yield similar results), the resulting rates of technical change are nearly all larger by preindustrial standards (Table 1). Apart from the 0.1 percent rate of change for French muskets, the rates of growth in productivity are all over 0.5 percent per year, and the figure is 0.9 percent for the manufacture of artillery in late medieval England. 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, at least in sectors of the economy as large as the military one was in early modern Europe.⁹ 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.¹⁰ 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.¹¹ How could the defense industry do so well over such long periods of time, and in two

economies—France and England—that for most of the years in the table were largely pre-industrial?

One could of course argue that all the evidence here is a chance result, because it all depends on initial and final price observations, which could vary randomly and be buffeted about by the costs of factors of production that remain unobserved.¹² If we enough data, we could settle the issue by estimating equation (2) and testing hypotheses about the sign and magnitude of the coefficient b . But we cannot do that, even with statistical methods that make up for missing data.

One thing we can do, however, is to compare the price of our military good with that of a similar civilian commodity that involved a similar production process.¹³ 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:

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

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

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

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.¹⁴ 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 we have to keep in mind that the coefficients and estimated standard coefficient errors may be biased in an unknown way. In addition, if we have prices of the factors of production for which the share differences e_i are likely to be relatively large, we can add them to the regression since they are likely to bias our estimate of d the most.¹⁵ The advantage of doing so is that we can find prices for factors such as iron or capital, which may be used more intensively in either the military or civilian good. We can include prices for these factors in a regression of $\ln (p/q)$ on a constant and time and assume that the small e_i 's for the other omitted variables will keep their contribution to the bias small. That amounts to running regression (3) with some of the $\ln (w_i/w_0)$ omitted, but it is possible to run such a regression when it would be impossible to get enough data to run a regression with all the variables $\ln (w_i/w_0)$.

Table 2 shows what happens when we run either a regression based on equations 3 (with some missing variables) or equation 4. Again, the regressions involve the prices of French and English handguns and artillery from the late Middle Ages to the eighteenth century, and now gunpowder is included too. The prices of the English military goods are expressed relative to the cost of spades, a non-military good that presumably had factor shares roughly similar to those involved in the production of handguns, for like spades, handguns were made of wood and metal. Admittedly, the factor shares were probably different for artillery and gunpowder, and it no doubt took more metal to make a firearm than a spade. But even cannons had wooden carriages, and wooden and metal tools were used to manufacture gunpowder. Despite these disadvantages, though, using the price of spades has certain virtues. Technical change in their production was probably small before the eighteenth century, and there are repeated price observations for spades with relatively little price variation at any given time. And where we have enough data, we can compensate for the different factor shares for iron in military goods by adding the relative price of iron to the regressions.

For French military goods, prices are compared to the cost of lathing nails. Although the price of something like spades might have been a better non-military yardstick for handguns, it proved impossible to find prices for spades or any other good made out of both wood and metal. Lathing nails, however, are not a bad choice for artillery, or for handguns either. 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 had to serve as the non-military good for gunpowder, but at least here I could compensate for what were probably different capital intensities by adding the rental price of capital. 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 well underestimate technical change for the military goods.¹⁶

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.¹⁷ To solve this problem, I took 50-year averages of the lathing nails prices that served as the non-military yardstick, and 25-year averages of skilled wages and iron prices. In England, I had to use 25-year averages for the price of iron and spades.

In the regressions of $\ln(p/q)$, the coefficient of time (the $-d$ in equations 3 and 4) is negative for all the military goods except for French gunpowder, when its price relative to the cost of nails is regressed on time alone (Table 2). With that exception, time always turns out to have a negative coefficient, whether the regressions are run with time alone or whether relative prices of some other factors of production are added. Graphs of $\ln(p/q)$ reveal a clear downward trend in the relative price of the military goods in nearly every instance (Figures 8 through 14). The only exceptions are for muskets and gunpowder in France, and the relative price of gunpowder price does at least drop first and then rise before falling again.

The regressions, in short, nearly all point point to technical change, at rates ranging as high as 2.4 percent per year and over periods stretching from the fourteenth to the eighteenth century. The median rate of technical change in the regressions with the year alone is 0.5 percent per year; if we look instead at regressions with prices of other factors of production added, the median is 0.8 percent per year. Again, these numbers are high relative to rates of total productivity growth elsewhere in the preindustrial world, or even during the Industrial Revolution. How could the defense industry do so well over such long periods of time, and in

two economies—France and England—that for most of the years in the table were largely pre-industrial?

Perhaps one should simply not believe the data. After all, the figures are fragmentary, the number of observations is small, and there are a huge number of assumptions involved. One could certainly worry that quality differences and biases from omitted prices for factors of production would make all of the tables and regression results purely random.¹⁸ Suppose, however, that the negative time 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? If we limit ourselves to the 7 regressions on time alone, 6 of the 7 coefficients are negative, and if each coefficient represents an independent draw, then the odds of getting six negatives by chance are only 0.06. If we substitute the regressions with the relative prices of other factors of production, all 7 time coefficients are negative, and the probability of getting that many negatives by chance in independent draws from a Bernoulli distribution is only 0.008.

We could raise the bar higher by asking whether the regression coefficients in Table 2 would be likely to arise if we were drawing them randomly from a population with median of negative 0.1 percent per year, or, in other words, from a population presumably typical of the sort of slow technical change one would find in a pre-industrial society. In the regressions on time alone, 6 of the 7 coefficients point to technical change at a rate of 0.1 percent per year or more. The odds of that happening by chance in independent draws from a Bernoulli distribution are 0.06. And if we substitute the regressions with prices of other factors of production, all 7 regressions yield rates of technical change of 0.2 percent or more per year. The probability of that happening by chance are only 0.06, even if the coefficients are drawn from a population with a median as high as 0.3 percent year.

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.¹⁹ And there are a number of reasons why the rates of technical change are likely to be biased downward as well. To begin with, the focus on prices overlooks all the advances in military tactics and organization that have nothing to do with the production of military goods, and the prices we have chosen also gloss over naval warfare, where western Europe's progress and comparative advantage were probably greatest. Furthermore, Tables 1 and 2 do not take into account all sorts of continued technical change in the eighteenth century: boring and turning of cannons, or the standardized production of flintlock muskets with at least some interchangeable parts.

One last reason why our rates of technical change may be biased downward deserves to be stressed too. It is the simple fact that price data for a new weapon (as we noted above) will typically 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 1993). Fortunately, we have one instance where we can verify that this took place, for some of the first handguns that were ever made—in this case, ones that the German city of Frankfurt had produced during the years 1399-1431. Thanks to the meticulous research of Bernhard Rathgen, an artillery officer and military historian who died in 1927, we actually have prices for the handguns, along with the wages paid to the metal workers who cast them and the cost of the copper which served as the raw material. These early guns resembled small cannons

(Figure 15) with barrels less than 500 millimeters long. Although they were not very effective, German cities like Frankfurt bought them in large numbers.²⁰

For these early handguns in Frankfurt, we actually have enough data to estimate equation (2) with prices for all the factors of production included among the explanatory variables.²¹ When we run the regression (Table 3), we end up with reasonable coefficients (the factor share for copper is 0.307) and a rate of total factor productivity growth of 3.0 percent a year, which is more rapid than what was achieved by the most dynamic sector of the British economy—the cotton textile industry—during the Industrial Revolution.²² And we know why productivity was climbing so fast: the metal workers were learning how to make the handguns with less copper, which cut the price of the guns drastically (Figure 16). To us, such an improvement may seem obvious, but given the frequency with which early cannons exploded and maimed gunners, it was a step that the gunsmiths must have taken with a great deal of trepidation.

Finally, if we turn from prices to physical evidence of greater productivity, the story is much the same: firing rates for guns increased, misfires diminished, and inventions such as the bayonet made it possible for armies to do away with pikemen and to arm more and more of their soldiers, all of which boosted armies' labor productivity. In the French army, the rate of successful fire per soldier jumped perhaps 13-fold between the early seventeenth century and the middle of the eighteenth century (Table 4), which translates into labor productivity growth of 1.7 percent a year. Other physical measures of productivity, such as the range of early cannons, also soared.²³

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 1991; Parker 1996). More evidence is of course essential; 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 and in a major sector of the economy to boot. 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 princes) 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, at least in the major states (Table 5). 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.

So too would the glory and honor that most European rulers (and European aristocrats too) attached to military victory. A European ruler such as Louis XIV could tell his son that war

was a means to “distinguish [kings] . . . and to fulfill the great expectations ...inspired in the public.” The glory that European rulers attached to warfare stood in sharp contrast to the goals that rulers were supposed to pursue in at least one other part of the world—China. There, the Ming emperors advised to focus on peace and use force as a “last resort.”²⁴ Europeans who traveled to China and knew it well were struck by the difference. One of them—the Jesuit missionary Matteo Ricci, who died in Peking in 1610 after spending 28 years in China—noted that although the China could easily conquer neighboring states neither the emperors nor Chinese officials had any interest in doing so. “Certainly, this is very different from our own countries [in Europe],” he noted, for European kings are “driven by the insatiable desire to extend their dominions.”²⁵

The eighteenth-century historian Edward Gibbon invoked the competition between European states to explain the West’s military prowess; so has the modern military and diplomatic historian, Paul Kennedy (Black 1998, 3-7; Kennedy 1989). But their insights could be pushed further using economic theory. One could model the military competition among the European states as a research tournament in which the prize for the victor would foster high rates of military innovation. Without competition, no state would have an incentive to innovate, but if more than one state was willing to vie for the prize, the tournament could push states to devote enormous effort to military innovation. Some rulers would off course choose not to enter the tournament, and in equilibrium one would expect that only states that could exert themselves at low cost would engage in military competition. But so long as you had two states competing, you could still elicit arbitrary high levels of effort devoted to innovation, and two competitors would in fact be the cheapest way to reach any given level of effort if you were in fact designing such a tournament.²⁶ Western Europe of course often had two states or blocks of states at war with one another in the late medieval and early modern period, such as France versus the Habsburgs in the sixteenth and seventeenth-centuries, or France and England in the eighteenth century.

If competition between states was the driving force behind the technical change in the military sector, then it could also be considered as the cause of western Europe’s comparative advantage in violence. This may seem to push the argument too far (particularly since the evidence is so thin), and it may not apply in every other part of the globe. But it does at least seem to fit what we know about China. There 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 2003, 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 precisely during periods when the Chinese Empire itself was fragmented or non-existent and rival powers fought with one another under conditions very much like those in Europe.²⁷ 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 2003 , 32-33). But for nearly 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.

One might argue that the Chinese emperors could have encouraged military innovations simply by offering prizes to inventors. That way the emperors could have better weapons without wasting resources in war. But even if the emperors had tried this, the offer of a prize might not have seemed credible to someone who made a better cannon or devised promising military tactics. Military innovators in China had no one else to turn to if they wanted to commercialize their ideas. They would have had a hard time selling their ideas abroad, and they would not find it easy to interest private purchasers either, for private ownership of weapons was restricted. (The Ottoman Empire imposed similar restrictions on private gun ownership.) In Europe, by contrast, a better cannon could be sold to a private merchant or to a foreign army or navy, and there was even an international market in Europe for military skills and tactical knowledge, in which mercenaries and skilled craftsmen such as gun founders were hired away by other countries.

Another force for productivity growth was the ease with which information about new military technologies and tactics spread in early modern Europe. European mercenaries and migrant craftsmen transmitted information from state to state; so did books written by commanders and military engineers. If we consider technology as a plan that can be used over and over again, this spread of information would lead to increasing returns, as in models of endogenous growth.²⁸ The same thing would happen when states drew up plans of successful ships and built templates and models of innovative weapons—all things that happened as early as the seventeenth century. And yet despite the increasing returns and the competition among states, all the progress in the military realm would fail to ignite economic growth overall, because warfare interfered with trade and destroyed capital in other parts of the economy.²⁹

Here one could even ask whether the military competition in Europe actually delayed economic growth by diverting talent and resources to destructive activity. Joel Mokyr (Mokyr 1990, 183-86) has argued persuasively that warfare did not spur technical change in the civilian economy, but perhaps the toll war took was even greater than he supposed. A careful assessment would have to take into account the occasional positive technological spillovers from the military sector (in areas such as metal production), and it would also have to acknowledge that borrowing for warfare helped create European financial markets. But what would have happened to the western European economy if the resources and talent that worked such wonders in the military sector had instead been allocated to the civilian economy?

That is an interesting question for economic history, but what can the price trends contribute to military history; in particular, what do they 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 there was such a key technology, and in his view, it 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. For Parker, 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 (Black 1991; Rogers 1993; Parker 1996).

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 1993). 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.³⁰ Other western European states then adopted volley fire, reducing the military advantage the Dutch had.

Military history also offers an alternative explanation for Europe’s comparative advantage in violence–geography. The military history 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 would apply elsewhere as well. Eastern Europeans, for instance, faced similar enemies from lands 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 2003).

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.

Appendix

Let $L = w \cdot x - \lambda (f(x, t) - y)$ be the Lagrangian of the firm's cost minimization problem; here x represents a vector of factors of production, which are chosen to minimize cost; w is the vector of their prices; $f(x, t)$ is the production function, which depends on time t since we are considering technical change; y is output produced; and λ is the Lagrange multiplier, which by the envelope theorem equals the marginal cost of production when x is chosen optimally. Let $c(w, y, t)$ be the firm's cost of producing y once x is chosen optimally; by the envelope theorem, the partial derivative of $\ln(c)$ with respect to time equals

$$-\frac{\lambda}{c} \frac{\partial f}{\partial t} = -\frac{\lambda y}{c} \frac{\partial \ln(f)}{\partial t}$$

which equals the rate of technical change times the ratio of marginal cost to average cost. Since free entry drives the firms to produce at minimum short run average cost, each firm's marginal cost will equal its average cost, and the rate at which c is declining will therefore equal the rate of technical change (the rate at which the production function is shifting out). Furthermore, since the firms are small relative to the size of the market, in the long run the industry supply curve will be flat at a price p equal to this minimum short run average cost. For each firm, c will therefore equal $p y$, and the partial derivative of $\ln c(w, y, t)$ with respect to time will be

$$\frac{\partial \ln(p y)}{\partial t} = \frac{\partial \ln(p)}{\partial t}$$

Since the long industry supply curve is flat, the price p will be independent of how much output firms produce and thus will be function of w and t alone. At any time t it will have to equal an individual firm's marginal cost, and since it is independent of y , we can assume that as a function of w it can be derived from a constant returns cost function, with $c(w, y, t) = y c(w, t)$. If (as in the body of the paper) we use a constant returns Cobb-Douglas cost function as a first order approximation to this cost function and assume that the rate of change of $c(w, t)$ is constant over time and cost neutral, then

$$\ln(p) = \ln(c(w, t)) = a - bt + s_0 \ln(w_0) + \dots + s_n \ln(w_n)$$

where a is a constant, $b > 0$ is the rate of technical change, s_i and w_i are the factor share and price of the i -th factor of production, and factor shares have to sum to one. We can then calculate b by regressing $\ln(p)$ on time and on the logarithms of the factor share prices; the error term in the regression will represent short term deviations from our numerous assumptions (cost minimization, U-shaped cost curves, open entry, small firm size, competitive factor markets, Cobb-Douglas cost function, and cost neutral technical change). We assume as well that these error terms are identically distributed and independent.

One additional concern with these regressions might be what would happen to prices if the state acted as a monopolist. This will not be a problem, for two reasons. First of all, states

were not monopsonists in most of western Europe. There were in fact many private buyers of arms and gunpowder besides the state: military contractors bought them, as did privateers merchants, city governments, and even colleges. Second, under our assumptions, even if the state is a monopsonist, the industry supply curve will continue to be flat at the minimum average cost. Weapons producers will not produce anything unless the price they receive at least this minimum average cost, and no monopsonist will ever choose a higher price. The price will continue to equal $c(w, t)$, and the results of the price regressions will be unchanged.

Table 1

Index of Prices Relative to Skilled Wages

Military Good	Date		Final Price Relative to Skilled Wages (Index, Starting Date = 100)				Implied Lower Bound for Rate of Technical Change (% Per Year)
	Initial	Final	Good	Iron	Copper	Wood	
France							
Artillery	1476	1690	32	109	147		0.5
Muskets	1451	1800	64	224		116	0.1
England							
Artillery	1382	1439	63	115		117	0.9
Muskets	1620	1678	63	77		77	0.6
Pistols	1556	1706	36	55		131	0.5

Source: England: Beveridge 1965 (prices of firewood), Phelps Brown and Hopkins 1955 (building craftsmen's wages), Tout 1911 (prices of artillery in 1382-88), Rogers 1993 (prices of artillery in other years), and Rogers and Rogers 1866-1902 (prices of other guns and of iron and firewood). For France: Avenel 1968 (prices of guns), Guyot 1888 (iron prices and prices of fir planks), Levasseur 1893 (mason's wages, copper prices).

Note: For France, wages (for masons) are 25-year averages, as are prices of iron, copper, and wood. Levasseur's figures would have changed the final relative price of iron for artillery from 115 to 76, but his iron prices are less reliable than Guyot's. For England, prices of iron (wrought iron) and firewood (fagots) are 25-year averages. Here and in subsequent tables, the French artillery include canons, couleuvrines, serpentes, 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. Handguns included arquebuzes, fusils, and mousquets; if the context made it clear that the mousquets or arquebuzes were large caliber, they were excluded. I also excluded guns that were made for ornament or collection. 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. To calculate the implied lower bounds for the rate of technical change, I assumed that the labor factor share was 0.5 and then chose the factor price in the table that would yield the lowest rate of technical change between the initial and final date if prices for all the factors of production other than labor had risen at the same rate relative to wages. Labor shares from 0.25 to 0.75 lead to similar results.

Table 2

Coefficients of Time in Regression of $\ln(p/q)$

Military Good with Price p	Non-Military Good with Price q	Period	Time Coefficient/ T-Statistic (Percent Per Year)	Factors of Production in Addition to Skilled Labor	Time Coefficient/ T-Statistic with No Other Factors of Production in Regression	N
France						
Artillery	Lathing Nails	1476-1690	-0.2 / 2.22	None		5
Muskets	Lathing Nails	1475-1792	-0.5 / 1.55	Iron, Capital	-0.1 / 0.71	36
Gunpowder	Lathing Nails	1359-1765	-0.3 / 1.95	Capital	0.1 / 0.75	68
England						
Artillery	Spades	1382-1439	-2.4 / 8.65	None		10
Muskets	Spades	1620-1678	-1.6 / 3.49	None		7
Pistols	Spades	1556-1706	-1.1 / 4.85	Iron, Capital	-1.3 / 8.33	12
Gunpowder	Spades	1650-1706	-0.8 / 9.29	Capital	-0.5 / 8.53	62

Source: English spade and gunpowder prices were kindly furnished by Greg Clark; the English rent charge prices used in calculating the rental cost of capital came from his 2002 article. The French lathing nail and gunpowder prices are from d'Avenel, and the legal maxima interest rates used in calculating the cost of French capital came from Guyot 1784-85, s.v. "Rente". All the other prices come from the sources listed in Table 1.

Note: See text for explanation of regressions; the negative coefficients are a sign of technical change, and N is the number of price observations for the military goods. Where there were more than 10 observations, I ran the regressions on the year alone and with additional factors of production other than skilled labor. The other factors of production were ones whose prices I could find and for which factor shares were likely to differ for the military good and the comparison good. It was difficult to find prices for the military and non military goods on the same date, and for that reason, I calculated the price of the non-military goods by computing averages over long periods. In particular, for France, the lathing nail prices (from d'Avenel) were averages over 50-year periods; iron prices and masons' wages (both from Levasseur) were averages over 25-year periods. There were no lathing nail prices available for 1650-99. Capital rental prices took the legal maximum on perpetual annuities as the interest and assumed that the sales price of capital goods was proportional to labor and that depreciation was 10 percent. Capital rental prices for English goods were calculated in the same way, except that Clark's decennial averages for rent charges were used for interest rates. Prices of iron and spades were 25-year averages. The price of gunpowder was clearly influenced by warfare; the table does not take that into account.

Table 3

Regression of the relative price of early handguns in Frankfurt on time and the price of copper

Coefficient in equation 2 and associated explanatory variable	Coefficient	T-statistic
a (the constant term)	45.062	6.39
b (the year; the opposite of the coefficient is then the total factor productivity growth rate)	-0.030	5.92
s_1 (the logarithm of the price of copper relative to the skilled wage; the coefficient is then the factor share for copper)	0.307	1.98
R-square	0.73	
Adjusted R-square	0.69	
Standard error	0.19	
Observations	21	

Source: Rathgen 1928, 68-74.

Note: The dependent variable is the logarithm of the price of the handguns divided by the skilled wage. The wages used were actually a piece rate (the money paid to the metal worker to cast a pound of copper). If metal workers got better at casting in general, then the regression would underestimate the rate of productivity increase. For some of Frankfurt's purchases, the accounting was incomplete, and Rathgen had to assume that the wage rate or price of copper was the same as in other transactions at nearby dates. I have used the prices he calculated for the handguns except in a few instances where his extensive quotes from the archives suggest that the prices were different; these differences were always small. As noted in the text, I have assumed that the interest and depreciation rates were constant and that the sales prices of capital was proportional to the skilled wage. The rental price of capital relative to the skilled wage is then constant, and its coefficient enters into the constant term.

Table 4

Military Labor Productivity in the French Army:
Rate of Successful Fire per Infantryman, 1600-1750

Approximate Date	Rate of Successful Fire per Handgun (shots/minute)	Handguns per Infantryman	Rate of Successful Fire per Infantryman (shots/minute)	Assumptions
1600 (1620 for handguns per infantryman)	0.25 to 0.50	0.40	0.10-0.20	0.5 to 1 shot per minute with matchlock; 0.50 misfire rate
1700	0.67	1.00	0.67	1 shot per minute with flintlock, 0.33 misfire rate; bayonets have led to replacement of pikemen.
1750	1.33	1.00	1.33	2 shots per minute with flintlock, ramrod, and paper cartridge; 0.33 misfire rate.

Source: Lynn 1997, 457-60, 464-65, 469-72.

Notes: The calculation considers only pikemen and infantrymen with firearms; it ignores unarmed soldiers, such as drummers. The implied rate of labor productivity growth over the 150 year period from 1600 to 1750 is between 1.3 and 1.7 percent per year.

Table 5

Probability That a Major European Sovereign Was Deposed After Losing a Foreign War

Period:	Fraction Deposed Because of Defeat in Each Year of War or in Each Year of War Loss			
	Conditional on:			
	Being at War		Losing War	
Country	1500- 1799	1800- 1919	1500- 1799	1800- 1919
Austrian Dominions	0.00	0.07	0.00	0.20
France	0.00	0.06	0.00	0.67
Great Britain	0.00	0.00	0.00	0.00
Hohenzollern Dominions	0.00	0.06	0.00	0.50
Spain	0.00	0.10	0.00	0.33

Source: Langer 1968.

Note: The calculation of the conditional probabilities begins with a count of sovereigns who were deposed after losing a foreign war for the Austrian Dominions, France, Great Britain, the Hohenzollern lands, and Spain. The count includes any assassinations provoked by loss in a foreign war, but it excludes assassination or removal from office during civil wars and internal revolutions, unless the cause was the loss of a foreign war. In particular, the executions of king Charles I of England and Louis XVI of France are not counted, and the same holds for the removal of James II of England and the deposition of Ferdinand II in Bohemia in 1618. The calculations also exclude the simple downfall of ministries. The number of deposed monarchs is then divided by the number of years the country was at war; that yields the probability of deposition after losing a foreign war conditional on being at war. War here is defined as any class of armed conflict significant enough to be included in Langer 1968; no formal declaration of war is necessary. It includes colonial fighting, but it excludes civil wars unless foreign powers are involved. The calculation of the probability of deposition conditional on losing a war is similar; the only difference is the number of deposed monarchs is divided by the number of years in which a war ended with a loss for the country concerned. Sovereigns included all monarchs, whether absolute or constitutional. For republics, the sovereign was the parliament or legislative assemblies; if the legislative assemblies shared sovereignty with a president or other executive, then the sovereign was the executive and the legislative assemblies together.

The Austrian dominions exclude Habsburg territory in Iberian Peninsula, Italy, Low Countries, and Latin America. Bohemia is excluded before Habsburgs assume the crown in 1526, and Hungary is not counted until it was fully integrated into the Habsburg holdings in 1699. For France, the Convention is counted as a sovereign; Napoleon's abdication in 1814 is counted as a removal after a loss, but not his second abdication after Waterloo. For Great Britain, the calculation concerns England and Ireland alone up until 1603; during the

Protectorate, the Lord Protector is counted as sovereign. For Spain, depositions do not include loss of Portugal or of non-Iberian possessions. All the probabilities are ex-post, and they clearly make more sense for monarchies than for republics.

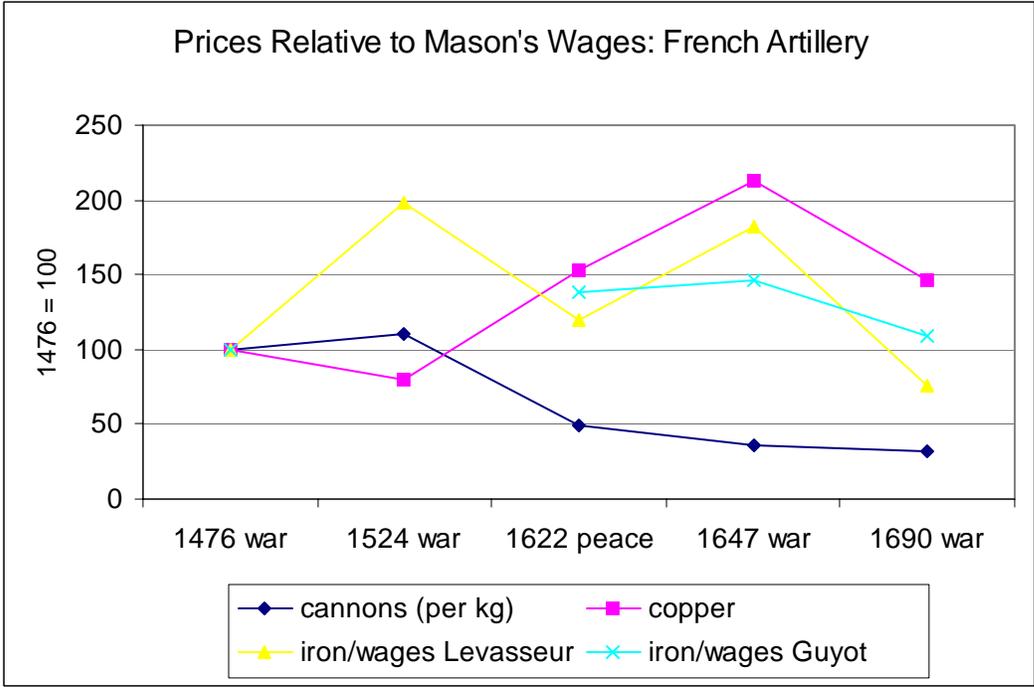


Figure 1. Prices relative to mason's wages: French artillery

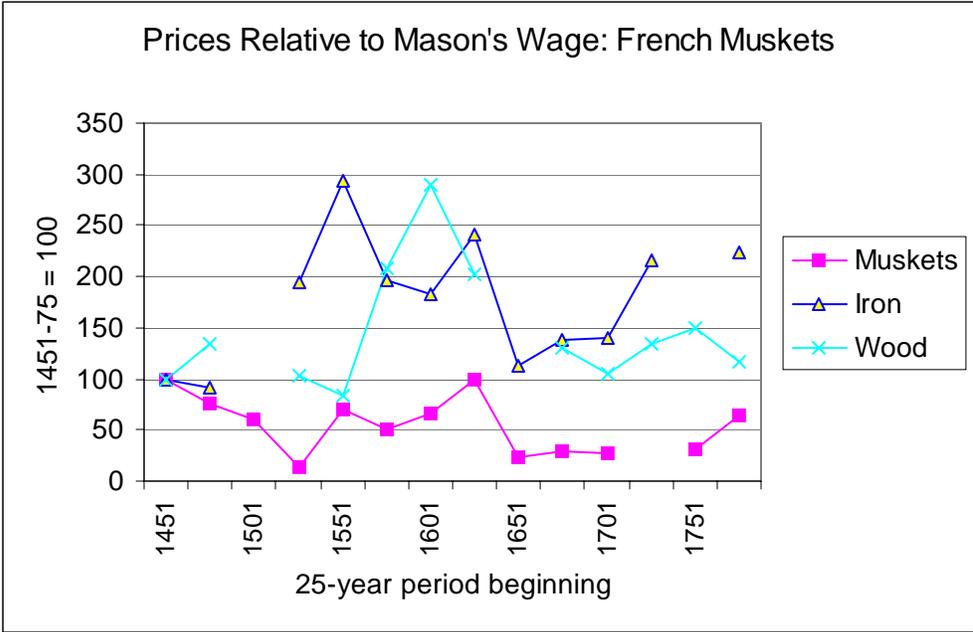


Figure 2: Prices Relative to Mason's Wage: French Muskets

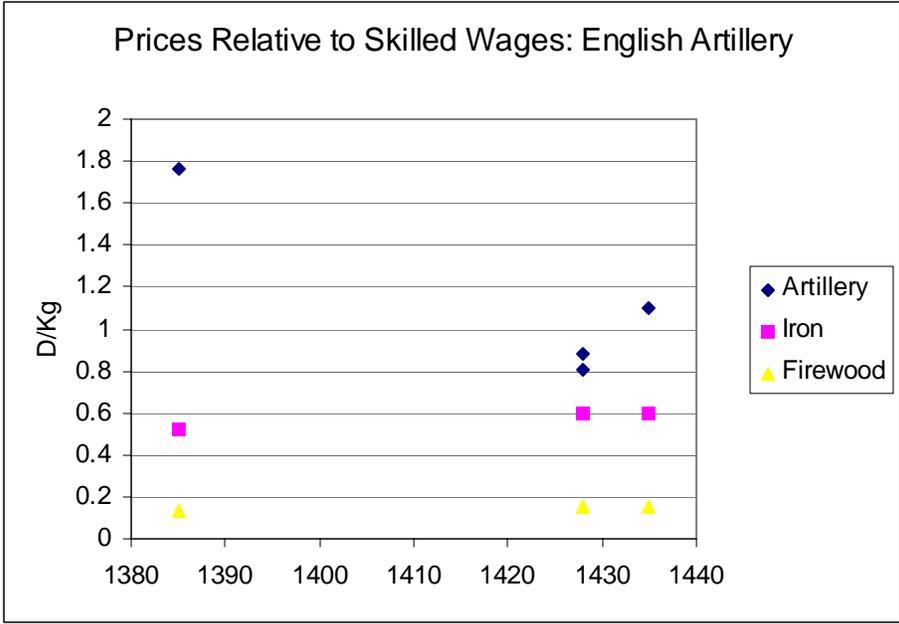


Figure 3: Prices Relative too Skilled Wages: English Artillery



Figure 4: Prices Relative to Skilled Wages: English Muskets

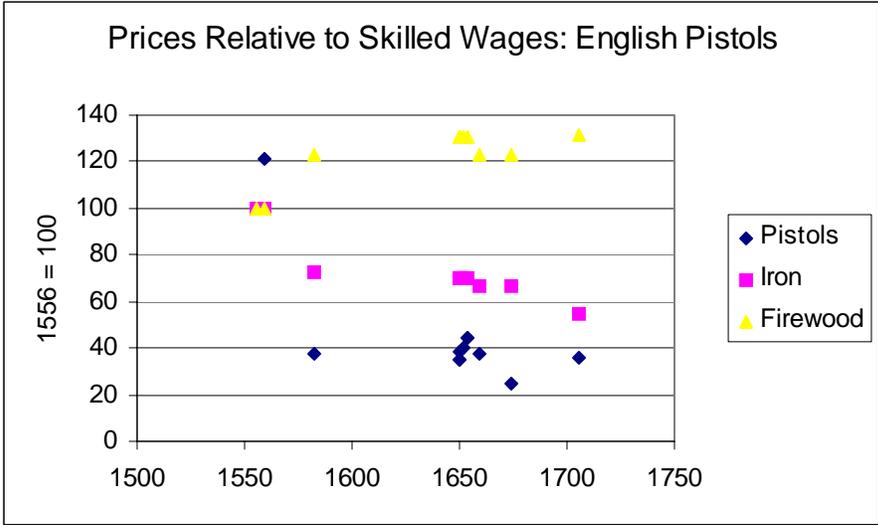


Figure 5: Prices Relative to Skilled Wages: English Pistols

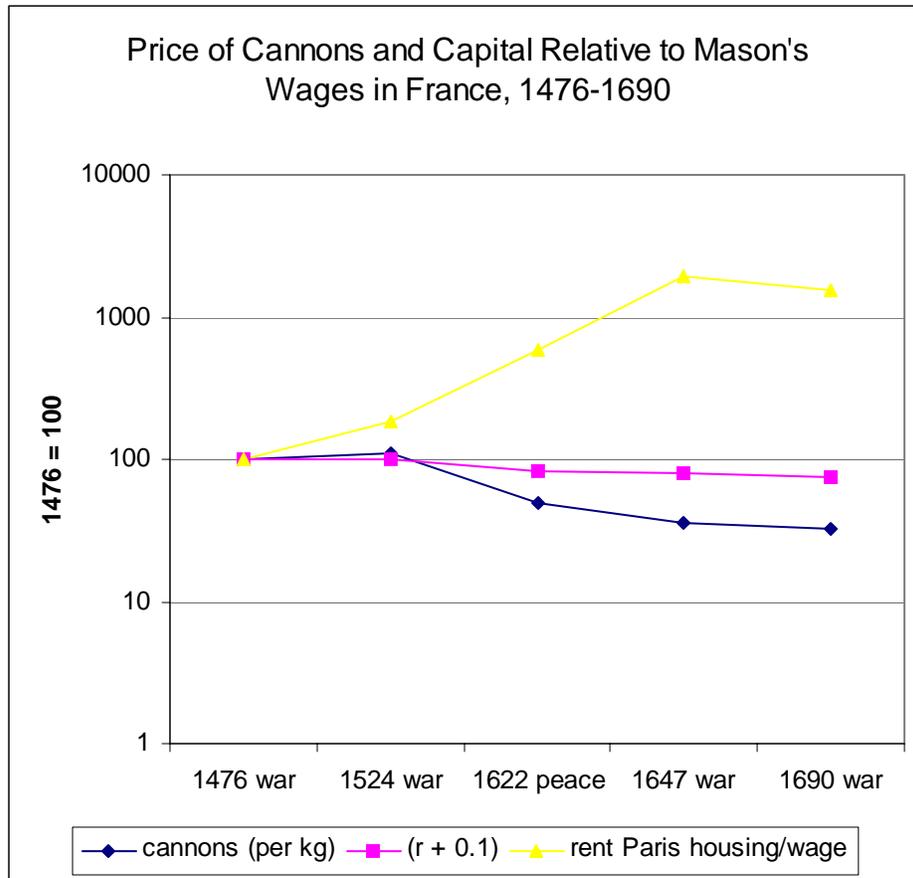


Figure 6. Prices of cannons and capital relative to a mason's wages in France, 1476-1690. There are two measures of the price of capital in the figure: the rental price of housing, and the rental price of a capital good whose sales price is proportional to mason's wage. Both are measured relative to the mason's wage. For the second good, I have assumed 10 percent depreciation and an interest rate r equal to the legal maximum on perpetual annuities.

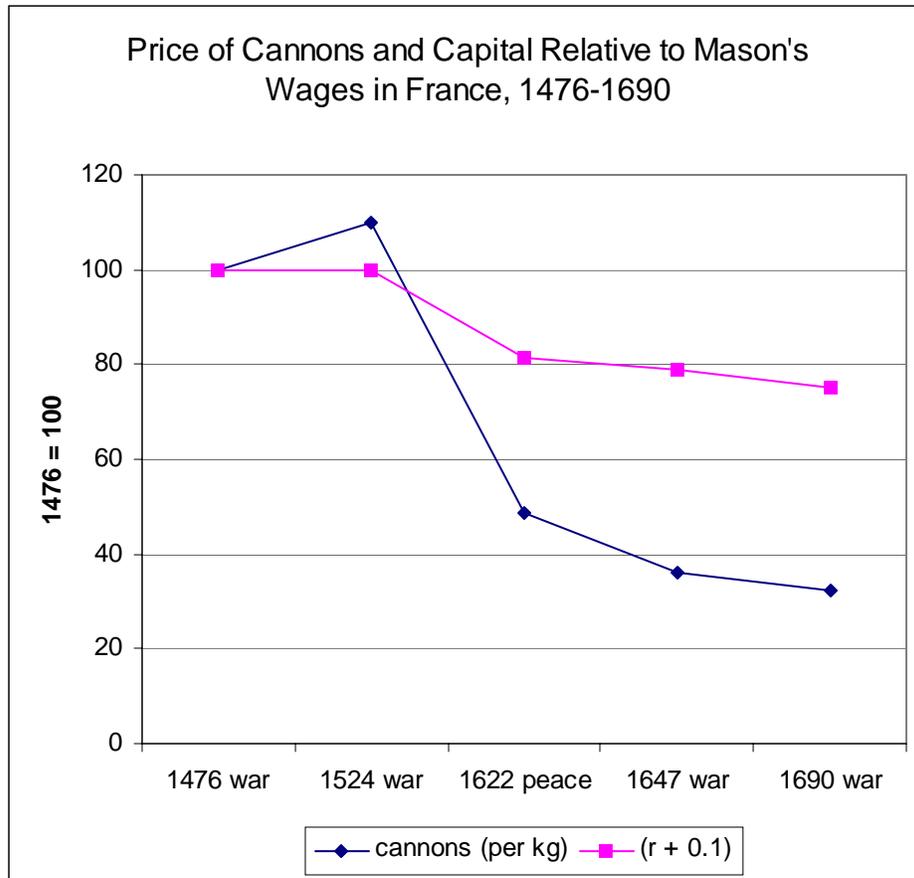


Figure 7. Prices of cannons and capital relative to a mason's wage in France, 1476-1690. The relative price of capital is the second one used in Figure 6.

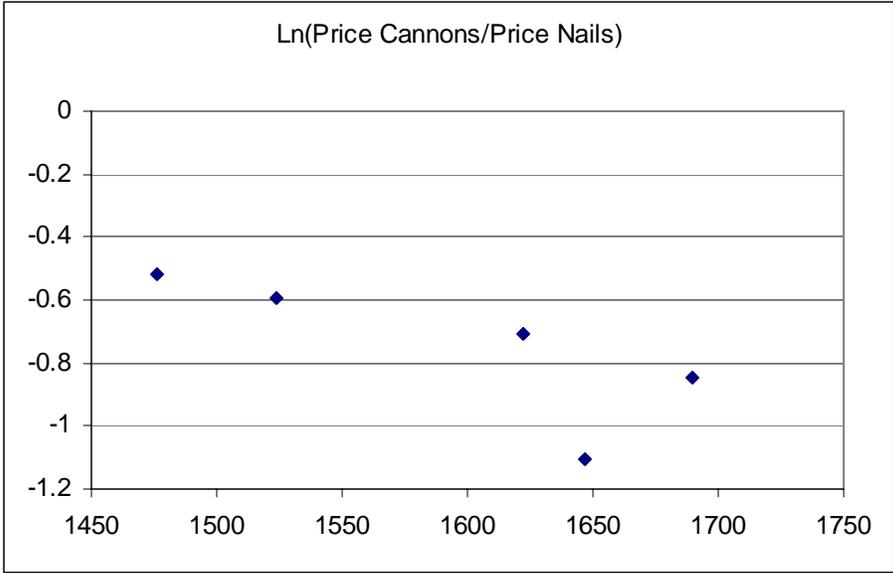


Figure 8. Ln(Price of cannons/price of nails) France

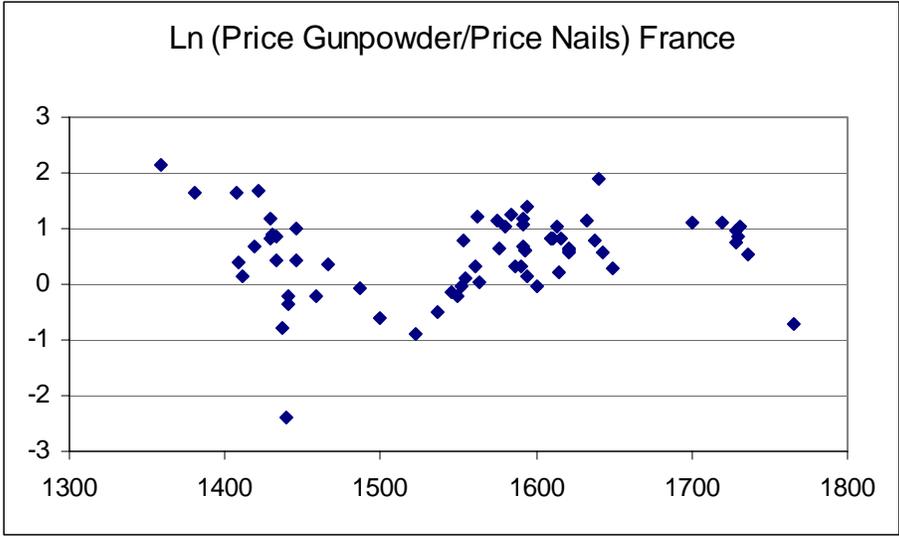


Figure 9. Ln(Price of Gunpowder/Price of Nails) in France

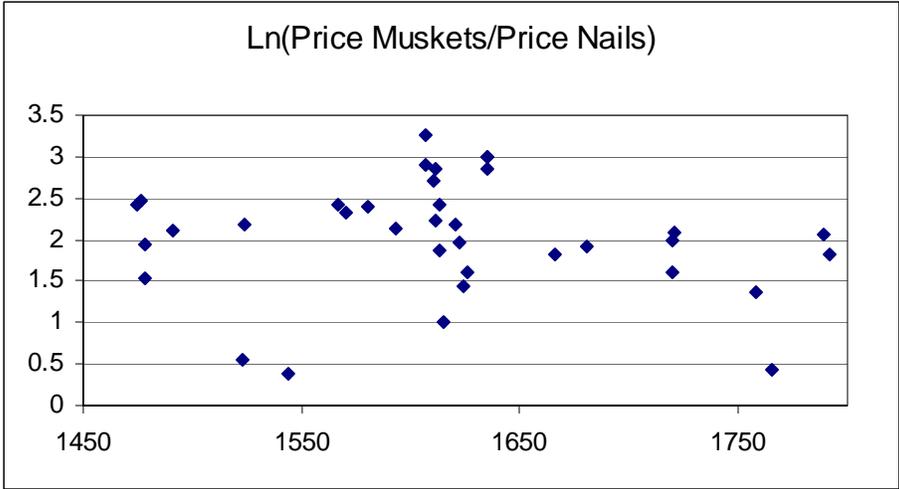


Figure 10. Ln(Price Muskets/Price Nails) France

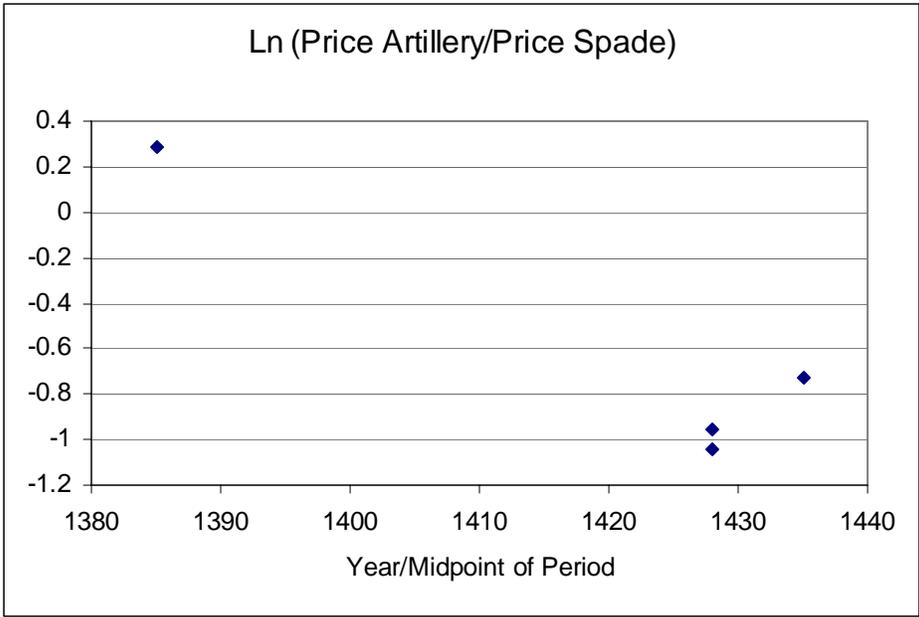


Figure 11. Ln (Price Artillery/Price Spade) England

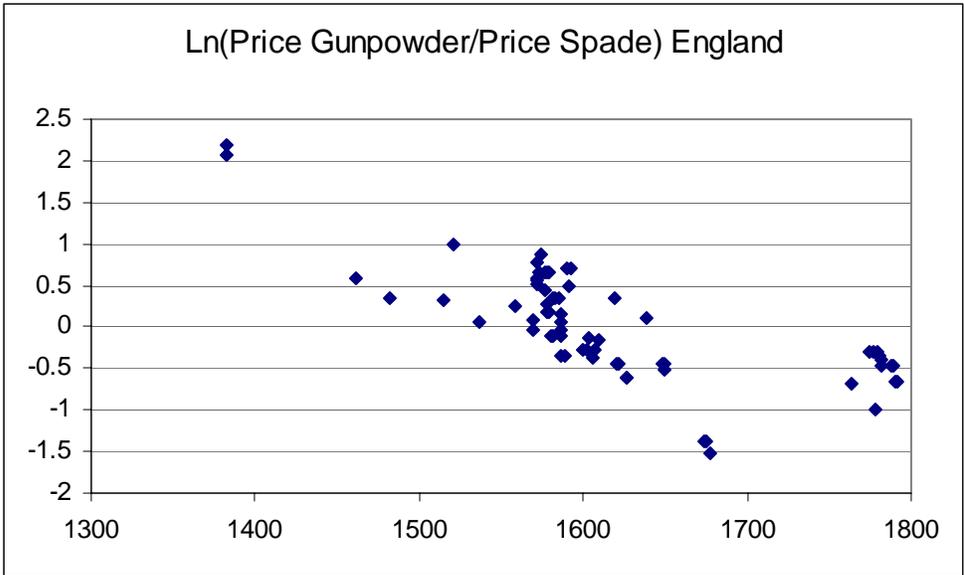


Figure 12. Ln(Price of Gunpowder/Price of Spades) England

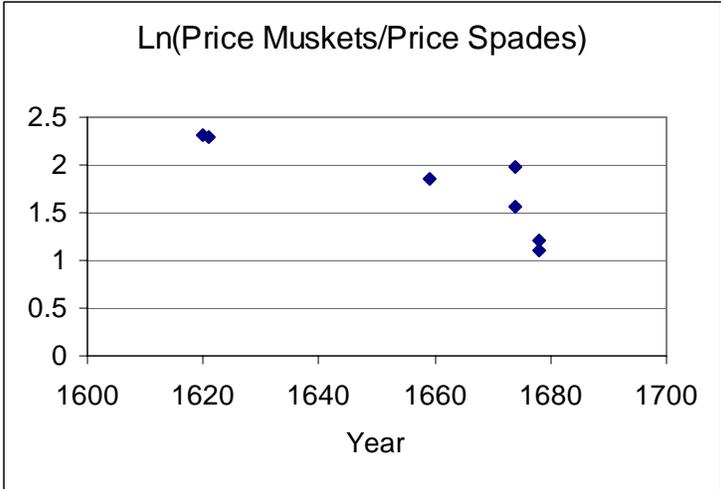


Figure 13. Ln(Price Muskets/Price Spades) England

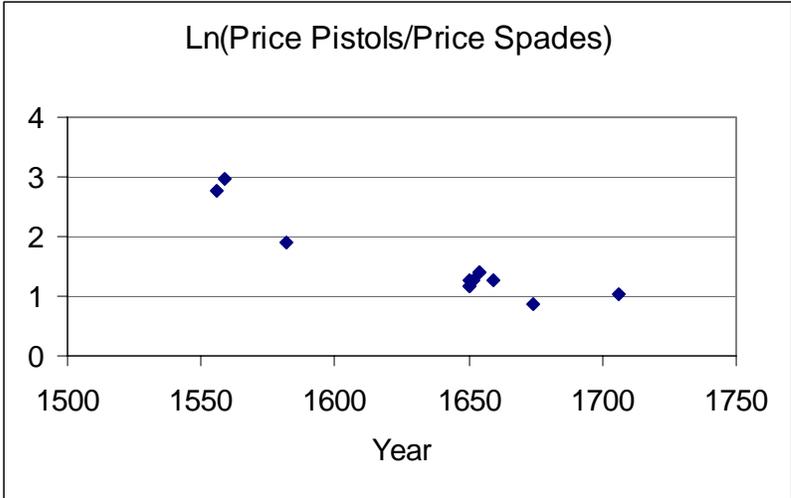


Figure 14. Ln(Price Pistols/ Price Spades) England



Figure 15. Drawing and dimensions of early handgun from the Tannenberg Castle in Germany. This handgun, which weighed 1.2 kilograms, was manufactured out of bronze at some point before 1399; the dimensions are in millimeters. Source: Rathgen, illustrations 29 and 30.

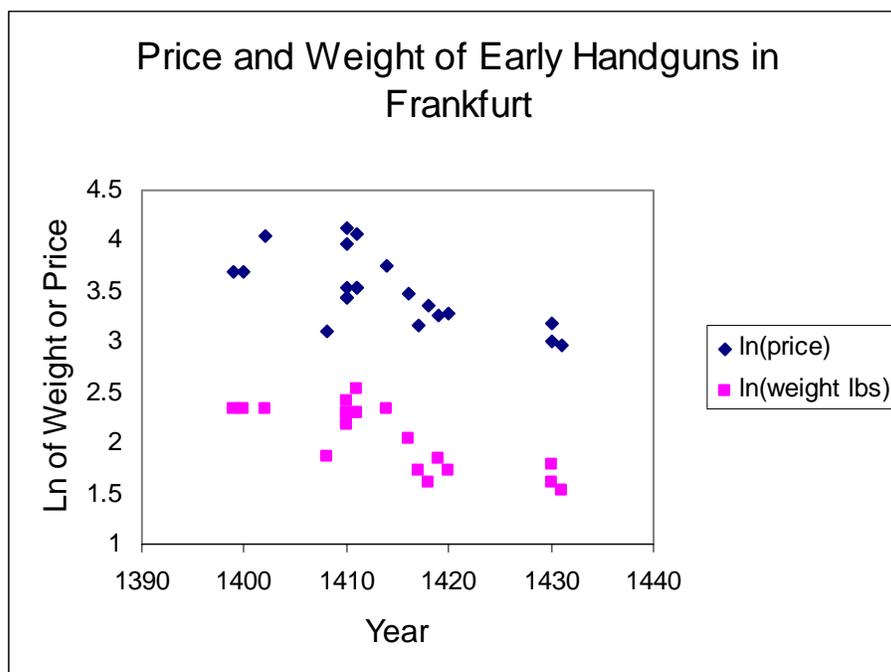


Figure 16. Ln(Price of Handguns) and Ln(Weight of Handguns) in Frankfurt. Prices are measured in grams of silver; unit of weight is the Pfund, which equals 0.467 kilograms.

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¹ Inalcik 1975; Chase 2003, 2, 97-98; Heywood 2002; Heywood 2002; Parker 1996, 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 1996, 18-19).

³ Cipolla 1966.

⁴ In his detailed study of gunpowder technology, for example, Hall focuses on the big breakthroughs and downplays all sorts of steady improvements in the late sixteenth and seventeenth centuries that would interest an economist. In Hall’s words, these steady improvements “made gunpowder and firearms cheaper, easier to produce, and still more readily available than ever before, but they did little or nothing to alter the basic characteristics of the guns themselves” (Hall 1997, p. 215). Other military historians and historians of technology are equally blind to the constant improvements in military technology.

⁵ 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.

⁶ The results would be the same if we assumed a constant returns technology, but that seems harder to verify than assume small firm size and open entry.

⁷ For examples, see Rodger 1998, 213-15, 225-226, 233, for naval cannon making and its regulation in sixteenth-century England; Peter 1995, for the same industry in late seventeenth-century France; and Rathgen 1928, for cannons and handguns in late medieval Germany. The English Ordnance Board nurtured the iron gunfounding industry in sixteenth-century England, but its goal was lower prices for cannons. Similarly, French officials, as Peter shows (see pp. 41-42, for an example), did detect occasional signs of collusion among cannon makers in a particular market, but their reaction was usually to see if prices were lower elsewhere.

⁸ The problem is that there are very few dates when we have all the prices available. There are ways of filling in the missing data, which fill in the missing values using relationships between available data and then estimate the regression coefficients taking into account the way the procedure affects the estimation process. Unfortunately, I do not yet have enough data to use these techniques for my weapons regressions, though it may eventually be possible for English pistols or muskets. I was able to use it, however, for gunpowder prices, as I mention below. For more on this technique, see King, Honaker et al. 2001.

⁹ Clark 2003. As Clark points out, industries such as printing did witness striking technical change in the early modern period, but they were relatively small. The military, however, was a major part of the economy, at least in Europe.

¹⁰ Mokyr 2002; Clark 2003, table 1; Hoffman 1996, especially tables 4.8 and 4.9; and, for English agriculture, Allen 1992.

¹¹ 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 (Crafts and Harley 1992, Table 5).

¹² Random variation of the error term u , for instance, could leave us with a change in u between the first and last period that quite different from its expected value of zero.

¹³Another possible tactic here would be to try to run regression for equation (2) with missing variables and then try to estimate the resulting bias in the coefficient of time; I will attempt this in the future, as more data becomes available.

¹⁴ 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 .

¹⁵ In this case, the bias in the estimate for d will be RE , where E is now the k by 1 matrix formed by the coefficients e_i of the omitted factor prices and R is the 1 by k matrix of time coefficients we get when we regress the k omitted prices $\ln(w_i/w_0)$ on the variables included in the regression. If we include factors for which the e_i 's are relative large and only leave out those with small e_i 's, the E will be small and so will the bias.

¹⁶ See the eighteenth-century Encyclopédie of Diderot and d'Alembert (Diderot 1751-1772), s.v. "Clous" 3: 548; Chisholm 1910, s. v. "nails"; and Mokyr 1990, 62. Although the Encyclopédie article does not show any obvious signs of a change in the way nails were made in mid-eighteenth-century France, the division of labor may have already progressed, and machinery devised to cut nail rods may have been put into use as early as the seventeenth century.

¹⁷ 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.

¹⁸Gunpowder is one case where factor prices might cause enough bias to account for the negative time coefficient. The reason is that the price of saltpetre, a major component of gunpowder, declined during the early modern period, at least in England. There I had enough prices to use methods devised to cope with missing data, and I was therefore able to run regressions with statistically imputed values for the missing prices of charcoal, saltpetre, and sulfur. The results suggested that the negative time coefficient could be a chance result, but only because the saltpetre prices were dropping rapidly. The problem then, however, is explaining why the saltpetre prices dropped. Saltpetre was one of the rare commodities for which intercontinental transport costs dropped before 1800 (O'Rourke and Williamson 2002), and if productivity was not growing in gunpowder production, then it was it in the production of saltpetre and its transport from places like India. Rathgen 1928, 93-99, provides evidence that in the late fourteenth and early fifteenth centuries German cities devised ways to produce saltpetre domestically at low cost rather than buying expensive imported saltpetre.

¹⁹ 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 (Rogers and Rogers 1866-1902; Avenel 1968) 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 mousquet (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 arquebuse (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 Hall 1997; Lynn 1997. Another problem with the data is that it includes some estimates for wholesale purchases alongside what primarily prices for smaller quantities; I have included these even though one might presume they would involve some sort of volume discount.

²⁰Rathgen 1928, 68-74; Hall 1997, 95.

²¹The meager evidence that exists suggests that long run interest rates may perhaps have been declining during the years 1399-1431, but very slowly: Winter 1895. I have therefore assumed that the interest rate was constant, as was the rate of depreciation, and that the sales price of capital was proportional to the skilled wage. Under these assumptions, the rental price of capital divided by the wage will be a constant, and its coefficient in equation (2) will be part of the constant term a . From Rathgen's description, the city of Frankfurt did not seem to act like a monopsonist; in particular, it sometimes bought guns from other nearby cities, where the prices were similar. In any case, even monopsony would not cause a problem, so long as entry was free, and Rathgen's evidence suggests that the gunsmiths and metal workers changed over time and came from other cities as well.

²²Harley 1993.

²³Rathgen presents evidence that the range of early cannons jumped from 240 to 3000 meters between 1388 and 1423 (Rathgen 1928, p. 21). He assumes that the projectile was the same (a 100 pound stone).

²⁴Chase 2003, 30. The quote from Louis XIV's memoirs for his son is taken from Louis-XIV and Sonnino 1970, 124.

²⁵Elia and Ricci 1942, 1:66.

²⁶The argument here is taken from McAfee and Fullerton's model of a research tournament among risk neutral firms with different costs of effort (Fullerton and McAfee 1999). A somewhat different argument could be made using other models of research tournaments, such as Reinganum 1985. Note that the argument here does not imply that European arms makers would become enormously wealthy. The competition is among rulers, and they receive the prizes. They would of course distribute resources to arms makers and generals to support and encourage innovation, but because the arms making industry was competitive in early modern Europe, long run profits would be zero, and arms makers would not become wealthy for long.

²⁷Chase 2003, 32-33.

²⁸Romer 1990.

²⁹For examples of how warfare destroyed capital and interfered with trade, see Hoffman 1996.

³⁰My account of the origins and spread of volley fire is borrowed from Parker 1996, 20-21.