The Great Divergence and the Economics of Printing

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1 Introduction

One of the finest paradoxes in global history is the statement by Francis Bacon, champion of empiricism and a major figure in Europe's intellectual ascendancy, about the importance of inventions in changing human lives. The three great inventions chosen by Bacon to make his case are printing, gunpowder, and the compass. All three were of Chinese origin.[1]

The failure of China to industrialize ahead of Europe, leading to what Kenneth Pomeranz has termed "The Great Divergence", has puzzled schol-

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[1] The statement in question is as follows:

"Again, we should notice the force, effect, and consequences of inventions, which are nowhere more conspicuous than in those three which were unknown to the ancients; namely, printing, gunpowder, and the compass. For these three have changed the appearance and state of the whole world: first in literature, then in warfare, and lastly in navigation; and innumerable changes have been thence derived, so that no empire, sect, or star, appears to have exercised a greater power and influence on human affairs than these mechanical discoveries."

Francis Bacon, *Novum Organum (1620)*, Book I, CXXIX.

ars ever since the facts on China's technological accomplishments were uncovered by the work of Joseph Needham.[2] China was very likely well ahead of Europe in terms of income per capita in the centuries preceding the European Renaissance. At its peak, 11th century China had a GDP per capita of between 1,200 and 1,500 US dollars of 1990 according to the most recent set of estimates (Broadberry et al. 2014). England, the future cradle of the Industrial Revolution, had a GDP per capita of 754 US dollars around that time (Broadberry et al. 2013). While significant effort has been directed towards the modelling of endogenous transitions from pre-industrial to modern economic growth (Galor and Weil 1999, 2000), the question of how Europe could leapfrog China and why this would take place over the early modern period rather than at any other time in human history has not been explored to the same extent.

Whatever happened in Europe, it is clear enough that it started happening around the 16th century and progressively accelerated over the 17th and 18th centuries. The change is perceptible not so much in figures of income per capita, which took long time to rise beyond Holland and Northern Italy, but rather in the several intellectual and social revolutions that Europe was to experience from the 16th century onwards: the Scientific Revolution, the Enlightenment, the Industrial Revolution.

Given the apparent change of trend in European development beginning around the 16th century, it is tempting to search the historical literature for a structural break; an exogenous factor crashing into the European scene at this time and shifting the continent's trajectory towards faster accumulation of knowledge and, eventually, modern economic growth. As it turns out, a significant body of literature in the social sciences has long argued for precisely such an event in the European sphere. I am referring, of course, to the invention of printing.

The advent of printing has long been regarded as a pivotal moment in European history. In the words of Myron Gilmore (1962, p. 186), "It brought

[2] Needham (1954 - 2008), Pomeranz (2000).

about the most radical transformation in the conditions of intellectual life in the history of western civilization." Printing made existing knowledge far more accessible than it had been hitherto: Europe passed from producing 2.7 million books during the 14th century to 217 million books during the 16th century (Buringh and van Zanden 2009). If we follow the endogenous growth literature and consider existing knowledge as the primal input in the production of new knowledge, the consequences of printing can be readily grasped.[3]

Recent research in economics corroborates this view. Dittmar (2011) shows how an early adoption of printing technology is associated with faster economic growth among European cities. Reverse causality does not seem to explain the trend as the early adopters of printing had no previous advantage. Along the same lines, Baten and van Zanden (2008) use country-level data covering the pre-industrial period to show how book production per capita during any given 50-year period is a good predictor of economic growth over the next 50-year period.

But if I am to argue that the invention of printing put Europe on a transformative track leading among other things to the Industrial Revolution, I have by no means reduced the puzzle of the Chinese experience - if anything I have increased it. For as mentioned above, printing was invented in China - a full seven centuries earlier than in Europe. And while printing did spread and was eventually to exert an important influence on the Chinese civilization, it did not lead to anything as momentous as the transformation of European thought and society over the early modern period. The aim of this paper is to contribute to our understanding of why this was the case.

The central argument of this paper is as follows: the invention of printing

[3] As an example, consider the figure of Nicolas Copernicus, whose revolutionary work presupposes a mastery of Greek astronomy - as summarized in Ptolemy's *Almagest*. Would Copernicus have been able to study Ptolemy in detail without the invention of printing? In the words of Elizabeth Eisenstein: "As a student at Cracow in the 1480s, the young Copernicus probably found it hard to get a look at a single copy of Ptolemy's *Almagest* - even in a corrupted medieval Latin form. Before he died, he had three different editions at hand" (Eisenstein 1984?, p. 234).

had different consequences in China and Europe because the Chinese writing system made printing much more difficult than the European one. In other words, China had a severe handicap with respect to Europe when it came to knowledge dissemination (and therefore knowledge creation), and this handicap manifested itself only from the moment in history when printing was invented. Most of the paper will be concerned with the analysis of how the Chinese writing system leads to higher printing costs and to the adoption of block printing technology - as opposed to the technologically more advanced technology of movable type. Once this is well established, the final two sections will return to the issue of how developments in the printing world may have influenced the long-term evolution of knowledge and economic development in these two major civilizations.

2 The evolution of printing in China and Europe

While both China and Europe developed printing over the pre-industrial period, and China did so significantly earlier, the two regions differed on the technology employed. Most of Chinese printing used xylography, commonly called block printing, while essentially all European printing employed the comparatively more advanced technology of movable type. To make matters even more intriguing, both types of technology were first invented in China.

With block printing technology characters are carved onto a wooden block, which is then inked with the help of a brush, and an impression is taken by laying a sheet of paper over it and rubbing. Blocks could then be stored for future usage. The invention of block printing takes place in China no later than the 8th century CE, possibly earlier, and precise details regarding the inventor are unknown. By the 10th century, the technology was used on a truly enormous scale for the printing of the entire canons of Confucian, Buddhist and Taoist scriptures by the government and religious orders in China.

Movable type differs from block printing in that each character is carved or cast into a separate piece of wood, metal, or other material. The characters (or "types") are then assembled together into a "form", which is laid on a tablet and from which impressions can be taken as in block printing. The form is disassembled after use, and the types stored for future usage. The invention of movable type is ascribed to a certain Pi Sheng sometime in the years 1040s. Sheng used ceramic for his types, but we have no surviving texts or pieces; we know of his invention by the account of the renowned polymath Shen Kuo in his *Dream Pool Essays* of 1088. From that moment, and throughout the early modern period, China experimented with different materials for movable type and the invention spread to neighbouring nations - most notably Korea, where we find the first recorded use of metal in movable type technology in the year 1236 .

Despite this early invention, a full four centuries in advance of Europe, movable type remained a marginal technology in China up until the late 19th century. China printed books in large quantities, and developed a dynamic private publishing sector from the late Ming dynasty onwards (Meyer-Fong 2007), but almost all of this printing was made using block printing. Chow (2004, p. 68) tells us that we know of about 100 book titles printed using wooden movable type during the Ming dynasty which, when reported to the total number of titles printed during this period, equals no more than 1.5% of all titles.

Indeed, movable type was never forgotten, but its use was largely limited to two particular areas. First, large government printing projects. These took place no more than once or twice per century and could reach truly gigantic scales. As an example, the Grand Encyclopaedia of Ancient and Modern Knowledge (Gujin Tushu Jicheng), presented to the Chinese Emperor around the year 1725, consisted of 5,020 volumes, 800,000 pages and over 100 million Chinese characters. Sixty-six copies of the full Encyclopaedia were made (Tsien 1985, p. 185, 216). Next to this, the second instance of repeated usage of movable type technology in China will appear surprising: itinerant printers of family genealogies (Heijdra 2004, p. 227; Chow 2004, p.68). These were printing entrepreneurs travelling from province to province with their set of movable types and offering to produce genealogies for the exclusive circulation among kin members. Their types were made on wood, a much cheaper alternative to the metal types often used by the government. The next section will return to this issue with an explanation for the choice of movable type technology by these two seemingly very different printing purposes.

In opposition to China's early invention and slow and progressive transition to printing, the West discovered printing only towards the middle of the 15th century and saw the invention spread like wildfire. Block printing and movable type appear at about the same time, though the techniques used in block printing can be traced back to the printing of sacred images during the 14th century (Febvre and Martin 1976, p. 45-49). Block printing pretty much disappears as a technology for producing text shortly after its invention, while movable type becomes ubiquitous. Europeans printed their first book using movable type in the 1450s, yet the technology was in place in 110 towns and cities throughout Europe by 1480 and in as many as 236 places by 1500 (Febvre and Martin 1976, p. 182, 186). Printing shops were present from Portugal to Russia and far beyond the main cities, in places such as Angoulême, L'Aquila or Kuttenberg.

It is also the case that European printing, right from the start, was in the hands of private firms and the state never played a dominant role in it. While the Chinese state was comparatively a larger player, especially in earlier centuries, by the 16th century the private printing industry had developed enough as to be the dominant player in China as well. Thus, for most of our subsequent analysis, it will be relevant to consider printing as a for-profit activity.

3 Costs of early modern printing technologies

Scholars of the history of Chinese printing have long pointed at the complexity of China's logographic script as the main reason behind its failure to adopt movable type technology. As Denis Twitchett explains, "The basic problem of Chinese typography was, and still remains, the fact that the repertory of Chinese characters is virtually limitless. Even today, after decades of efforts at limiting the number of characters in use, a Chinese printer needs an active stock of more than 8'000 characters, [...] No Chinese printer ever had a 'complete' font including every Chinese character" (Twitchett 1983, p.76).[4]

To be clear, the problem was not that Chinese printers needed to produce thousands of types in order to use movable type technology, for that was also the case in the West. A medium-sized, private-owned printshop in China would have been able to operate with about 40,000 types (Heijdra 2004). That is not more than what was common in the West, as inventories of early modern printshops commonly reveal fonts of 40,000 to 80,000 types (Febvre and Martin 1976, p. 110-11). Western alphabets may consists of less than 30 distinct characters, but each character is repeated a large number of times within a given page. The problem, then, was not the total number of types needed but their structure. Europeans needed a large number of copies of a reduced set of distinct characters, while the Chinese required a small number of copies of a very large set of distinct characters.

These different requirements resulted in very different printing costs, and that for at least two reasons. First, the cost of producing a large number of copies of a reduced set of distinct characters is much smaller than that of producing a few copies of a very large set. There are important economies of scale in the production of copies of a given character. Indeed, the most important contribution of Gutenberg to printing technology was arguably not the invention of the printing press but rather the development of the punch-matrix process for the production of types. In this process, a punch was carved with the shape of each letter in a hard metal like steel, which was then used to strike a soft copper matrix to create a mould. The moulds could then be used to cast a large number of copies of each letter by filling them with hot metal in liquid form. The process is economical as long as the

[4] Similar opinions regarding the difficulty of implementing movable type printing with the Chinese script can be found in Carter (1955, p. 242), Febvre and Martin (1976, p. 75), McLuhan (p. 152) and Eisenstein (1979, p. 27, f. 65).

number of copies to be produced out of each distinct character is large. If that is not the case, the preferred method is to carve each individual type on a soft metal such as copper or even on wood, as was indeed done in China. Using the punch-matrix process Europeans were able to produce a set of several thousand western characters for a fraction of the cost of a full font of Chinese types.

But this was not all, for a second and equally imposing problem faced Chinese printers brave enough to employ movable type. Once types are produced, the largest use of labour involves the composition of the text into a form. This is an easy enough job with a western alphabet, as copies of every existing character can be arranged within a middle-sized box with a few dozen compartments. In contrast, the challenge of finding the precise Chinese character among a collection of several thousand ones is of a different magnitude. The Chinese developed practical methods to navigate their collection of types in search of the required one, but a standard page of text could always be composed much faster, *ergo* for a fraction of the cost, in Europe.

In what follows I translate the above descriptions into precise statements about the differences in cost functions for printing between China and Europe.

The total cost of any printing project may be divided into two broad categories. First, for every page of text there is the cost of producing woodblocks under block printing and composing the text under movable type. This cost is thus proportional to the number of pages being printed. Second, there is the cost of producing copies out of each page. This corresponds to the cost of paper, ink and labour employed in printing; plus the cost of replacing types or woodblocks as these wear off with usage. This cost is proportional to the total number of printed pages, which equals the print run of the title being printed times the number of pages. To this, movable type printers should add a third item: the initial cost of producing a full set of types, which must be in place before the first page is composed.

Let us note as n the number of pages to be produced and r the number of copies to be taken from each page - i.e. the print run. The total number of printed pages is therefore nr. The cost function for block printing would then be of the form:

$$C_b = \alpha_b nr + \beta_b n \tag{1}$$

and that for movable type printing:

$$C_m = \alpha_m nr + \beta_m n + F \tag{2}$$

with α_b and α_m being the cost per page of making copies out of existing woodblocks or forms, β_b the cost of creating a one-page woodblock, β_m the cost of composing one page of text, and F the cost of a full set of types.

As presented above, the cost functions cover the case where a single book title of n pages is to be printed r times. A simple change of variables allows us to use the same formulas for the case where J different titles are to be produced, each with its own number of pages n_i and its own print run r_i, where $i = 1...J$. In that case, the total cost using block printing technology would be $C_b = \alpha_b \sum_i n_i r_i + \beta_b \sum_i n_i$. Defining n as the total number of pages for all books, that is $n = \sum_i n_i$, leads to $C_b = \alpha_b \sum_i n_i r_i + \beta_b n$. This may be rewritten as $C_b = \alpha_b n \sum_i \frac{n_i}{n} r_i + \beta_b \sum_i n_i$. Finally, defining r as the weighted average of print runs, that is $r = \sum_i \frac{n_i}{n} r_i$, leads to the exact same expression as equation (1), with n and r interpreted as just described. The same applies to equation (2).

In the cost functions above, parameter β_m will be considerably smaller than β_b since composing a page of text, even with Chinese characters, is less costly than carving a woodblock of the same page. This translates into a cost advantage in the production of new pages of text when using movable type. It follows that, for a profit-maximizing printing entrepreneur, the decision to use movable type depends on whether the cost advantage on the production of new pages is important enough to justify the initial fixed cost expenditure in a full set of types. On the other hand, the production of copies out of each page is not lower under movable type (parameter α_m is not lower than α_b). The cost of paper, ink and labour for printing are in principle the same for both technologies, and movable type producers would need to replace types far more often than block printers replace woodblocks (see next section).

Let us now imagine that a printing entrepreneur wishes to produce one or more book titles for a total number of distinct pages equal to n and an average print run of r. Using equations (1) and (2), it is easy to show that $C_m < C_b$ - and movable type will be his chose technology - when the following condition is satisfied:

$$n > \frac{F}{(\beta_b - \beta_m) - (\alpha_m - \alpha_b)r} \equiv n^*(r) \qquad (3)$$

Equation (3) tells us that movable type will be preferred when the number of distinct pages to be printed is large enough - an intuitive result as the entrepreneur saves on each page of text that has to be composed instead of carved. The shape and position of the $n^*(r)$ function is determined by the values of the different cost parameters, and once its position is known we may determine the printing technology of choice for any combination of n and r. To advance in the analysis, then, we need quantitative estimates of the cost parameters of the model for both pre-industrial China and Europe. I turn to this in what follows.

4 Estimating cost parameters

I estimate the different parameters of the cost functions for pre-industrial printing from the historical literature as I detail below. For analytical purposes, cost parameters may be used in local currency units as these are canceled out in equation (3). For the purpose of building up intuition, however, it will be useful to express these parameters in a common metric which allows for comparisons between Europe and China. I will thus normalize all cost parameters by the daily wage of low-skill labour in, respectively, early modern Europe and China. To avoid comparability issues between different sources I obtain all cost parameters for a given technology from the same source. The wage for low-skill labour is also, as much as possible, obtained from the same source.

Block printing in China

My source for this is the detailed analysis of Chinese printing in Chow (2004). The first element would be the cost of producing woodblocks. Chow estimates labour and materials for producing a standard 400-characters page in woodblock at between 0.10 and 0.15 taels during the early modern period (p. 37). I will use the middle of this interval, or 0.125 taels per woodblock, in what follows.

This same source also provides us with a figure of 1 tael per month as the remuneration for construction workers (p. 53), which I will take as a reasonable definition for low-skill labour. Van Dyke (2005) quotes Chinese wages in both monthly and daily form for the 18th century, revealing a ratio of between 20 and 25 among them. This results in a low-skill wage of between 0.04 and 0.05 taels per day for the early modern period. This figure is corroborated by Allen et al. (2011), who calculate an average daily wage of 0.044 taels for unskilled labour in late 18th century China. Using a figure of 0.045 taels per day results in a cost of 2.78 days of low-skill labour for a one-page woodblock.

Turning to the production of copies, Chow gives a detailed example in which the total cost for paper, ink and labour for printing comes to 4.48 taels for 560 copies of a 24-page document - or 0.00033 taels per page (p. 45). The paper employed in this case was bamboo paper, the most popular type of paper used in commercial Chinese printing and one of the least expensive ones. This implies a cost of paper, ink and labour equal to 0.73% of the daily wage per printed page. About 78% of this, or 0.57% of the daily wage rate, corresponds to the cost of paper (p. 35), and I will assume that ink and printing labour are equally responsible for the remainder (0.08% of the daily wage for each).

In addition to the cost of paper, ink and labour, woodblocks could also need to be replaced due to wear and tear if a sufficiently large number of copies is produced. I am choosing not to include this cost in my calculations as the print runs of early modern works fell far below the estimated lifetime of woodblocks. Indeed, the literature suggest that up to 25'000 copies may be taken from a woodblock before replacement is needed (Tsien 1985, p. 370). We have hardly any evidence on print runs in early modern China, but European books were typically produced in print runs of between 500 and 3,000 copies during this period - and there is no reason to believe Chinese print runs were much larger than this (Buringh and van Zanden 2008).

Movable type in China

My source in this case is Heijdra (2004), who reports printing costs for movable type in China during the early 19th century. An underlying assumption is therefore that Chinese movable type technology did not improve significantly between the early modern period and the early 19th century which, on the face of it, appears reasonable given China's limited use of the technology throughout this time.

Heijdra (2004) reports the cost of a set of 40,000 types, enough for a small commercial publisher, at 597 Spanish dollars when the types are made of wood. Metal types would cost four times as much. We do not have data on Chinese wages in Spanish dollars from this same source, but a comparison is possible by passing through an intermediate step. Heijdra (2004) estimates the total cost of producing woodblocks at 1 Spanish dollar per page. Given my previous estimate of 2.78 days of low-skill labour per woodblock, a full set of wooden types in early modern China would then cost the equivalent of 1660 days of low-skill labour. For metal types the figure would be 6640 times the daily wage.

A full set of wooden types would need to be replaced due to wear and tear approximately every 500'000 pages (Heijdra 2004). Obviously types do not break up all at once but need progressive replacement in proportion to the number of pages being printed. This implies a cost of 0.33% of the daily wage per printed page in replacement of wooden types. Metal types would last 12.5 times longer, resulting in a cost of 0.11% of the daily wage per page in replacement of metal types. If we add the cost of paper, labour and ink derived above - which we may assume the same as in block printing - we obtain a cost per printed page of 1.06% of the daily wage for wooden types and 0.84% for metal types.

The last element missing is the cost of composition when using movable type. This was very high when using Chinese characters, and is estimated by Heijdra (2004) at 0.5 Spanish dollars per page. This equals 1.39 times the daily wage for low-skilled labour using the same transformation as above.

Movable type in Europe

My source is the seminal work of Febvre and Martin (1976), which details printing costs for early modern France. One aspect that needs discussion is the fact that the estimates above for movable type in China correspond to a very small printing enterprise - one operating with a single full set of types. Most European printing firms were larger than this: they would have several fonts available (with a full set of types for each font), and quite possibly two or three printing presses (a piece of equipment never introduced in China). In theory, a small printing shop could be set up for as little as 50 livres, as the cost of a full set of types ranges between 20 and 30 livres and a printing press would sell for between 23 and 30 (Febvre and Martin 1976, p. 110-111). While this constitutes a plausible lower bound, I will focus on larger estimates which represent better the average European printing firm. Febvre and Martin give inventory values for three different printing firms in early modern France. Their middle example, corresponding approximately to an average workshop, comes at a value of 351 livres. Dittmar (2011) corroborates this value by giving an interval of between 250 and 600 livres for the cost of setting up a printing enterprise in early 16th century Europe.

Febvre and Martin report a wage for low-skill labour of 6 sols per day (p. 132), where 20 sols make up one livre. An average European printing workshop would therefore cost the equivalent of 1170 days of low-skill labour. As all European printing was made using metal types, this figure is to compare with the 6640 days of wages for a single full set of metal types in China.

In addition to this, composition was much easier with the small set of characters of European languages. Compositors in 16th century France were paid about 12 sols per day, and would produce between 1 and 3 full forms per day (Febvre and Martin 1976, p.131-132). In European printing, several pages were composed within a single form and printed at the same time - thus taking advantage of the larger surface that a printing press could cover as compared to the hand method employed in China. Each European form would have 4 pages of text in a folio format, 8 pages in a quarto format and 16 pages in an octavo format (Febvre and Martin 1976, p. 69). Assuming that the rate of 1 to 3 forms per day refers to 1 octavo, 2 quartos or 3 folio forms, the rate results in between 12 and 16 pages per day. Taking folio as the format best comparable to the Chinese one, a rate of 12 pages per day implies a composition cost of 1 sol per page, or 1/6 of the daily wage of low-skill labour.

The one area where Europeans were almost certainly at a disadvantage was the cost of paper. Paper was more expensive in Europe since it was produced from rags, which were always in short supply, as opposed to the large abundance of bamboo and other cheap materials in China. Febvre and Martin (p. 112) give a rather very broad interval of between 10 and 30 sols for one ream of paper (500 pages). This corresponds to between 1.67 and 5 times the daily wage of labour, but additional evidence leads me to prefer the upper bound of this interval. Chow (2004, p. 29), who clearly states that paper was far more expensive in Europe, discusses how Dutch workers during the 16th century would have to sacrifice between 6 and 8 days of wages to buy a ream of paper; while the data on English prices and wages from Clark (2005, 2007) suggest an even larger ratio - between 15 and 25 day wages for a ream of paper. While Clark's data may refer to higher quality paper, the overall impression of paper being considerably more expensive than in China appears vindicated. In what follows I will use the upper bound estimate of Febvre and Martin, or 30 sols per ream of paper. This leads to a per page cost equal to 0.06 sol or 1% of the European daily wage - slightly less than twice the Chinese cost. All the conclusions of the paper would continue to hold if I were to assume a lower cost of paper instead.

Next to the cost of paper, other costs per printed page are of second order. The labour for operating the printing press was remunerated quite well: about 12 sols per day, or the same as compositors (Febvre and Martin 1976, p. 132). Two pressmen were needed to operate a printing press, and together they would produce about 3'000 impressions per day, each impression consisting of 4 pages in the folio format. Thus, 24 sols would pay for printing 12,000 pages - a cost of exactly 0.002 sol per page. The cost of replacing types, assuming a cost of 30 livres for a full set of types and the same durability as metal types in China, comes to just 0.0001 sol per printed page. Finally, Febvre and Martin do not give any indication of the cost of ink, so I'll assume this to be similar to the cost in China and set it to 0.08% the daily wage per printed page - or 0.0048 sol. This adds to a total cost of paper, ink, printing labour and replacement of types equal to 0.0669 sol per printed page, or 1.115% of the daily wage for low-skill labour. Clearly paper dominates this total and different estimates on the other components are unlikely to change our conclusions.

The final piece of the puzzle would be the cost of block printing technology in Europe. To the best of my knowledge, there are no direct cost estimates for this technology in Europe for the simple reason that it was hardly ever used: movable type replaced it shortly after its European introduction. As the technical side of block printing would not have differed much between China and Europe, a reasonable approximation may be obtained by assuming that the cost of producing woodblocks, when expressed in terms of daily wages, would have been the same as in China, that is 2.78 times the daily wage. The cost of paper, ink and printing labour may be assumed to be the same as for European movable type - which assumes that block printers would have been able to use printing presses.[5] This leads to

[5] A reasonable assumption, as Europeans printed images using carved blocks, and copies

a cost per printed page equal to 0.0668 sol or 1.113% of the daily wage - essentially the same as the per page cost for movable type.

The above discussion is summarized in table 1, which reports the estimates of parameters $\alpha_b, \beta_b, \alpha_m, \beta_m$ and F for both China and Europe. As anticipated above, large differences exist in parameters β_m and F between China and Europe. China has some advantage in parameter α_b given its lower cost of paper, but not so much in parameter α_m as the dearness of European paper is to a large extent compensated by the very low cost of replacing types. With these parameter values at hand, I proceed to analyze the choice of printing technology in China and Europe for any given printing job.

[Table 1]

5 Choice of printing technology

For any printing project characterized by n distinct pages and an average print run of r, movable type will be the printing technology of choice if the inequality in (3) is verified; otherwise block printing will be preferred. The values for n and r are to be thought as the output of a printing enterprise over a reasonable planning horizon, say one or two years. Over the early modern period most printing enterprises were quite small, producing just a few titles per year, so reasonable values for n would range from the high hundreds to the low thousands. Print runs over this period would range from as little as 500 to as much as 3,000 - rarely beyond that figure.[6] Buringh and van Zanden (2009, p. 415) assume an average print run of 1,000 for early modern Europe, while explicitly stating this is a conservative estimate.

For the comfort of readers, I reproduce the inequality from expression (3) hereafter:

were extracted with the same printing presses as for text.

[6] Dittmar (2013) presents some data on European print runs.

$$n > \frac{F}{(\beta_b - \beta_m) - (\alpha_m - \alpha_b)r} \equiv n^*(r)$$

In we plot the $n^*(r)$ function on a bidimensional space with variable r on the horizontal axis, we will find it intercepts the vertical axis at $\frac{F}{(\beta_b - \beta_m)}$ and, provided $\alpha_m > \alpha_b$, it is increasing in r. Under this last assumption, the function tends towards infinity for $r = (\beta_b - \beta_m)/(\alpha_m - \alpha_b)$.

Using the parameter values from table 1 for Chinese block printing and wooden movable type, figure 1 displays the function $n^*(r)$ for the case of China. The area above $n^*(r)$ corresponds to combinations of n and r which would be produced using wooden movable type, while combinations falling below this function would be produced using block printing. As is readily apparent, only printing jobs characterized by a large number of pages and a small print run would be produced with movable type. The result is intuitive: movable type saves on the cost of creating new pages, when n is large these savings dominate. On the other hand, the cost of making copies out of a given page is actually lower with block printing, so larger print runs render block printing more attractive.

[Figure 1]

It is important to realize that, in figure 1, $n^*(r)$ tends towards infinity for quite a low value of r , as $(\beta_b - \beta_m)/(\alpha_m - \alpha_b) = 421$ in this case. In fact, any printing project with an average print run above 350 would almost certainly be produced using block printing - as the number of pages to make movable type viable becomes exceedingly large beyond that. This is important because 350 is quite a small number of copies, well below the lower-bound estimate of 500 given above. Unless average print runs in China were significantly lower than European ones, essentially all commercial publishing in China would have been performed using block printing - as was indeed the case.

Furthermore, the type of printing project that would have been produced using movable type, works with a large number of pages produced in small print runs, corresponds well to what we know about its historical use in early modern China. Government projects such as the *Gujin Tushu Jicheng* consisted of hundreds or even thousands of volumes, a very large n, while the print run was quite limited since the work was not for sale but for distribution in a few selected places. Similarly, family genealogies were printed in very small runs since the only potential buyers were the members of the family in question. At the same time, no two family genealogies are alike, so printers had to produce different pages for each family, leading to a large value of n.

In fact, we can take the explanatory power of the model even further and give theoretical grounding to one additional historical briefly mentioned above: that commercial printers of family genealogies used types made of wood while the government often commissioned metal types.

Figure 2 below plots two versions of function $n^*(r)$ for China. The first one, which simply reproduces the one displayed in figure 1, compares block printing with movable type using wood (notice the change of scale in the vertical axis). The second one compares block printing with movable type using metal. The area below *both* of these two curves would then correspond to the combinations of n and r printed using block printing technology. Combinations above *only one* of the two $n^*(r)$ functions would be produced using either wooden or metal types, according to which curve is below them. There are, however, certain combinations of n and r which lie above both $n^*(r)$ curves. In order to identify the version of movable type being used, we can compare the cost functions under each case. Using equation (2), it is straightforward to show that metal movable type would be preferred to the wood-based version of this technology if the following condition is met:

$$n > \frac{1}{r}\frac{F_{met} - F_{wood}}{\alpha_{m,wood} - \alpha_{m,met}} \equiv \widetilde{n}(r)$$

where F_{met} and F_{wood} are the cost of a full set of types using metal or wood and $\alpha_{m,met}$ and $\alpha_{m,wood}$ are the printing costs per page using metal or wood. The function $\widetilde{n}(r)$ is plotted in figure 2 over its relevant range (when a movable type technology is chosen), and it completes the characterization of the choice of printing technology for all possible combinations of n and r.

[Figure 2]

What we observe is quite revealing. Movable type using wood is the preferred technology for low print runs but only up to a certain number of pages. As an example, for a print run of 150 you would use wooden movable type with works up to 15,000 pages; but metal types become more economical beyond that. Government-led printing projects such as Imperial Encyclopedias were pretty much the only type of printing endeavours running into the tens of thousands of pages - and the model predicts correctly they would employ metal-based movable type. Family genealogies, in contrast, were typically short titles and even a large number of them would not stretch beyond a few thousand pages.[7]

The final part of the analysis incorporates Europe. Figure 3 juxtaposes function $n^*(r)$ for the European case with the corresponding function for China as first displayed in figure 1 (that is, the one comparing block printing with wood-based movable type). As α_m and α_b are almost the same for the European case, the function $n^*(r)$ looks like a horizontal line crossing the n axis at the value $\frac{F}{(\beta_b - \beta_m)}$ which, for the European case, equals 448 pages. The implication is that in Europe any printing project of more than 450 pages, whatever the print run, would have been produced using movable type. This is quite an undemanding condition, as even a small printing firm planning to produce 3 titles of 150 pages each would have opted for movable type.

[Figure 3]

In definitive, and despite its mathematical simplicity, the analytical method adopted above gives a surprisingly good account of why movable type was universally adopted in Europe, block printing was the preferred

[7] Figure 2 also reduces the range where block printing is the technology of choice with respect to figure 1, but the combinations of n and r for which this happens are hardly relevant in practice.

technology for most of Chinese printing, and even in which instances movable type, whether using wooden types or metal types, was to be preferred in China. The remainder of the paper expands on this understanding of the printing world into the wider consequences for society and economic development.

6 From printing to knowledge creation

So far I have argued that the Chinese writing system, with its myriad of different logographic characters, entailed very different costs for movable type printing and consigned China to the use of block printing technology. Was this of any importance beyond the world of printing?

While the data on Chinese book production is not as comprehensive as what we know for the European case, it appears to be undeniable that early modern Europe produced a far larger number of book titles than China.[8] For China, we have two reasonably good estimates for the second half of the Ming dynasty, a period that saw a rapid development of commercial printing in China's largest cities. The total number of book titles printed during this period, the years 1522-1644, has been set at 3,300 by Buringh and van Zanden (2009) and 6,618 by Chia (2003). During this same period, Western Europe produced a total of 457,500 book titles according to the careful analysis of Buringh and van Zanden (2009). Given that both regions had a comparable total population and similar levels of income per head, the difference is staggering. Even the larger estimate for the Chinese case, which I will use in what follows, leads to a ratio of about 70 European titles for every Chinese one.

[8] Comparisons of book production will be made in terms of number of titles, and not total books printed, and that for two reasons. First, from an analytical perspective, it is the number of titles that gives us a more accurate representation of the amount of knowledge being put in circulation in printed form. Second, from a practical perspective, we seldom have information on print runs in order to calculate total book production. By assuming an average print run of 1,000 Buringh and van Zanden (2009) provide figures for the European case, but no such exercise has been attempted for the Chinese case.

Could such a large difference be explained by factors such as China's relative linguistic homogeneity as compared to Europe? Indeed, the estimates for the number of titles produced in Europe during this time includes translations of works originally published in another language whereas Chinese publications were, with some rare exceptions, all in Chinese. We may thus hypothesize that a large number of European titles would not have been produced if all Europeans had read the same language.

While the idea is sensible, a look at the available evidence reveals that translations were a relatively modest share of European publications - 14.68% of the total for the Netherlands, the only country for which such detailed information exists.[9] If the Netherlands, a very small country for which one would expect translations to be relatively important, is taken as representative of Europe, the ratio of 70 to 1 identified above would only be reduced to 60 to 1. Incidentally, the main reason for the modest importance of translations was that early modern Europe, unlike today's, did have a common language for scholarship and religious writings: Latin. The Universal Short Title Catalogue, a pretty much exhaustive list of all books printed in Europe between Gutenberg and the year 1600, tells us that 45% of all titles produced during the 16th century were in Latin.

The importance of Latin in early modern Europe helps us to deal with a second plausible objection to the above figures on book titles, namely the development of national literatures in Europe, each with its own set of titles written in vernacular. According to this idea, each European nation would develop its own fictional (and to a certain extent, non-fictional) literature, whereas in China the same titles would be read everywhere. While such a development did take place, it would only concern titles written in vernacular since books written in Latin had the same standing in Europe as books written in Classical Chinese had in China - they were accessible to every literate person. To put a lower bound on Europe's title production we

[9] Source: Short Title Catalogue for the Netherlands. The figure of 14.68% refers to the period 1522-1644. For all books in the catalogue, covering the period 1451-1800, the share of translations is 11.20%.

may assume, implausibly, that Europe's vernacular literature contained no additional ideas or knowledge to what was already present in the Latin literature. In other words, we would assume that the vernacular literature is entirely a re-telling of Latin books, created for the sole purpose of satisfying a local readership in vernacular. Under this extreme assumption, Europe's title production would have been about 45% of the overall estimate in the absence of national literatures, leading to a ratio of 31.5 European titles for every Chinese one. This is as low a ratio as one could possibly argue, and still every bit as imposing.

As books were the main carriers of knowledge in pre-industrial times, the figures on book titles suggests that a far larger number of ideas circulated among the European cultural area than among the Chinese one. Could printing be, at least partially, responsible for this? Of course, a natural explanation would be that Europeans put more ideas in circulation simply because they created more ideas. In other words, the larger number of titles would be a consequence - not a cause - of the intellectual and social revolutions in early modern Europe. China would have produced few books because, in the words of David Landes, it "had long slipped into technological and scientific torpor" (Landes 1998, p. 342).

While nobody would dispute the pre-eminence of European science since the 17th century, and European technology at least since the 18th century, it is seldom the case that socioeconomic forces act in a single causal direction. The intellectual development of Europe no doubt had an impact on the number of ideas being printed, but it seems plausible to argue that the technological capacity to print more ideas had also an impact on Europe's intellectual development - as Elizabeth Eisenstein and many others have argued. And here comes the crux of the matter for while the Chinese had access to printing technology, the cost of introducing new ideas with it, in other words producing new titles, was far higher for them.

The production of a new title entails a fixed cost equal to the manufacturing of woodblocks with block printing technology or the composition of the text with movable type. Unlike the costs of paper, ink and labour for printing, which are proportional to the number of copies printed, these fixed costs would have been particularly problematic for works with a small print run.

In Europe, composition costs were a mere 0.167 of the low-skill daily wage per page - a 200-page book would entail a fixed cost investment equal to 33.3 daily wages. Contrast this with China where a one-page woodblock costs the equivalent of 2.78 the daily wage while text composition with movable type brings this down only to 1.39. A 200-page book in China represents a fixed-cost investment equal to 556 days of labour with block printing and 278 days with movable type - very substantial sums. It seems inevitable that Chinese printers would only proceed with the production of titles with a broad and more or less guaranteed readership, whereas European ones had a far larger margin to explore new topics and niches with a limited readership. Scientific books would fall under the latter case - less than 1% of all titles published in Europe during the 16th century are classified in the category "Science and Mathematics" within the Universal Short Title Catalogue.

Thus China had printing, but the intricacy of its writing system meant that printing was useful for reproducing a limited variety of texts, not for experimenting with the work of new authors. Europe, not because of an inherent cultural superiority but simply because of its simpler writing system, could afford the reproduction of a much wider variety of texts. Arguably this would give an opportunity for new and bold ideas being circulated in print form.

Having put forward the above thesis, I would not like to push it to the extent of saying that printing, in and of itself, explains the Great Divergence. That would be claiming too much, as the example of the Muslim world (who had an alphabetic writing system, knew of the printing press, and yet failed to use it and to experience significant development) clearly shows.[10]

[10] For a discussion of the Muslim case, see Cosgel et al. (2012).

There are many more differences between China and Europe other than their writing systems and the costs of printing, starting from culture, geography, and institutions. The case for the importance of such factors has been made and will continue to be made in the literature. My aim, then, is simply to advance that printing, and more specifically, the economics of printing, are probably an important part of the story. Printing itself does not take place in isolation, and I would certainly expect that the capacity to print more titles in Europe had an influence of European culture and institutions (though not on its geography!). Printing probably started a virtuous cycle in Europe, as more people educated themselves, demanded more books, and produce themselves new ideas. The cycle did not take place in China - at least not to the same degree - and a major reason for that may have been the difficulty of printing a large variety of texts using the Chinese writing system.[11]

7 Concluding remarks: Chinese printing in the modern world

China eventually made it, of course. After a disastrous 150 years where western technological superiority meant China lost complete sovereignty over its own affairs, the last decades of the 20th century saw China becoming the fastest-growing economy in the world - soon enough, it will once again be the largest. If printing technology was once an obstacle, it clearly isn't one any longer. The production and distribution of information in written form, using either paper or an electronic format as support, is nowadays not more difficult in Chinese than in any other language. Something changed,

[11] It is worth noting that higher printing costs may not be the only difficulty that China had to endure because of its notoriously complex writing system. There is no doubt that learning to read and write in Chinese requires a much higher investment in time than for alphabet-based languages. De Francis (1984, p. 153) cites Chinese sources indicating it takes between six and eight years for a young Chinese speaker to master three thousand characters.

On a more speculative level, language scholars have long discussed whether the characteristics of written Chinese, in and of themselves, made tre transition towards abstract science less likely. Bode () offers an insightful book-length discussion on this last topic.

then, and it's instructive to note it was not China's writing system which, despite significant efforts at simplification by the Chinese government over the 1950s, remains at least two orders of magnitude more complex than western alphabets when it comes to the number of symbols. The change was technological. China did not adapt itself to better suit printing; printing eventually changed and was then able to reach its full potential in China.

Three phases may be identified in the transition from ancient printing technology to its modern counterpart in China and East Asia. First, beginning in 1859, the electrotype process greatly reduced the cost of producing metal types. In this process matrices for types are produced by electrolysis, and types are cast from them as in the western method. Thanks to it, block printing had been largely abandoned in China, Korea and Japan by the 1910s. The next technological breakthrough came in the 1960s with the application of phototypesetting, which dispenses with metal types altogether as characters are drawn on film and printed using the mechanics of photography. It may be remarked that East Asians, led by the Japanese, were the earliest adopters of this technology for printing. Finally, a third technological revolution came about in the 1980s with the arrival of computerized typesetting.

Could it have been otherwise? Should we wonder at China's failure to attempt a transition towards an alphabetic writing system during early modern times? After all, they knew of the existence of such writing methods - Europeans were regularly present in China since the mid-16th century and the contacts with the Muslim world were even more numerous. It is not far-fetched to suppose that the Chinese, ingenious as they are, would have realized that much lower printing costs could be obtained by using an alphabet. What is more, the transition would not require new inventions and arguably no prohibitive costs; it is, mainly, a matter of coordination at the society level. And there, I would argue, lies the reason why it was never tried.

A change in a country's writing system could only be engineered by the state. There was, however, no obvious gain to be made by the Chinese state from such a transition. The state did not print books for a profit, and those who did, the printing entrepreneurs throughout China's territory, did not have the power and influence to push for such change. The printing projects of the Chinese state were prestige works, intended to display the refinement of Chinese civilization within and outside China. Producing them at a lower cost may have been an advantage, but doing so using the writing system of a foreign culture would have been unthinkable, as it would defeat the prime purpose of the project. To this we may add that the Chinese literate class had (and still has) a strong attachment to its writing system - witness the development of calligraphy as an art form. Sacrificing the esthetic and cultural value of its ancient writing system for pecuniary reasons would have seemed sacrilegious for most Chinese throughout this period.

And yet, the thing was almost successfully attempted - not in China, but in neighbouring Korea. In what constitutes a fascinating episode of the history of printing, during the early 15th century Korea developed an alphabet, Hangul, that could replace the Chinese characters then in use. It is noteworthy that Korea, considering itself as different from China, did not have the same attachment to that country's writing system. Given that Korea actively engaged in movable type printing during this period, it may seem surprising that the adoption of this writing system failed to spur the kind of change observed in Europe about a century later. The explanation, I believe, lies once again in printing technology.

As it turns out, the Korean alphabet did not reduce the cost of movable type printing because of its reliance on syllabic grouping. To elaborate a bit, in the western writing system letters never need to change in size or shape (other than at the beginning of a phrase). An "e" looks exactly the same each and every time, which makes the system ideal for standardization. In the Korean system, however, letters are grouped in blocks, each block transcribing a syllable. Within each block, the size and shape of each letter will change according to which and how many other letters they are combined with. The system is clearly reminiscent of the Chinese one, with every syllabic group roughly corresponding to one Chinese character. Because of this, movable type using Hangul had to manufacture a different type for each syllabic group - not for each letter. The number of possible syllables run into the thousands - it is 11,172 in present-day Korean - and thus offers no improvement over the Chinese writing system when it comes to printing costs.[12]

To conclude, I shall say that this analysis of the economics of printing in early modern times ought to solidify our understanding that people everywhere are equally capable of great intellectual achievements. As pointed out by Thomas Francis Carter, author of the first history of Chinese printing ever written in the West, "Given similar conditions, the two ends of the world have done similar things" (Carter 1955, p. 242-43). To this vision of common humanity I am happy to subscribe.

[12]On the other hand, Korean Hangul does offer a major advantage when it comes to learning how to read and write. According to the tradition, this was precisely the reason for its invention - by order of King Sejong of Korea in the year 1443. History suggests that King Sejong was too far ahead of its time: Hangul was banned by his successors in 1504, and it was only towards the end of the 19th century that it became the preferred writing system of Korea.

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Table 1
Costs of printing in China and Europe

Item	*Cost (in currency units)*	*Cost (in days of low-skill labour)*
Block Printing in China		
β_b (woodblocks)	0.125 tael per page	2.78 days per page
α_b (production of copies)	0.00033 tael per printed page	0.0073 days per printed page
Movable type in China (wood)		
F (full set of types)	597 Spanish dollars per set	1660 days per set
β_m (text composition)	0.5 Spanish dollars per page	1.39 days per page
α_m (production of copies)		0.0106 days per printed page
Movable type in China (metal)		
F (full set of types)	2388 Spanish dollars per set	6640 days per set
β_m (text composition)	0.5 Spanish dollars per page	1.39 days per page
α_m (production of copies)		0.0084 days per printed page
Block Printing in Europe		
β_b (woodblocks)		2.78 days per page
α_b (production of copies)	0.0668 sol per printed page	0.01113 days per printed page
Movable type in Europe		
F (cost of printing workshop)	351 livres	1170 days per workshop
β_m (text composition)	1 sol per page	0.167 days per page
α_m (production of copies)	0.0669 sol per printed page	0.01115 days per printed page

Figure 1

Block printing vs. movable type in China

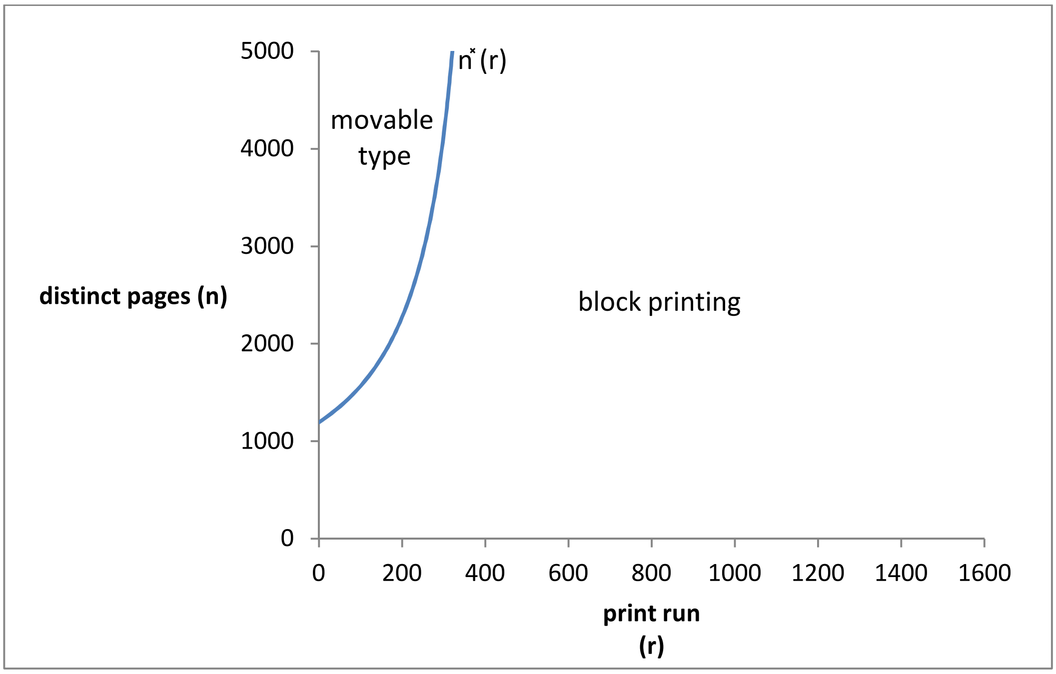

Figure 2
Movable type using wood and movable type using metal in China

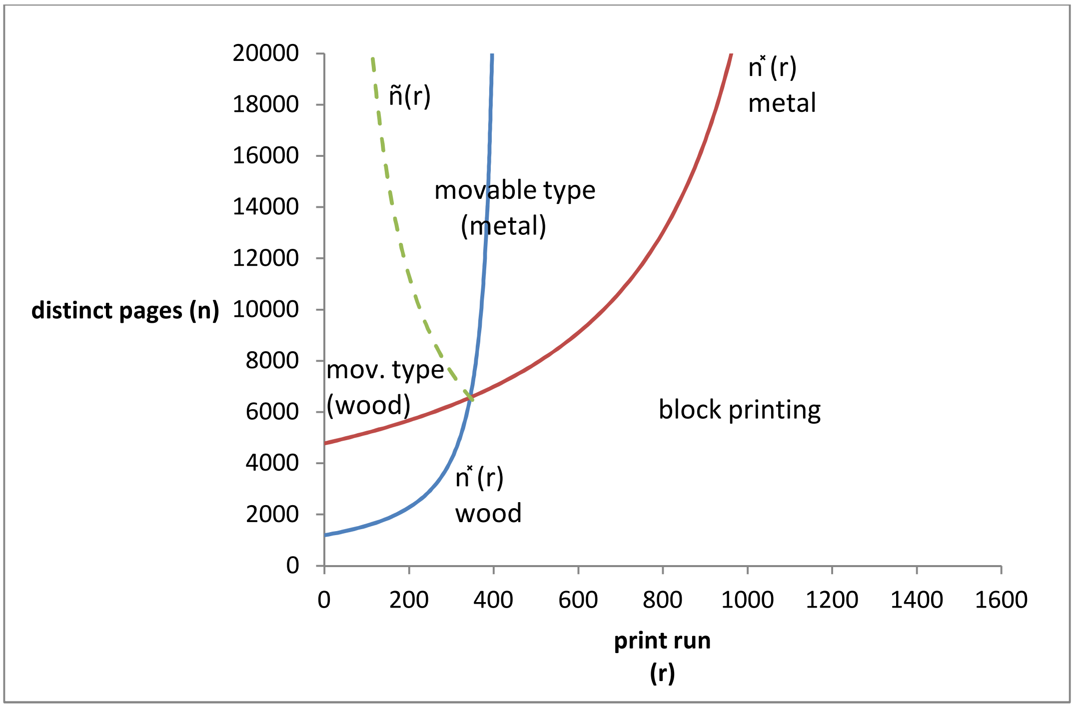

Figure 3
Block printing and movable type in Europe