Font Wars Note 31: A working paper*

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1 Technological ideas and economic growth

The IEEE article on the Font Wars (Bigelow, 2020) focused on modern and ancient ideas that drove the transformation of analog type into digital fonts.

Coincidentally, during the time of the Font Wars, a theoretical paper by economist Paul M. Romer analyzed the importance of technological ideas in generating economic progress (Romer, 1990). For his work, Romer received a Nobel prize in economics in 2018.

Romer's analysis offers a fresh perspective on the role of ideas in the technological transformation of typography in the 20th century, and also on the invention of typography in the 15th century, making for an interesting comparison.

Nowhere in Romer's paper does he mention fonts, but of course, his paper was printed with fonts, else the Nobel Committee might never have known of it. Romer thus follows in the tradition of eminent philosophers and mathematicians who disseminated their ideas through writing and typography but did not turn their attention to the history and features of written forms, the medium that communicated, and communicates, their ideas.

Hence, it falls to the lot of a typographer to sketch how Romer's abstract theory of ideas in economic processes can be applied to the concrete histories of typographic technologies. For further discussions of the significance of Romer's theory, see the Notes on Romer (section 5) at the end of this article.

"Nonrival" vs. "rivalrous" goods. This is Romer's fundamentally important distinction. "Nonrival" goods are mainly ideas or concepts that can be used simultaneously by several different parties or "rivals". "Rivalrous" goods are mainly objects, though also human and physical capital, that cannot be used simultaneously by rivals.

"Ideas". The broad category of nonrival "ideas" encompasses many kinds of discovery, invention, and design. Romer includes as examples: "a scientific law; a principle of mechanical, electrical, or chemical engineering; a mathematical result; software; a patent; a mechanical drawing; or a blueprint". (Romer, 1990)

Ideas contribute to economic growth because once they have been conceived, they do not need to be re-researched and rediscovered in order to be used again. To manufacture more of a product according to a blueprint or invention, more labor and materials are needed, but the ideas are already known and cost little or nothing to use again. To borrow an observation that Yogi Berra is said to have said, ideas are just "*déjà vu* all over again".

"It is sometimes observed that a design cannot be a nonrival good because it is itself tied to the physical piece of paper or the physical computer disk on which it is stored. What is unambiguously true about a design is that the cost of replicating it with a drafter, a photocopier, or a disk drive is trivial compared to the cost of creating the design in the first place." (Romer, 1990)

Monopoly profits from ideas. The inventor or creator of an "idea" can earn monopoly profits by using the idea to produce goods for the marketplace. To increase production of the goods does not require reinvention of the idea, which has already been paid for. To print a book requires a press, paper, and ink, but the technology of printing does not need to be re-invented.

Nor does a book already written need to be re-created by an author. Reprinting an existing novel, say, Dashiell Hammett's classic hard-boiled mystery, *The Maltese Falcon*, does not require writing a new book. In metal typography, Hammett's text can simply be reprinted if the type is still standing. In electronic typography, it can be reprinted from a computer file. To produce an electronic edition without paper, ink, or presswork may involve new technologies, such as e-readers with "e-ink" or LCD displays, but if those have been produced, Hammett's words written in 1929 can be displayed to the reader today. Detective Sam Spade can once again tell Wilmer the gunman, "The cheaper the crook, the gaudier the patter."

"Exclusion". A competitor may use a nonrival idea conceived by an inventor or a work by an author or other creator, and thus capture some of the profits that the inventor or creator might otherwise receive from the creation. Hence, many societies provide legal "exclusion" as a means of preventing expropriation by a rival, as by copyright.

Hammett's copyright on *The Maltese Falcon*, first published in 1929, benefitted him and his heirs as well as publishers. For inventions and processes, exclusions may be achieved through secrecy, whether trade secret or encryption of digital data and code, or copyright of code, or patent of software. The last of these continues to be controversial, with some scholars, individuals, and companies plausibly arguing against it.

"Spillover". Exclusion of ideas is usually imperfect because exclusions are limited in duration, jurisdiction, encryption, secrecy, or some combination. Thus, ideas "spill over", spread, leak out, and so on. For instance,

copyright of *The Maltese Falcon* will (under present law) expire in 2026 in the USA, after which we may be treated to exciting new adaptations, like *The Maltese Falcon Meets The Walking Dead*, and *Sam Spade Joins The Avengers*.

2 Two histories of typographic invention: Gutenberg and Xerox PARC

Romer's model can be used to compare two major typographic inventions and milestones. The first, by Gutenberg, from around 1448 to 1455, transformed writing into typography. The second, by Xerox PARC, from around 1970 to 1981, developed personal computing with interactive raster graphics screen displays, laser printing, and fonts. Parallels between those two inventions that are separated by more than 500 years of history are nevertheless close enough to illustrate how Romer's theory unites two of the most consequential inventions in the technology of literacy, the first in the late Middle Ages and the second in the late 20th century.

Invention: Gutenberg. Johann Gensfleisch zur Laden zum Gutenberg is generally regarded today as the inventor of typographic printing in the West, but few definitive facts are known about him and the details of his invention. Born in the city of Mainz in the Holy Roman Empire (now in Germany), Gutenberg as an adult resided in Strasbourg for several years where he pursued various inventions before returning to Mainz.

In Strasbourg in 1439, Gutenberg was a defendant in a lawsuit over one of his inventions, the nature of which remains uncertain. Gutenberg's invention involved a press of some kind and a mysterious object made of four pieces that Gutenberg asked one of his business partners to separate so the nature of the object could not be seen. In the same proceedings, a goldsmith testified that Gutenberg had paid him for work involving "trucken", a word that meant "pressing" or possibly "printing" though that latter meaning was probably not used until a decade or more later.

A record of that lawsuit led Theodore Low De Vinne, an eminent 19th century typographer and printer, to suppose that the mystery object was a type mould, which was the essential type casting device on which printing was based from the 15th century to the end of the 19th century. A flaw of De Vinne's enticing supposition is that no further evidence has emerged to support it or later conjectures of the same kind. Moreover, other evidence suggests plausibly that Gutenberg's 1438–1439 invention involved fabrication of small mirrors for pilgrims to supposedly capture sacred light from holy relics.

Nevertheless, what can be gleaned from the Strasbourg records is that by 1438–1439, Gutenberg was an inventor and entrepreneur, had gleaned investments on expectations of profits from goods produced from his ideas, and had attempted to "exclude" knowledge of an object based on his ideas. Thus, elements of invention, profit, ideas and their exclusion, were characteristic of Gutenberg's endeavors. Exclusion of ideas or techniques by guilds and craftsmen were not uncommon in the Late Medieval and Early Modern era, before privilege, patent, and copyright laws became common in states and nations. Trade secrets continue to be methods of idea exclusion in modern times.

By 1448, Gutenberg was residing in Mainz where a relative took out a loan on his behalf, for a project unknown. Around 1450 (or perhaps later), Gutenberg received a loan (or investment) from Mainz financier Johann Fust, for something called "the work of the books" and around 1452 he received additional funding from Fust for "the work to our common benefit".

Other evidence indicates that around 1452, Gutenberg was using movable type of his invention to print Latin grammars and Papal indulgences. It is supposed that Gutenberg actually had two shops, one printing Latin grammars and indulgences, and the other printing a book more substantial in size and significance: a Latin Bible called "the 42-line Bible" or popularly the "Gutenberg Bible". Completed in late 1455 or early 1456, the 42-line Bible sold well, mainly to churches and monasteries. The 42-line Bible does not credit Gutenberg but is called the Gutenberg Bible on the basis of early references to it and him, and on research in later centuries.

In November 1455, around the time the Bible was completed, Fust sued Gutenberg for repayment of the loans with interest. A substantive issue was whether the money Fust had funded to Gutenberg were loans or investments. A contemporary document, the "Helmasperger Notarial Instrument", doesn't say how the lawsuit turned out, but Fust evidently gained possession of Gutenberg's Bible print shop with its type and equipment, and began to print other works, assisted by a former Gutenberg employee, Peter Schoeffer, who had appeared as a witness for Fust in the lawsuit. Gutenberg appears to have continued to print in a different shop, as evidenced by the Mainz Catholicon of 1460, a massive Latin dictionary and grammar, well printed with a new font and a different typographic technique.

In summary, it seems that, having invented typographic printing technology by the early 1450s or earlier, Gutenberg raised capital through loans or investments to fund the substantial costs of printing books and documents, which commenced by 1452. Despite the

possible financial setback and loss of equipment in the 1455 Fust lawsuit, Gutenberg appears to have continued to print major works and to innovate printing technology.

Recent reference works on Gutenberg and early printing are listed in the bibliography:
Scholderer, 1970; Ing, 1988; Davies, 1996; Kapr, 1996; Needham, 2013; Needham, 2007; White, 2017.

Invention: Xerox PARC. If the problem in understanding Gutenberg's inventions is the paucity of information, then the converse problem in understanding Xerox PARC's inventions is the plethora of information.

The Xerox Palo Alto Research Center (PARC) was established in 1969 to research and develop future technologies for the Xerox Corporation. Located on Stanford University land in Palo Alto, California, PARC was somewhat independent of Xerox's corporate headquarters 3,000 miles away in New York.

PARC attracted a broad range of scientists in several fields, including computer science and imaging. Among many inventions, PARC is famous for developing much of the foundation of modern personal computing. Its innovations include laser printing, bitmap graphics on screens and in print, graphical user interfaces, WYSIWYG interactive text and document editing, local networking and file serving, and a graphical page description language.

Several of the ideas behind these developments had been invented elsewhere by others, notably by Douglas Engelbart at the Stanford Research Institute, Ivan Sutherland at MIT, and researchers at Bell Labs, but the scientists and engineers of PARC combined and augmented such ideas in multiple iterations of computing systems, especially the "Alto" personal computer, the conceptual progenitor of most personal computing today.

The story of PARC has been told often. Recollections by several former PARC scientists on the origins of desktop publishing appear in the *IEEE Annals of the History of Computing*, 40(3), July–September 2018. Books include Hiltzik (1999) and Smith and Alexander (1988). Notable online articles include: a Wikipedia article, `wikipedia.org/wiki/Xerox_Alto`; a summary at the Computer History Museum, `www.computerhistory.org/revolution/input-output/14/348`; and a chronology of Xerox PARC demonstrations to Steve Jobs, `web.stanford.edu/dept/SUL/sites/mac/parc.html`.

Development: Gutenberg. Gutenberg's *magnum opus*, the 42-line Latin Bible, has been praised for several qualities, including the regular texture of its pages, its large, crisp blackletter "textura" type, rivaling or exceeding hand-written calligraphy of the era, its sophisticated text composition using a font containing nearly three hundred characters, abbreviations, and ligatures to produce a regular visual pattern on the page, and its rich black ink.

The high quality of the Bible printing suggests that not only was Gutenberg an inventor, he was also intent on improving his technology. The illustrious 20th century type designer, Hermann Zapf, has opined that Gutenberg was not merely trying to imitate handwriting, he was trying to improve upon it.

The 42-line Bible took around three to four years to print, around 1452–1455, give or take a year on either side. Calculations of the dates of the loans from Fust suggest a beginning around 1450. Sample sections of the 42-line Bible were shown at a Frankfurt book trade fair in 1454, as seen and reported by Aeneas Silvius Piccolomini, the future Pope Pius II. The 42-line Bible is not dated internally, but is believed to have been completed in late 1455 or perhaps early 1456. An estimated 180 copies were printed, of which 49 bound copies survive, 21 complete and 28 incomplete, as well as a few dozen separated leaves and fragments.

Of course, Gutenberg did not have to invent everything involved in typographic printing. Paper was made at Italian mills by the 13th century, having been invented in China around 100 CE and brought to Spain around 1,000 CE through Arab-Moorish conquest. Presses were known and used to press grapes and fruits for wine. Goldsmiths and mint workers were skilled in the engraving of hard metal punches, the stamping of punches in softer metals, the making of alloys and the casting of multiple small metal objects.

The ingenuity of Gutenberg's invention was his successful improvement and combination of known techniques with a crucial innovation: precise reproduction of letter forms as type in thousands of units, along with composition of them into pages.

Development: Xerox. Laser printer.
Gary Starkweather invented the first laser printer in 1969 at the Xerox Research Center in Webster, New York. In the early 1970s, Starkweather transferred to Xerox PARC, where he continued research and development of experimental laser printers. His inventions eventually became a product: the Xerox 9700 high-speed laser printer launched in 1977. The 9700 became a highly profitable product for Xerox for several years and was followed by several later generations of Xerox laser printers.

Personal computer. The concept for the Alto was proposed at Xerox PARC in 1972, and the first few systems were built in 1973. Several iterations of Alto hardware and software were produced over the next six years for internal use by Xerox. The Altos had bitmap graphics

display screens, keyboards, "mouse" pointing devices, and graphical user interfaces with approximately typographic fonts. The full systems were linked with a local area network connected to a shared file server and laser printer.

However, the Alto was a research system, not a commercial product. Around 1,000 Alto units were built for use by Xerox scientists, engineers, other researchers, font developers for laser printers, document producers and secretaries. A few hundred more were used for research outside Xerox and donated to a few universities. In all, around 2,000 were produced. In 1977, Xerox began developing a commercial product based on the innovative Alto, to be marketed as the "Office of the future".

Development time: Gutenberg. It is difficult if not impossible to determine the exact amount of time Gutenberg needed to develop printing with movable type. Interpretations of meager legal records and deductions based on surviving materials suggest that Gutenberg may have needed as long as seventeen years to develop his ideas into his first major printed product (that is, from 1438 to 1455), but that assumes that Gutenberg's Strasbourg invention was printing, not mirrors for religious pilgrims. The time could have been as short as five years from concept to printing of minor works such as grammars and indulgences (that is, from 1448 to 1452).

The longer estimates rely on brief, ambiguous statements in the 1439 Strasbourg lawsuit, though there are no extant printed artifacts from Gutenberg's time in Strasbourg, and there are doubts that he was actually working on printing at that time. The shorter estimates rely on suppositions about the purpose of Gutenberg's 1448 loan in Mainz and speculations about Gutenberg's printing with movable type by 1452, of which there are no surviving examples. The earliest indulgence is dated to 1454. Yet another estimate would begin with the estimated date 1450 date of the first loan by Johann Fust to Gutenberg and end with completion of the Gutenberg Bible in late 1455 or early 1456, so around five to six years. Perhaps seven years from concept to the printed 42-Line Bible is a compromise estimate.

Development time: Xerox. Laser printer.
From invention of the laser printer in 1969 to launch of the 9700 in 1977 took roughly eight years.

Personal computer. It took Xerox around four years of R&D in hardware, software, and interface/interaction design to turn the laboratory research Alto used by savvy scientists and engineers into an easily usable system for general office employees. The commercial product was launched in 1981 as the Xerox 8010 Information System, popularly known as the "Star". From the first designs and constructions of Altos in 1973 to the launch of the Star in 1981 took around eight years.

Time from idea to product: in comparison. Gutenberg appears to have been an undercapitalized inventor in constant need of loans and investments to fund his research and development. Xerox was a profitable enterprise that supported large research laboratories and funded development of the Alto research system into a commercial office system. Despite the vast differences between the lone inventor and the corporate research group, the time from basic idea to commercial product appears to have taken around nine years. Shorter development times were usually based on some years of previous research.

The roughly similar time from idea to product may be coincidental, but between the Gutenberg Bible and the Xerox Star, there were other similarities. Both were products of continuing technical improvement; both were admired in their time and are still admirable today. The ideas behind both inventions spread far beyond their inventors and ultimately became widely profitable, though not for their inventors. Their ideas spilled over to other entrepreneurs and thus the major profits were reaped by rivals. Hence, such "spillover" is a significant factor in progress from new idea to profitable product.

2.1 Exclusion and spillover

Spillover: Gutenberg. Gutenberg was concerned about secrecy as early as 1438–1439, when he asked one of his partners to separate the four pieces of a device on his press, so it could not be recognized. His partners had apparently sworn an oath to keep the invention secret. Later, Gutenberg may have required similar oaths from his employees in Mainz, as there seems to have been no spillover of printing technology until 1455.

In November of that year, however, Johann Fust sued Gutenberg for interest and repayment of loans and apparently won the suit, taking possession of Gutenberg's equipment and the edition of the 42-line Bible. Gutenberg's employee, Peter Schoeffer, testified on behalf of Fust in the lawsuit. If Schoeffer had sworn an oath of secrecy, it was not enough to protect Gutenberg's invention. Fust won the lawsuit, went into partnership with Schoeffer to establish a successful business, with Fust handling sales, marketing, and finance, and Schoeffer handling the printing, a famous early instance of technology spillover through a former employee.

In 1457, Fust & Schoeffer printed a Psalter (a book of Psalms), an innovative production in two sizes of type and two colors with black. The Psalter may have already

been in preparation by Gutenberg at the time of the 1455 lawsuit, but the eventual printing had a colophon giving the date and the names of Fust & Schoeffer as printers, which suggests early understanding of marketing and branding as well as printing. Fust & Schoeffer continued to produce books until Fust died in 1466, after which Schoeffer married Fust's daughter and continued the printing and typography business, which their sons and grandsons carried on in various ways until 1555. Printing has been called "the black art" because of its black ink, and there was an unfounded but persistent legend that Johann Fust, when selling printed books in Paris, was accused of witchcraft because all the copies were exactly the same.

Until 1458, there were apparently only two printing establishments in Europe, both in Mainz. One was that of Fust & Schoeffer, as evidenced by the 1457 Mainz Psalter, and the other was that of Gutenberg, as evidenced by the Mainz Catholicon. Gutenberg died in 1468 and his printing materials were possessed by a Mainz lawyer but seem not to have been used in later printing and have since been lost, like those of the Fust & Schoeffer shop.

The Gutenberg–Schoeffer–Fust story, full of suspense and conflict, triumph and loss, and three generations of the thriving Schoeffer family, is worth a full Hollywood production: "The Black Art and Dark Deeds: Mainz, the Silicon Valley of 1455".

Apart from the technology of printing, the text of the Gutenberg Bible also spread. The texts of several later Bibles from other printers in the 15th century were based on the text of Gutenberg's Bible.

It has been said that Fust & Schoeffer required their workmen to take an oath of secrecy, but that seems not to have prevented spillover into other cities and countries in the 1460s, especially in the exodus spurred by the 1462 sacking and plundering of Mainz by troops of Archbishop Adolph of Nassau in a politico-religious war that drove many inhabitants from the city.

Spillover from Mainz to printers of the 1460s and 1470s has been linked to the shops of Gutenberg or Fust & Schoeffer: Ulrich Zel's printing in Cologne; Heinrich Kefer in Nuremberg; Berthold Ruppel in Basel. Albrecht Pfister of Bamberg printed with Gutenberg's types, though a direct connection to Mainz and Gutenberg is unclear. The connection between Johann Mentelin, who began printing in Strasbourg around 1460, and Gutenberg is also unclear.

Of special interest for the history of roman type are the German (and one French) printers who learned the art of printing in Mainz, presumably in the shops of Gutenberg or Fust & Schoeffer, and took the techniques to Italy in the mid- to late 1460s.

These include Conrad Sweynheim & Arnold Pannartz, who began printing in Subiaco, Italy, in 1465 and later moved to Rome, and Giovanni and Vindelino da Spira (Johann and Wendelin von Speyer). Johann had been a goldsmith in Mainz, who moved to Venice in 1468 and was joined by his brother Wendelin. They finished their first book in 1469.

The most famous early printer in Venice was Nicolas Jenson, who is believed to have been a French mint worker sent by the king of France to study printing in Mainz in 1458. There is some evidence that Jenson was a "tailleur" (engraver) in the Paris mint, so Jenson was probably an engraver of dies and punches for stamping coins and medals.

A fascinating and not implausible conjecture by Lotte Hellinga is that in Mainz, Jenson worked with Peter Schoeffer and introduced technical knowledge and skills from the French mint, particularly the punch-matrix-mould type technology that became the standard in typography for the next 450 years. This is unproven, however, and Schoeffer may have already been familiar with the punch-matrix method by 1457.

Jenson began printing in Venice in 1470. Hellinga (2018, ch. 3) has discussed a suggestion made by Daniel Berkeley Updike in the 1920s, that Jenson cut the first roman typeface of Johannes da Spira a year earlier. This is plausible but also unproven. Jenson's 1470 roman type is better than da Spira's 1469 type.

In 1469, the Venetian Senate granted Johannes da Spira a five year exclusive "privilege" to print within the Venetian Republic. The privilege would have been a form of exclusion equivalent to a modern patent. The privilege would have precluded Jenson from printing in his own right in Venice, though he could have cut punches and perhaps cast type for da Spira. Johannes da Spira died in 1470 and his printing privilege with him, allowing Jenson and others to engage in printing. Without printing exclusions, Venice rapidly became a flourishing center of book publishing. Between 1470 and 1500, more than 200 printers worked in Venice at one time or another, printing around two million copies of books in those three decades: a spillover of printing technology on a grand scale.

Whether or not the da Spira roman of 1469 was the first roman type cut by Jenson, the first roman he cut for his own books in 1470 defined the humanist letter form in print for five decades to follow, becoming a major milestone in the evolution of the "roman" style (though actually cut and printed in Venice). Later printers in Italy copied and refined Jenson's roman, and yet later printers in Paris copied the Italian refinements, thus establishing the idiom for the next centuries and into the modern era.

Spillover: Xerox. The goal of Xerox PARC's development of the "office of the future" differed from that of Gutenberg. Gutenberg's goal was to invent a cheaper, faster, and more reliable method of producing books that were in most other respects nearly identical to the familiar form of codex manuscripts (books of bound pages, not scrolls). Readers of Gutenberg's printed books, and books printed after him, did not need to learn how to handle a codex, to turn pages, to recognize the letters, and to follow the layouts of columns. Those were already well known. Gutenberg did not need to train or convince anyone to use the results of his invention.

Spoofs of the technical help needed to learn to use the codex form of book have been popular on the Internet; e.g., see `youtube.com/watch?v=JCguAlvJBqQ`, `youtube.com/watch?v=yUQRbqc2qtY`.

The computer scientists at Xerox PARC were not inventing something that looked and acted like existing products. Keyboard typewriting was well known, but PARC invented tools that brought the look of computer text closer to traditional typography, improving on the monospaced typewriting and the line printer output of older computer systems. But the hardware and software developed at PARC was unfamiliar to average office workers who needed to learn new ways of inputting, editing, structuring, and printing documents.

A consequence of Xerox's need to promote the concepts of the computerized office information system, exemplified by the Alto, was copious spillover. Nearly all the scientists and engineers of PARC were graduates of universities and were accustomed to academic exchange of knowledge through publications and personal interactions. PARC scientists generated documents, papers, and demonstrations, some for internal use and others for publication. PARC hosted visiting scientists and interacted with universities. Xerox donated Alto systems to Stanford, MIT, Carnegie Mellon, and University of Rochester. Thus, the ideas implemented in the Alto became nonrival among technically knowledgeable students and faculty of computer science and electrical engineering.

Unlike Gutenberg, PARC was well funded by Xerox and didn't need to borrow money from financiers or venture capitalists. PARC's problem was to convince potential users, including Xerox corporate upper management, to recognize the revolutionary potential of unfamiliar products. PARC scientists produced descriptions of the Alto and associated technologies for internal use at Xerox (Thacker and McCreight, 1974; updated in Thacker, McCreight, Lampson, et al., 1979), though copies leaked out. Xerox was, after all, the dominant copier company.

PARC researchers also published articles on Alto-related research, in both technical journals and mass market magazines, thus exposing the Alto's capabilities to wider readerships (Kay and Goldberg, 1977; Kay, 1977).

In the second edition of their pioneering textbook on computer graphics, *Principles of Interactive Computer Graphics*, William Newman and Robert Sproull (1979) covered the bitmap graphics of the Alto and utilized several of the composition, layout, and publishing tools developed at PARC to prepare the book. Sproull describes the production of the *Principles* book in (Sproull, 2018).

By the time the Xerox Star was launched in 1981 as the 8010 Office Information System for major corporations, many of its concepts were well known and rival systems had been released. These included: the 1980 "Lilith" personal computer developed by Niklaus Wirth at ETH Zurich after Wirth had spent time at PARC. The Lilith was never commercialized but for a time, America's biggest printing firm, R.R. Donnelley, investigated it as a corporate system. The PERQ workstation was launched in 1980 by the Three Rivers Corporation, one of whose principals had been at PARC. The Apollo workstation was launched around 1980. Other Alto-like workstations were launched soon after the Xerox Star. The Sun workstation, developed as the Stanford University Network for a Ph.D. thesis in 1980–82, was modeled on the Alto and launched commercially by Sun Microsystems in 1982. Notably, these early spillover systems were produced not for use by the general office workers but by scientists and engineers, including computer circuit designers, who easily mastered the interfaces and workings of the systems.

The most famous spillover was the Apple Macintosh, launched in 1984, not for scientists or office workers in major corporations, but for the growing market of users of relatively inexpensive personal computers, including the IBM PC and the Apple II. The story of how Steve Jobs and Apple engineers toured PARC and recognized the market potential has been recounted many times from different perspectives (references given on page 3).

Beyond papers and publications, spillover of the ideas of PARC occurred in the diaspora of PARC scientists who went to other computer companies in the late 1970s and early 1980s. To name a few, Bob Sproull went to Carnegie Mellon University in 1977 and later co-founded the consulting firm Sutherland, Sproull & Associates in 1980; Larry Tesler went to Apple in 1980; Charles Simonyi to Microsoft in 1981; Charles Geschke and John Warnock founded Adobe Systems in 1982, where they were soon joined by other PARC alumni.

Although separated by 520 years, the spillover of technological ideas from Xerox PARC to other corporations resembles the spillover of printing technology from the shops of Gutenberg and from Fust & Schoeffer. In both eras, much of the spillover occurred through the diaspora of their employees.

Though the original inventors of new technologies, Gutenberg the individual and Xerox the corporation, did not reap monopoly rewards of their innovations, spillover of their ideas inspired and enriched later entrepreneurs and more broadly, society, by transforming the technology of literacy.

As Romer wrote in his 1990 paper:

"Both spillovers and price setting seem essential to capturing the features of knowledge in a model of growth. There is little doubt that much of the value to society of any given innovation or discovery is not captured by the inventor, and any model that missed these spillovers would miss important elements of the growth process. Yet it is still the case that private, profit-maximizing agents make investments in the creation of new knowledge and that they earn a return on these investments by charging a price for the resulting goods that is greater than the marginal cost of producing the goods." (Romer, 1990)

Effects on society. Another way to look at the power of technological ideas is through their effects on society. Bibliographers and book historians long recognized that the 15th century invention and development of typography and printing was an important epoch in the history of Europe, but studies of early printing tended to concentrate on artifacts such as presses, punches, matrices, moulds, types, and above all, the books that survived from the early days of printing and offered tantalizing but often puzzling indications of the technology that produced them. The other main concentration was on the people who invented and developed type and printing, and where, when, and by whom printing with movable type was first developed.

Moving beyond artifacts, two French historians, Lucien Febvre and Henri-Jean Martin broadly examined the influence of printing on European society in their now-classic 1958 book, *L'Apparition du Livre*. Its 1976 English translation, *The Coming of the Book*, was called by British historian Hugh Trevor-Roper, "one of the most exciting scholarly books ever written on printing".

In 1979, American historian Elizabeth Eisenstein caused controversy among English-speaking scholars of printing history but gained a wider general readership with her two-volume treatise on the historical importance of the printing press (Eisenstein, 1979). She examined the impact of typography and printing on modern society and culture, arguing that printing with movable type spurred the Renaissance, spread the Reformation, underpinned the Scientific and Industrial Revolutions, and contributed to modern ways of thought.

Desktop publishing in general, and digital typography in particular, transformed the technology of literacy and integrated it into the electronic information origination, computation, and transmission systems in the late 20th century. These technologies generated their own profusion of artifacts. In hardware, there were laser printers, image setters, personal computers, bitmap display screens, networking with file servers (with ever larger disk drives). In software, there were text editors, bitmap editors, drawing programs, page-imagers, document describers, digital fonts. The history of this era is still being written (the *IEEE Annals of the History of Computing* journal is dedicated to this subject).

3 Type as object, art, and idea

Through most of the history of typography, fonts have been viewed both as objects and as art. The claim that type design includes both functionality and artistry was made early on. After the death of Nicolas Jenson in 1480, an advertisement praising his books stated: "They give delight by their exactness and precision; they do not harm one's eyes, but rather help them and do them good. Moreover the characters are themselves are so methodically and carefully finished by that famous man that the letters are not smaller or larger or thicker than reason demands or than may afford pleasure. . . " (quoted in Updike, 1937).

In his 1969 book, *A View of Early Typography up to about 1600*, typographer and type historian Harry Carter stated succinctly the nature of type as object: "Type is something you can pick up and hold in your hand", but he also stated that type is an art: "In considering the face of a fount of type we are in a world of art . . . a humble art. . . ".

Carter wrote "a humble art" probably because type is small in size, perceived near the limit of recognition, and designed to be copied and reproduced as a means to an end rather than an object of contemplation or admiration, and, presumably for those reasons, its features were ignored by the general public, except, of course, during reading.

Carter used the words "beauty", "symmetry", and "harmony" to describe certain early typefaces, and referred to punchcutters as "artists". He called the first italic type, used by Venetian printer Aldus Manutius in 1501, "beautiful and legible", indicating functionality as well as beauty. Carter also used the term "design" in quoting the 16th century type punchcutter, Guillaume

Le Bé, who termed large model letters he made for a Hebrew font a "portrait and design".

But, even before Carter's words were printed, the essence of type had begun to shift from object to idea. By 1966, the firm of Dr.-Ing. Rudolf Hell had invented and installed the first digital typesetter, the Digiset, for which raster fonts were computer data, man-made electronic patterns.

To borrow and repurpose a general observation attributed to science-fiction writer William Gibson, the future of typography had already arrived but was only sparsely distributed.

The shift from metal type to phototype to digital type successively reduced the mass of the object called "type". This was called "dematerialization" by Alan Marshall in his 1991 Ph.D. thesis (Marshall, 1992, p. 326; Marshall, 2003, p. 313).

An artistic vision of dematerialization had been expressed in 1928 by Paul Valéry, in an essay "La conquête de l'ubiquité", republished several times since:

"There is in all the arts a physical part that can no longer be seen or treated as formerly, that cannot remain uninfluenced by the workings of modern knowledge and power... Neither matter nor space nor time are what they always were... We must expect great innovations to transform the entire technique of the arts." — Paul Valéry, 1928

Valéry's essay was the inspiration for a 1935 essay by Walter Benjamin, "The Work of Art in the Age of Technological Reproduction" (Benjamin, 1935). Benjamin mentions stamping and casting as ancient Greek methods of reproduction. (In the punch-matrix-mould technique of typography, stamping and casting were standard.) Benjamin then discusses film and especially the reproduction of fine art, in which a unique object becomes mass produced, with implications for the concept of art in modern society. Benjamin's essay has been republished several times, in English translation as "The Work of Art in the Age of Mechanical Reproduction". Benjamin used the German word "technische" — 'technical or technological' — translated through French into English as "mechanical".

Like many philosophers and critics before and after them, neither Valéry nor Benjamin discussed the art of type design *per se*, but of course, their words were reproduced by typographic means.

Thus, dematerialization of type was not simply an economical reduction of material, it was also, in terms of Paul Romer's model, a transformation of objects into design ideas.

3.1 Romer's model applied to the history of font technology

There have been four major shifts in typographic font technology in its 500 year history.

(1) The first shift was from handwriting to printing type, which began around 1450 and was propagated over the next five decades.

(2) The second shift was from hand typesetting to mechanical composition by keyboard, invented in the 1880s and well underway by 1900. Mechanical composition speeded up composition and became the dominant form of typesetting for the first half of the 20th century.

(3) The third shift was from metal type to phototype, invented in the 1940s and prevalent from the 1950s to the 1990s.

(4) The fourth was the shift from phototype to digital type, beginning in the late 1960s and dominant by the end of the century.

In each of these technological shifts, type became less like objects and more like ideas. As the material diminished, the visible images carried took on greater presence and significance as designs — ideas of forms.

In Romer's model, traditional metal fonts are rivalrous, because they are physical sets of cast metal "sorts" (letters). If a font is being used by one printer, it cannot be used by another printer at the same time.

Type forms are potentially nonrival. They are of course openly and easily visible; that is their function. A rival punchcutter can copy a type design cut by another, but cutting the physical objects, the steel punches, requires skill, labor, and investment, so imitation does not reduce manufacturing costs. What it does reduce is the risk of devoting labor and capital to the production of an unfashionable font.

If a certain style, "look", or "genre" of type becomes popular, then the copyist doesn't need to invent a new form; the popular one can be copied. Traditional text type forms tended to endure over centuries but with small, incremental changes, partly because hand-cut imitations were difficult and imperfect, partly because changing fashions and functions induced punchcutters to cut slightly newer interpretations of the style, and partly because the best punchcutters brought something of their own skill, vision, and imagination to the task.

It has been claimed that most early printers in the 15th century made their own fonts, though that is not entirely true; there was evidently some exchange of fonts even early on. For instance, in Venice in the 1470s, some of the types cut by Jenson were sold by him, either as cast type or matrices. Some were sold after his death in 1480, spreading Jenson's type forms beyond his

printing house. Types in Jenson's style were still being used fifty years after his death, notably by Geoffrey Tory in 1529 as the text type of his book, *Champ Fleury*, which promoted Italian Renaissance typography in France.

In the 16th century, punchcutting become less rivalrous. A single punch cut in high-quality, hard steel could be struck into many copper blanks to make "strikes" that could be regularized and fitted to make "matrices" that closely replicated the forms of the letters and could be used in casting. Hence, printers and typefounders could purchase strikes from a punchcutter and have them justified to make a regularized set of matrices from which many letters and fonts could be cast. Thus, the same type forms could be used by more than one printer at a time. The designs were to an extent non-rival, though the objects remained rivalrous because there was still a substantial amount of investment in the physical process of fitting strikes and casting fonts.

Moreover, a printer could exclude the use of a given typeface or font by purchasing its punches and not selling strikes, matrices, or types. The illustrious and prolific 16th century punchcutter Robert Granjon cut some sets of punches for exclusive use of certain printers but also sold matrices of his other type styles for which he kept the punches for himself.

Many later typefounders kept certain type styles exclusive by selling cast type fonts but not punches. In the Arts & Crafts movement near the end of the 19th century and in the early 20th century, fine printers including William Morris, Count Harry Kessler, Giovanni Mardersteig, and others, commissioned exclusive typefaces. Something of the sort has continued into the digital era with the commissioning of exclusive typefaces for newspapers, magazines, and corporate identities, as well as various technical applications.

Technique as design. The type-making method of punch + matrix + mould was established at least as early as 1470, perhaps earlier if the conjecture that Jenson worked with Schoeffer is true. It is clear that the technical principles of type-making are "designs" in Romer's model. To some extent exclusion of type technology was achieved through secrecy, as punchcutting and matrix justifying were taught only to apprentices, while print shop workmen were probably sworn to secrecy. But, technology exclusion was imperfect, and the concepts and techniques spilled over, as former apprentices went out on their own and former employees carried knowledge with them into new ventures. These kinds of spillovers occurred first in Mainz, then in other German cities, and then in Italy and Switzerland. After those spillovers, the basic technique changed little for around 400 years.

Forms as ideas. Early European printing types imitated the nonrival forms of then-current scribal handwriting. This was later the case for nearly all handwritten scripts transformed into typography in other cultures as well. In written culture, letter or character forms could not be kept secret nor excluded from use. Some letter forms may have been disfavored from time to time, for reasons involving religion, culture, aesthetics, politics, or fashion, yet to function as transmitters of information, letters had to be visible, learnable, writable, and readable. Early printers did not need to reinvent the shapes of letters and characters; those already existed in manuscript books, where they could be seen, studied, and imitated. The shapes were ideas to be imitated. Peter Schoeffer is said to have been an accomplished scribe in Paris before learning printing in the employ of Gutenberg. Importantly, readers did not need to learn to recognize and read new letter shapes in printed books; printed letters looked much like texts handwritten by skilled scribes, a high standard of quality originally established by Gutenberg.

It must be admitted, however, that standards of readability are often based on aesthetics and convention, not on strict utilitarian measures like reading speed. Human vision is so adaptable that people are able to read a poorly designed and poorly rendered font fairly well. The main problem is, they don't like it.

Nevertheless, early printers did not copy handwriting exactly. Jenson, for instance, refined the regularity and harmony of the capitals and lowercase alphabetic forms in his roman types. Although Humanist scribes had combined roman capitals with minuscules (lowercase) early in the 1400s and Sweynheim and Pannartz had done so in the 1460s, Jenson was the first to achieve an aesthetically harmonious combination, as judged by readers then and now. Of Jenson's types, as with nearly all early printing types, we do not know which manuscripts were copied nor the names of the scribes.

Gutenberg had used more than 200 variant characters in the 42-line Bible, but in later decades, as the printing business became competitive and readers became accustomed to printed books, printers reduced the costs of punchcutting, typefounding and composition by eliminating most ligatures, digraphs, abbreviations, and alternate forms. Print no longer needed to imitate handwriting, and the exemplars for later typefaces were mainly earlier typefaces, not handwriting. The roman types cut by Griffo for Aldus appear to have been based on the types of Jenson from a generation earlier, though Griffo's cuttings were more refined.

In the 16th century, type technology stabilized, presumably because of wide adoption of the punch-matrix-mould technique and also because of advances in the metallurgy of punches and type metals, so the

rate of technical innovation in the material objects of type slowed, while innovation of forms continued. In early printing, typographic interpretations of gothic scripts by Gutenberg, Peter Schoeffer, and other German printers dominated typography, but when German printers migrated to Italy, they often adopted Humanist or "roman" styles to market books to Italian readers, despite the cost of cutting new punches and casting new fonts. By the end of the 15th century, Humanist roman typefaces were common in Italian printing, though types in the gothic rotunda style of Italian handwriting continued to be used for legal and technical printing, including in several books printed by Jenson.

Following Humanist roman, the next innovation in printing came in 1501 when Aldus used a fashionable writing style, Humanist cursive (today's "italic") cut in type by Griffo, in printing small format pocket books. Venice granted Aldus an exclusive privilege to use the fashionable new italic type style, but Venetian legal jurisdiction extended only to the borders of the Venetian Republic, so there was spillover when imitations of Aldus' books were soon printed in Lyon, France. Griffo left Venice and Aldus and cut additional italic fonts, initially for the printer Gerson Soncino in Fano, Italy. Over the next 30 years, more and different styles of italic type were designed and produced in Italy, notably the "chancery" handwriting styles of Arrighi and Tagliente. The Italian cursive font fashion spread to France and for a time competed with roman before being made a subordinate companion to roman sometime after the middle of the 16th century.

Semiology and structure as typographic ideas. Types are organized sets of symbols that have relationships to each other, first in representing various elements and levels of spoken language, and second to indicate structural and semantic relationships among the symbols themselves. Over the centuries, typography innovated symbols as well as the marking of structural relationships among them. Capitals, lowercase, italic, bold — these are graphical innovations to mark and organize typographic distinctions.

Introduction and replacement of numerals. Humanist manuscripts used Roman numerals, but by the end of the 15th century, Arabic numerals, already used for two centuries in handwritten mathematics and bookkeeping in Italy, began to be used in Italian printing, first with gothic rotunda, for as in Luca Pacioli's *Summa de Arithmetica* printed by Paganini in Venice in 1494, and then with roman type for indexes in *Hypnerotomachia Poliphili* printed by Aldus in 1499. The use of Arabic figures with roman types continued to increase through the 16th century in various contexts such as tables, schedules, and tabulations, until Arabic figures harmonized with roman were merged into standard fonts, as seen in a type specimen of François Guyot, circa 1569.

Mergers of italic, capital, roman and bold. Griffo's 1501 italic cut for Aldus was lowercase only, and italic was a separate style used without roman for several subsequent Italian cursive typefaces, all with upright capitals. By the 1530s, printers began to use italics with inclined capitals, thus filling a logical matrix — upright capitals with roman (upright) lowercase, and inclined capitals with italic (inclined) lowercase.

In the second half of the 16th century, italic styles, originally independent of roman, began to be used as a companion or subordinate style with roman, and these began to be cut together as a family, as seen in the Guyot specimen circa 1569. Roman and italic, capitals and lowercase sufficed as a family for around 300 years, until bold faces were designed in the mid-19th century and roman bold styles began to be used with normal weight romans. By the early 20th century, bold roman and bold italic began to be designed in families with normal weight roman and italic, extending the matrix. In the era of digital type, sans-serif styles began to be designed in extended families with seriffed types. By the 21st century, these serif/sans families were not uncommon, though not numerous.

In the 20th century, there was a shift from regard of type as object to regard of type as design. Among other examples, a classic study of printing types by A. F. Johnson, *Type Designs: Their History and Development*, first published in 1934 and later in subsequent editions (Johnson, 1966), is concerned with the images carried by type, not the physical objects. Other studies of type forms call them "printing types" by convention, as in Daniel Berkeley Updike's equally classic two-volume study of the forms of type, *Printing Types* (Updike, 1937). A relatively recent study by Hendrik Vervliet of all French typefaces of the 16th century likewise focuses on the designs (Vervliet, 2010).

From these and other surveys of early type designs, major changes of type design over time can be classed approximately as follows, bearing in mind that type classification is a complicated task.

Imitation and refinement of handwriting. Early printers created gothic (blackletter), roman, and italic types imitating handwriting. In nearly all cases we don't know the names or the works of scribes imitated by the early printers and punchcutters. An exception is Garamond's cutting of Greek punches for the printing house of the King of France, based on the handwriting of Ange Vergèce, also known as Angelos Vergetios. [This writer has scrutinized some of those

Greek punches. Their cutting is so exquisite they seem like rare jewelry.]

Jenson's roman of 1470 is intriguing because some of its features are already typographic but do not appear to imitate the few previous typefaces which, to a greater or lesser degree, imitate Humanist handwriting. In 1501, Francesco Griffo cut the first italic typeface, based on cursive humanist handwriting, though we don't know whose.

Imitation and refinement of previous types. Francesco Griffo cut imitations and refinements of the roman type of Jenson in the decade before cutting the definitive roman for Aldus in 1495. In the 1530s, Parisian printers and punchcutters Simon de Colines, Antoine Augereau, and Claude Garamond refined the Aldine type of Griffo of 1495. Some refinements may have been technical, such as better steel for punches, better alloy for type metal, better magnifier lenses for punchcutters. But their enduringly influential refinements were visual, appealing to style, fashion and taste.

Other innovations were new styles of type that imitated or modified distinctive handwriting. Robert Granjon, a master of several italic type styles as well as non-Latin cursives, cut characteristically French gothic cursive "civilité" types around the mid-16th century. Though much admired for their grace, refinement, and ingenuity, Granjon's civilités have not gained the popularity of the many revivals of his italics. Leaping ahead four centuries, Hermann Zapf's Zapfino is a popular example of his freely cursive handwriting made into a digital font, as is Kris Holmes' Apple Chancery, based on Lloyd Reynolds' italic handwriting.

3.2 Further thoughts on type forms and ideas

Given that type forms are ideas, not objects, then Romer's model explains several aspects of typeface creation, imitation, and piracy in traditional and digital typography.

The slow evolution of traditional typeface designs. Traditional type forms were inextricably linked to physical type objects, which were not easy to change and thus were rivalrous. The "look" or "idea" of a particular typeface design could not be copied without cutting new punches, themselves rivalrous objects. Punchcutting was practiced in each historical era by only a few highly skilled artisans, themselves a form of rivalrous human capital. A punchcutter working on punches for one font cannot be working on another. A trade in replicating type by selling multiple strikes and matrices to printers and typefounders did develop over time, but still, the punches remained rivalrous. Hence, copying type designs was neither fast nor cheap. The one advantage of copying the design or "look" of a typeface was that the copyist punchcutter could choose to copy only the more successful designs, thus avoiding the time, expense, and risk of cutting something original that might not become successful. So, punchcutters tended to be conservative in design, as were printers. Thus, forms evolved slowly. Copying had the drawback, however, that it precluded success by innovation.

Innovation in type forms despite the difficulties of fabricating type. The first printed books were competing against — but much cheaper than — handwritten manuscripts, so the challenge of innovation was the crafting of type that looked like professional handwriting, to assure book buyers of quality and tradition. Early printers in Germany produced types imitating various familiar gothic letter forms that prospective book purchasers and readers would have expected. The early German printers who moved to Italy, however, had to cut new, Humanist roman types, because educated Italians favored Humanist handwriting. Innovation was thus prompted by customer demand based on cultural fashion. Jenson's roman of 1470 was not the first of the genre but its skilled execution won praise, customers, and imitations. Later, Aldus' romans were admired as refinements of Jenson's roman, and Aldus' italic was novel but based on fashionable, cultured handwriting.

Cutting punches, justifying matrices. These were skills that required considerable training, usually through long apprenticeship. Hence, the fabrication of type was rivalrous because it depended on skilled artisans. There were thousands of printers in early modern Europe but only a few skilled punchcutters at any given time, because punchcutting required the greatest skill among the typographic arts. Punchcutters didn't just cut steel, which was difficult enough, but also made their own tools including gravers, gauges, instruments, and work stands. They had to acquire and rig their own magnifying lenses, if available, possibly from Italian glass makers. They needed understanding of metallurgy, heating and quenching steel. And they needed exceptional manual dexterity.

Vervliet (2010) identifies seventeen French punchcutters of roman, italic, Greek, or Hebrew typefaces for the whole of 16th century France. Vervliet mentions a dozen other artisans or printers who may have cut types but for whom solid evidence is lacking.

Mastering punchcutting required years of apprenticeship and journeyman work before becoming a master in one's mid-20s. The art, or craft, was painstaking, minute, tedious and laborious, so relatively few entered the profession. It was not wholly rivalrous, however, because typefaces could be replicated by sale of strikes

and matrices (justified strikes), though justification of matrices was itself a skill. Of the seventeen punchcutters whose work is discussed by Vervliet, a few cut only a handful of types, while others cut many. Robert Granjon cut more than ninety types over his long career of astonishing versatility.

Punchcutting and matrix-making as still practiced in the 20th century are described and shown in a fine and well illustrated essay by Nelly Gable and Christian Paput (2016). Among many details of interest, they list the names of the major French punchcutters of the 20th century as a tribute to workmen who would otherwise be forgotten.

Metal type foundries in the 20th century. During the first half of the 20th century, many of the traditional type foundries were stressed by competition from the big mechanical composition companies: Linotype, Monotype, and Intertype. The foundries often created innovative type designs, ranging from scripts to sans-serifs, which involved financial risk that paid off when faces became popular but not when sales were low. Over time, some smaller foundries were acquired by the larger composition firms.

During the second half of the 20th century, the advent of phototype technology stressed even the big mechanical composition companies as well as the traditional foundries. Structurally in the printing industry, this was because phototype technology was more efficient, faster and cheaper when printing transitioned from letterpress with metal type to offset lithography using photographic technology. In particular, spillover of type designs through photographic techniques made it much easier, faster, and cheaper for phototype machine manufacturers to make film copies of popular metal typefaces. Had the old-line typesetter manufacturers and foundries been able to exclude type piracy, the new photo technology typesetting manufacturers would have had to invest more in type origination and development and less in manufacturing and technology. Without international copyright for typefaces, most of the smaller foundries could not protect and profit from their typeface designs and hence went out of business or were acquired.

A major loss was when type foundries were liquidated and their materials sold as scrap. Thousands of person-years of creation of exquisitely refined, jewel-like objects vanished. The steel punches were the greatest relative loss because they were worth little as scrap but were priceless as the hand-work of artists. Because the details of specific type designs were bound to specific type objects, the details were lost, though not the general ideas. As throughout history, writing and types were not recognized as art. Nevertheless, in retrospect, the dissolution of the old type foundries was an irretrievable and lamentable loss of the objects and forms of typographic history. Though no longer commercially marketable, those materials were nonetheless priceless objects bearing evidence of consummate artistic skill and craftsmanship produced over decades and centuries.

Digital type technology and typeface design spillover. When digital type was invented in the late 20th century, some manufacturers kept digital font files in a proprietary format. The outline font format of the Linotron 202, for example, was not disclosed to users, printers, or competitors, despite entreaties from customers. Linotype did not want leakage or spillover of its fonts to third parties. Bell Labs' reverse-engineering of the Linotron 202 font format, described elsewhere, was therefore a threat to Linotype's font business and to its more profitable machine business. To the extent that machine sales depended on Linotype's library of exclusive typefaces, if rival firms could copy Linotype's digital fonts, then Linotype would lose not only exclusivity for hundreds of typefaces developed over nearly a century, but also lose machine sales motivated by font exclusivity.

When Adobe and Linotype agreed on font and PostScript cross-licensing in 1984, Adobe encrypted Type 1 PostScript fonts to prevent unauthorized distributions. Initially, Adobe and Linotype fonts were technically excluded from use by rival firms except those that also licensed PostScript technology. Linotype lost some exclusivity, but gained a head start in the market for high-resolution image setting machines.

For a time, Adobe also used another form of exclusion — copy-protection — to prevent copies of fonts being exchanged or traded between users. As the personal computer software market matured, widespread user objections to font copy protection persuaded Adobe to drop copy-protection but to retain encryption.

Adobe has stated that it did not patent its font technology because a patent would presumably reveal enough of the principles of the technology that rivals could invent work-arounds, thus shortening their R&D of an alternate technology. Instead, Adobe used secrecy as exclusion. For example, Adobe's use of the term "hints" referenced its technology for improved type quality, but without disclosing any technical features. This tactic was effective for several years, but eventually, several rivals caught up to Adobe with other "hinted" or "instructed" font technologies.

TrueType designed as an open font format. Operating systems are channels of information and gatekeepers of information flow. For them, fonts are content,

part of the flow. But fonts also enhance the user interfaces and human-computer interactions with operating systems and associated applications that involve the display of text. A user interface relies on fonts. Text editors and word processors rely on fonts. Page layout applications rely on fonts. Web browsers rely on fonts. Search engines rely on fonts. Spreadsheets rely on fonts.

At the time that Apple developed TrueType and later when Microsoft adopted it, those companies had few or no proprietary fonts of their own and hence no motivation to protect font intellectual property by encryption. In fact, lack of font protection benefitted the system purveyors. From their standpoint, the more fonts, the richer and more expressive the user experience; moreover, fonts they didn't have to pay to develop or license were nonrival goods, all the better.

Adobe chose to market the PostScript page description language for high-end graphics and publishing as well as medium resolution desktop publishing. For prestige and acceptance of PostScript in the quality-conscious publishing and typography market, Adobe produced well-known, popular, and respected typefaces to establish PostScript and promote its wide adoption. Adobe encrypted its Type 1 fonts to exclude their use by competitors.

On the artistic side, type designers are creators of graphical content in which they make considerable investment. As an analogy to literature, the writing of a novel involves roughly the same amount of work and skill as the designing of a family of typefaces by a designer. After initial design, type manufacturers add value to fonts as products. For instance, the development and production of Times Roman into a widely successful font family involved considerable testing and reworking by the Monotype Corporation in the early 1930s. To maintain profitability of their intellectual property, font firms needed to exclude appropriation of their fonts by copyists, plagiarists, and pirates. Encryption was a form of exclusion; copy protection was another.

Similarly, Adobe's production of early PostScript Type 1 digital fonts was analogous to a publisher's editing and typesetting a manuscript and designing a book for publication. Adobe thus had a profit motivation to exclude use of its fonts except by those who licensed and paid for them.

Thus the implicit business motives of operating system makers were opposed to the motives of font developers. For the system makers, fonts were more profitable as nonrival ideas than rivalrous objects, because nonrivalry made more fonts available to more users. For type designers and digital font developers, however, the opposite was true: fonts were more profitable as rivalrous objects than as nonrival ideas, because the former had to be paid for, whether by system or software vendors, while the latter could be freely replicated without payment.

Adobe abandons encryption of fonts. Adobe dropped copy protection for fonts as part of a general software industry shift away from copy protection. Copy protection was acknowledged to be generally frustrating to users, and it was believed that copy protection of fonts reduced sales and profits.

However, Adobe's decision to disclose the Type 1 font encryption and format came from a different motivation. Adobe wanted to protect PostScript itself by encouraging and facilitating a greater supply of Type 1 fonts, to compete with an expected surge of TrueType fonts when Apple and Microsoft bundled TrueType font technology in their operating systems. In this view, the PostScript page description language had become a graphics and desktop publishing industry standard on its own, and was therefore more like a platform than an application. Hence, it was reasoned that a greater supply of Type 1 fonts would enhance and support the PostScript platform and help protect it from the coming competition from TrueType from Apple and Microsoft.

TrueType was unencrypted partly as a convenience to users, but it also worked as a tactic against Adobe's font technology hegemony. When Microsoft or Apple licensed TrueType technology to third party firms such Hewlett Packard, it opened up the market to newcomers, weakening the exclusionary power and licensing restrictions of established font firms. Together, Microsoft and Apple created a large market for fonts in which demand was initially unfilled.

It remains unclear if Adobe's dropping of Type 1 font encryption in 1991 achieved Adobe's objectives, as it appears to have resulted in unintended consequences. At the time, Adobe and its PostScript licensees such as Linotype had produced more than 1,000 PostScript Type 1 fonts, whereas in 1991 and 1992, Apple and Microsoft together produced fewer than 100 TrueType fonts, whether bundled with their respective operating systems or sold separately as font packs. Hence, PostScript font technology enjoyed a 10:1 advantage in font supply, but the loss of encryption with disclosure of the Type 1 font format enabled virtual font osmosis from Type 1 to TrueType. Instead of developing more Type 1 fonts, opportunistic font vendors instead converted Adobe Type 1 fonts into TrueType, swelling the supply of fonts for Microsoft and Apple platforms more than for Adobe PostScript.

For typeface designs, legal exclusions such as trademark, copyright, and design patent have been nonexistent or weak compared to exclusions for literary, artistic,

photographic, and other works of authorship or art. Trademark can protect fonts' trade names but a name change suffices to evade trademark exclusion. Since the 1970s, the US Copyright Office has refused to register typeface designs, claiming that a typeface is an industrial design which cannot exist independently and separately as a work of art. That claim has been challenged in legal arguments, for instance by Terrence Carroll (1994).

Nonetheless, the Copyright Office has remained adamantly against typeface copyright. Design patent is applicable to typefaces, but only to new and original designs, while the patent process is restrictive, slow, and expensive, and the duration of protection was limited to fourteen years, now fifteen years for filings after 2015. Copyright of computer code is registrable as software, but copyright of font software applies only to the code, not to the design. Some legal exclusions were available in Germany and thence in the European Union, but the US market was beyond the European laws.

The loss of legal methods of exclusion along with loss of exclusion by encryption caused the traditional business model of font development and marketing to collapse. Lawsuits over infringements of software or design patent were possible and sometimes successful, but usually only after years of litigation during which opportunities and profits were reduced or lost.

As a sequel to the Font Wars, in the 21st century, other commercial approaches to generate revenue from fonts arose, such as utility-like metered micro-fees for delivery of web fonts though cloud software.

4 Dematerialization of fonts

Unlike traditional metal fonts, which are objects and rivalrous, digital fonts can be copied instantaneously, indistinguishably, and essentially costlessly, and can be distributed as easily, thus becoming very nearly nonrival in Romer's definition. The dematerialization of fonts, with resultant ease of digital font copying and distribution, compared to metal or photo fonts, illustrates the transition from rivalrous material objects to nonrival digital designs, and their respective excludability or non-excludability.

To create new fonts from scratch requires skilled design and substantial technical development. For opportunists in the Font Wars, it was far easier, faster and cheaper to produce TrueType fonts by converting Adobe's meticulously prepared Type 1 fonts into hastily produced TrueType fonts. Font pirates peddled bundles of copies of Adobe and Linotype Type 1 fonts converted to TrueType, at low prices. Despite complaints that such pirated fonts were of poor quality, they were cheap and flooded the market, reducing profits for Adobe and other licensed Type 1 font producers. Analogous to Gresham's Law that "bad money drives out good", bad fonts drove out good. As font profits fell, Adobe shed employees and designers from its font production staff, and in 1995 brought a lawsuit against a firm that Adobe alleged had infringed Adobe's font software copyrights by copying and converting around 1,100 Adobe fonts. The core issue in the dispute was whether Adobe's font software, not typeface designs, qualified as a work of authorship protectable under software copyright. Adobe showed that it did and won the case in January, 1998 (`en.wikipedia.org/wiki/Adobe_Systems,_Inc._v._Southern_Software,_Inc.`).

Still, by the time of the court judgment, there had been unauthorized copying and distribution of fonts for several years, adversely affecting the profitability of original typeface design and development. By the time the Font Wars had quieted down in the early 21st century, all the established type firms and composing machine manufacturers owning substantial libraries of type designs, whether analog or digital, had gone through bankruptcy, merger, acquisition, or other reorganization, some more than once.

In the 21st century, however, despite the severe font business disruptions, the number of digital fonts available to users expanded greatly. This was partly because digital type and font design tools on personal computers lowered entry barriers to type design, and because Internet sales and transmission of font software made font distribution easier, faster, and cheaper than in previous eras. These changes illustrated the "creative destruction" by industrial innovation analyzed by economist Joseph Schumpeter (1942, 1976).

Economic destruction of traditional type and font businesses was already underway in the 1950s and 1960s as photographic typesetting replaced metal composition, in the process of font dematerialization observed by Alan Marshall in 1991. Hence, digital font technology cannot be blamed for the demise of traditional type foundries, though the last major American metal type foundry, American Type Founders, did finally fail in 1993 during the Font Wars. The later demise of the major composing machine manufacturers may, however, be attributed to digital font technology.

After the Font Wars, in the 21st century, the number of digital fonts expanded by two orders of magnitude. From a few hundred, or at most around a thousand, popular fonts available for keyboard composition in 1980, available fonts have increased by the year 2020 to around one hundred thousand, though that number includes technical format variants, and various sorts of re-workings, copies, imitations, and other variations, and the same typeface may be instantiated

in several different font formats for different purposes. If there were copyright for typefaces, many of those fonts would be considered infringements. The number of type designers has also increased by a similar factor, as the tools of digital type design have lowered the barriers of entry and some design schools and universities now offer courses and degrees in type design.

There were not enough digital fonts in 1980, but a typographer could know them all. In 2020 there are so many that it is difficult to recognize, categorize, and enumerate them all, as yet more continue to be designed and launched.

4.1 Dematerialization and nonrivalry as font objects become font ideas

In his 1990 paper, Paul Romer wrote:

"Like any scientific concept, nonrivalry is an idealization. . . . For simplicity, the arguments here will treat designs as idealized goods that are not tied to any physical good and can be costlessly replicated, but nothing hinges on whether this is literally true or merely close to being true." (Romer, 1990)

By the end of the Font Wars, some typefaces were close to being nonrival, principally those without exclusions based on software copyright or design patent. Exclusion by encryption or trade secret had been lost during the Wars.

The general history of the Font Wars illustrates Romer's theory by tracing the historical, technological, and economic trends in typography.

From the technology perspective, a major trend is the collapse of type-as-object into type-as-design. Digital fonts are intangible, man-made-patterns of data that can be rendered as visible shapes but do not possess the physical mass of traditional fonts. The forms of a digital typeface can exist independently and separately of a material object. This view of fonts as technological constructs ignores the fundamental purpose of fonts: they are made to be read. What is important is the image that falls on the retina, not the technology that puts it there. It must be admitted, however, that the technology of writing has historically influenced the forms of letters and characters. It is intriguingly uncertain how digital technology might influence the shapes of fonts of the future.

From the economic perspective, using Romer's model of ideas and endogenous growth, a major trend is the concomitant transformation of type from rivalrous object to nonrival idea, as digital fonts can be costlessly replicated or very nearly so.

There are now many free digital fonts in circulation, and there have been for more than three decades, the Computer Modern typeface design of computer scientist Donald Knuth being an early and prominent example.

One recent example that combines free, open source fonts with free web servicing to browsers is "Google Fonts". The service began in 2010 with fourteen open source fonts that supported Latin alphabets. The fonts were not tied to any physical goods, could be downloaded from Google servers for use on web browsers, could be modified and reused with no fees, nor exclusions of copyright, patent, or encryption. By 2020, the number of Google Fonts had grown to nearly 1,000 fonts supporting alphabets for around 24 languages and local variations.

Of interest is that, despite the tens of thousands of fonts now extant, both commercially and free, most of the top ten downloaded Google Fonts vary somewhat in the aesthetics of typeface design features, rather than in utilitarian function, but their variance is rather slight compared to the rich variations of historical typefaces. The past century of legibility research has shown that it is difficult to prove the existence of statistically significant legibility differences among a range of typefaces that designers, publishers, and, now, cognizant readers, can distinguish intuitively. Yet, far more striking visual variations in font designs are now achievable, though some are so unfamiliar that readers will need to re-learn how to read them, a problem that Gutenberg wisely side-stepped in 1455 (Bigelow, 2019).

Thus, there are now freely available thousands of fonts as close to nonrival as any fonts in history. Typeface designs have been dematerialized into nonrival ideas that can exist independently of industrial objects, and their features are more often aesthetic than utilitarian. Among other consequences, this appears to contradict the reasoning of the US Copyright Office's objection to typeface copyright. Hence, there may be reason to revisit Carroll's argument in favor of typeface copyright.

5 Notes on Romer

As mentioned at the beginning, (Romer, 1990) is the key work for which Romer was awarded the Nobel, and from which the present article grew; see also (Romer, 1993). The analysis in (Jones, 2019) was also crucial. Following are selected quotes from these and other sources.

"Here is the key insight [by Romer]: ideas — designs or blueprints for doing something or making something — are different from nearly every other good in that they are nonrival. Standard goods in classical economics are rival: as more people drive on a highway or require the skills of a particular surgeon or use water for irrigation, there are fewer of these goods to go around. This rivalry underlies the scarcity that is

at the heart of most of economics and gives rise to the fundamental theorems of welfare economics." (Jones, 2019)

"Ideas, in contrast, are nonrival: as more and more people use the Pythagorean theorem or the Java programming language or even the design of the latest iPhone, there is not less and less of the idea to go around. Ideas are not depleted by use, and it is technologically feasible for any number of people to use an idea simultaneously once it has been invented." (Jones, 2019)

"[Romer] argued that "ideas", though produced with capital and labor inputs, are different than ordinary goods and services along two dimensions: the extent to which they are rivalrous — whether they can be used by more than one actor at once — and excludable — how easy it is to prevent others from using them. Romer emphasized that ideas are non-rivalrous and, to a varying degree, excludable." (Nobel Scientific Background on Romer, 2018)

"Even if an idea can be used by two firms at the same time, it may be possible to exclude one of them from this use, either by regulation/patent law or by means of technical protection (e.g., via encryption). Excludability is critical for ideas to be produced in the marketplace, Romer reasoned, and not all ideas allow it. For instance, some forms of basic research do not fall in this category and may, hence, best be produced in universities." (Nobel Scientific Background on Romer, 2018)

"Next, Romer argued, the production of ideas typically entails increasing returns to scale, with large initial costs for the blueprint and low, arguably constant marginal costs for later replication. Romer thus emphasized that ideas and market power go hand in hand: market power is the typical way in which higher-than-marginal cost prices can be guaranteed, allowing firms to recoup the fixed costs of blueprints. In this sense, monopoly profits is the engine of market R&D. However, the fundamental non-rivalrousness of a productive idea can be regarded as a (potential) positive spillover. . . " (Nobel Scientific Background on Romer, 2018)

"In the first dimension, physical and human capital are rival goods. If a particular machine, or a trained engineer, is used in one factory, the same machine or engineer cannot be used at the same time in another factory. Ideas, on the other hand, are non-rival goods: one person or firm using an idea does not preclude others from using it too." (Nobel 2018 on Romer, Popular Science)

"In the second dimension, these goods may be excludable if institutions or regulations make it possible to prevent someone from using them. For some ideas, such as results from basic research, this is difficult or even impossible — think about mathematical insights like the Pythagorean Theorem." (Nobel 2018 on Romer, Popular Science)

"For other ideas, however, users can be excluded through technical measures (such as encryption) or patent laws. Romer's breakthrough article showed how the rivalry and excludability of ideas determine economic growth." (Nobel 2018 on Romer, Popular Science)

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