

Introduction:

The Middle Ages as Metal Ages

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Metals have played a central role in the history of culture for many thousands of years. Indeed, the exploitation of metal tools defines the end of the “stone age,” setting the stage for the first great flourishings of ancient civilization in the “bronze age” and the “iron age.” As this nomenclature demonstrates, archaeologists and historians clearly recognize the literally epoch-defining importance of metalworking and related technologies in the ancient world. At the other extreme of the historical spectrum, even the proverbial man in the street knows that metal components figure prominently in the construction of such quintessentially modern products as airplanes, automobiles, skyscrapers, and electronics of all sorts. The modern world was forged in the fires of the Industrial Revolution, which saw metals being used in a variety of dramatic new ways, most notably in the construction of engines. In the twenty-first century, it may seem that the age of industrial metals is giving way to an age of plastics and silicon, but the association of metals with modern technology remains strong.

In accounts of metalworking, as in accounts of cultural history more generally, the achievements of the ancient and modern worlds have often overshadowed those of the period in between, typically and tellingly known as the Middle Ages. This is unfortunate, because the metalworking traditions of the Middle Ages richly deserve study, both for their intrinsic interest, and for their importance as links between their ancient antecedents and their modern sequels. Metal objects may have been rarer in the Middle Ages than in the Roman Empire or modern world, but this in no way undercut their social importance. In fact, the prestige of metalwork was probably never higher than in early medieval culture, which produced a wide range of precious metal artifacts used to indicate both sanctity and social rank. Medieval societies also made use of a wide variety of more utilitarian metal items, including arms and armor, coins, building components, and tools of all kinds. Contrary to the popular stereotype of the Middle Ages as a time of technological backwardness, moreover, the period witnessed many complex and sophisticated applications of metalworking technology. These enrichments and extensions of the Roman legacy, together with the increasing regulation and intellectualization of metal production processes in the late Middle Ages,

effectively prepared the way for the flowering of metallurgical research and industrialization in the early modern era.

The present volume presents 23 papers that together begin to suggest the richness and refinement of medieval metalworking practice. Its title, *De Re Metallica* – “about metallic things” – echoes that of the masterful sixteenth-century treatise by Georgius Agricola, which may be understood both as the culminating document of medieval metal lore and as the foundational study of modern metal scholarship.¹ In a similar but humbler vein, it is hoped that this collection of papers can provide a useful and suggestive sample of recent scholarship related to medieval metal use, while simultaneously serving as a call to arms of sorts, alerting scholars in a variety of disciplines to the interest and importance of metal in medieval culture.

Although a single collection such as this cannot convey a complete picture of medieval metal use, these papers have been deliberately chosen to cover a broad chronological, geographical and thematic range. The first two sections of the book concern the use of precious metals such as gold and silver to create dazzling visual symbols of worldly and sacred power. The first section, *Indices of Identity*, considers the social function of secular jewelry, with an emphasis on the early medieval period in northern Europe. The second, *Handling the Holy*, discusses the closely related use of precious metals to glorify reliquaries and other liturgical appurtenances, with examples drawn from the early Middle Ages down to the dawn of the Italian Renaissance. The next two sections of the book deal principally with less glamorous but more obviously useful metals such as lead, tin, and especially iron. *Mundane Metals* explores the fabrication of practical metal objects such as arrowheads and water pipes, while *Strengthening Structures* investigates the widespread but rarely celebrated role of metal components in medieval architecture. *Technical Texts*, finally, examines the emergence of metal-related technical writing in the late Middle Ages.

Before introducing the contents of each of these sections in more detail, it makes sense to consider the properties that make metals useful, prestigious and socially significant. As the broad division between precious and mundane metals begins to hint, all metals are not created equal. Indeed, the term “metal” has been used to label a wide variety of substances with wildly divergent material properties. Modern astronomers, recognizing that 99.9 per cent of the observable cosmos consists of hydrogen and helium, choose to call all elements heavier than these two “metals.” More typically, though, modern chemists and materials

¹ For full citations on Agricola’s work and its contemporaries, see David Connolly’s “A Research Bibliography” (Chapter 23 in this volume). An annotated English version of Agricola’s treatise was published in 1912 by Herbert Hoover, who served as a mining engineer before becoming the 31st president of the United States. More recently, the name *Metallica* has been employed by a popular “heavy metal” rock band. For an insightful discussion of the history of metal-related terminology in popular music and culture, see Robert Walser, *Running with the Devil: Power, Gender, and Madness in Heavy Metal Music* (London and Hanover, 1993), pp. 1–2, 8–9.

scientists consider the metallic elements to be those in the middle columns of the periodic table, which include long-known substances such as iron, lead, gold, silver, copper and zinc, along with such more recently fashionable substances as chromium and titanium. Many metals are good conductors of electricity, and some, such as iron, respond strongly to magnetic fields. These properties of metals are seen as crucial in our electronic age, but they were of little consequence in the Middle Ages. Although early versions of the magnetic compass began to be used as navigational aids in the Mediterranean by the thirteenth century,² the electromagnetic properties of metals were far less important for medieval society than their more obvious physical properties, such as hardness, workability and beauty.

The properties of metals became obvious to early societies only slowly, because few metallic elements occur naturally in a pure state. Instead, most are chemically bonded with other non-metallic elements such as oxygen, sulphur and carbon, forming ores. Because heating has been the most typical method of liberating metals from ore, the history of metal use has been strongly shaped by the variance in metal melting points. Tin, lead and zinc, with melting points of 232, 327 and 419° C, respectively, can be isolated relatively easily with even a primitive furnace. Silver, gold and copper, meanwhile, melt at 961, 1063 and 1083° C respectively, but iron does not melt until 1535° C. For this reason, many early societies learned to work with metals such as tin and copper long before they were able to produce iron tools. In the mean time, they often learned to make useful hybrids, called alloys, of the metal elements that they had already isolated. Bronze, for example, is an alloy of copper and tin, which was particularly useful because it was harder and stronger than either of its original constituents.³ The strength of bronze, like the even greater strength of iron, was obviously an asset when the object to be manufactured was a tool, sword, shield or structurally functional architectural component. Strength and hardness, however, were by no means the only advantages that metals had over other substances. Metals, unlike wood, bone and non-metallic rocks, can be worked into new shapes by hammering or by being pulled into wires; these properties, known as malleability and ductility, allowed craftsmen great flexibility in creating complex and sophisticated

² The phenomenon of magnetism was well known to the ancient Greeks. Indeed, the word “magnet” reflects the fact that the magnetized iron oxide now known as magnetite was commonly found in Magnesia, in Thessaly. The Chinese, too, were familiar with magnetic effects, and they appear to have used primitive magnetic compasses for divining in the first centuries AD. It was not until the eleventh century, however, that the compass was first used by the Chinese for navigation. In Europe, compasses were used for navigation in the later Middle Ages, but astronomical navigational aids proved more reliable, especially for extra-coastal sailing, until the early modern era. See Julian A. Smith, “Precursors to Peregrius: The Early History of Magnetism and the Mariner’s Compass in Europe,” *Journal of Medieval History* 19 (1992), pp. 21–74.

³ Other alloys common in ancient and medieval society included brass (copper + zinc), “pot metal” (copper + tin + zinc) and electrum (silver + gold).

metalwork objects, most notably jewelry and religious appurtenances of various sorts. In the manufacture of such display objects, beauty and prestige obviously mattered more than raw strength. They therefore tend to be made not of iron, but of silver and gold – softer metals that owe their prestige in part to their resistance to corrosion, and in part to their relative rarity.⁴ In both sociological and metallurgical terms, therefore, it makes sense to distinguish between precious and utilitarian metalwork, even though items such as deluxe weapons and armor might bridge the gap between these spheres.

Because many of the most spectacular examples of early medieval metalwork were precious objects produced for secular elites, this book opens with *Indices of Identity*, a set of seven papers dealing with the role of precious metalwork in aristocratic display. Five of these papers consider the traditions of the early medieval north, from the fifth to the eleventh century, while the remaining two provide later perspectives, from the court culture of the thirteenth and fourteenth centuries. In all these cases, precious metalwork assisted in the establishment, maintenance and promulgation of various aspects of social identity and prestige, not only through adornment of the body with objects of valuable materials and fine craftsmanship, but also through the use of forms which could serve as indices of such group identities as ethnicity, gender and social rank.

Two papers here consider fine metalwork in Anglo-Saxon England. In Chapter 1, Gale Owen-Crocker discusses how archaeologists may interpret the metalwork items deposited in sixth- and seventh-century Anglo-Saxon graves as signifiers of social roles. After outlining the problems with previous readings centered on quantity of grave goods, perceived value of individual objects and visibility hierarchy, she posits that the criteria of prestige value of grave goods should foreground rarity and exoticism, investment of skill and labor, artistic quality, and overall effect of the assemblage. She further suggests that metalwork was also valued inherently because of its transformation from ore to object. In Chapter 2, Gabor Thomas considers ornamental metalwork in ninth-century Northumbria, a period in which that northern Anglo-Saxon kingdom has long been considered less productive because of the Viking incursions. Recent finds have begun to demonstrate that Viking disruption has been overestimated; Thomas identifies a local style of naturalistic animal interlace quite distinct from the more formalized version of Trewhiddle style in use elsewhere in England in the same period. He therefore postulates regional continuity of fine metalwork at several Northumbrian centers, which would bridge the gap between the earlier “Golden Age” of Northumbria and the later Anglo-Saxon period, while suggesting that production and display of high-end ornamental metalwork is not exclusively a feature of periods of political stability.

Three papers consider the interactions of the Scandinavians and their

⁴ The most common metal, in terms of relative abundance in the earth’s crust, is aluminium, comprising 8.1 per cent of the crust’s mass. Iron forms 5.0 per cent, while all other metals together add up to less than 1.5 per cent of the crust’s mass.

neighbors. In Chapter 3, Nancy Wicker looks at fifth- and sixth-century Scandinavian bracteates in the broader context of women's ornament; she reads the bracteates, worn singly or as part of a complex array, as indices of prestige, as markers of ethnic origin among Scandinavian women in foreign marriage alliances, and as bearers of cultural meaning through ostentatious display. Turning to tenth-century Ireland, in Chapter 4 Niamh Whitfield raises similar issues of mobility and display in another Norse context in her examination of a filigree panel recently found at Temple Bar, Dublin. Originally part of the ornament of a kite-brooch, the panel features both filigree and animal ornament of a type rarely but occasionally paralleled in other Irish contexts of this period. This suggests Irish influence on ornamental metalwork worn in the Viking settlement at Dublin, while attesting to the cross-cultural mobility and assimilation of such small but prominently displayed objects. Finally, in Chapter 5 Michèle Hayeur Smith explores the fabrication of bronze brooches in the Viking Age, bringing to bear both archaeological evidence and the results of her own experiments with the manufacture of similar objects. Based on careful analysis of the fabric patterns on the backs of these brooches, and on the variance in levels of detail achieved in casting, she demonstrates that many of these brooches were made from generations of other brooches, a conclusion that underlines the importance of efficiency and repeatability for the craftsmen originally involved in their production.

The two remaining papers in this section consider later medieval secular metalwork, both personal ornament and the equipment of courtly activities. Here, too, prestigious examples of secular metalwork served not only as vehicles of personal status, but also as foci of intercultural communication. In Chapter 6, Elisabeth Antoine examines a thirteenth-century signet ring inscribed in the bezel with the name of the owner, Guillaume de Flouri, who was Viscount of Acre between 1274 and 1277. On the body of the ring, a second inscription derived ultimately from kabbalistic formulae appears to protect the wearer from a range of associated ailments, from gout to epilepsy. In this instance, therefore, the object of personal ornament documents the cultural intersection between the Crusader kingdom's power structures and eastern Jewish mysticism. In Chapter 7, John Cherry investigates an analogous cultural rendezvous in the Savernake Horn, a twelfth- or early thirteenth-century carved ivory hunting horn, or oliphant, imported from the Mediterranean into the British Isles. There, in the first half of the fourteenth century, it was given silver banding and an elaborate enameled baldric with the coat of arms of the Scottish lord Thomas Randolph, Earl of Moray, although the horn was later associated with Savernake Forest in England. In addition to animals of the chase, the added ornament appears to record a historic agreement between a king and a mitred clergyman at which a horn is blown, possibly indicating the reason for the reornamentation of the horn. The addition of metalwork without recarving the horn itself, meanwhile, may reflect the trend away from ivory and toward metal horns in this period. Here, therefore,

several historical moments and changing taste in art are summed up in one high-prestige object.

Many of the same techniques and materials that were used in secular prestige metalwork were also used to glorify God and the saints, as the second section of this book, *Handling the Holy*, explains. Given the central importance of Christianity in medieval society, it is not surprising that many fine examples of precious metalwork were produced for the Church. Even so, the scale of ecclesiastical investment in such artifacts was absolutely stunning. The recent exhibition of the Basel Cathedral treasury, for example, provided one dramatic demonstration of the staggering wealth and splendor of such treasuries, principally composed of lavish metal liturgical equipment and reliquaries.⁵ Although only a small percentage of these have survived intact, even from the later Middle Ages, documentary sources make clear that similarly impressive ensembles of ecclesiastical metalwork were already being manufactured within a few years of Constantine's acceptance of Christianity. The Lateran Basilica, for example, housed the fastigium, a great screen topped by 18 nearly life-sized silver figures, together weighing 3125 pounds.⁶ Such monuments set a high standard for display that many subsequent ecclesiastical patrons would strive to match.

Because the manufacture of precious religious metalwork took place over the whole course of the Middle Ages, the three papers in this section can provide only glimpses of the phenomenon. Because they illustrate three very different phases in the history of ecclesiastical metalwork, though, they together begin to give some sense of the larger narratives involved. In Chapter 8, Michael Ryan discusses not only the form and construction of early Irish liturgical vessels, but also their architectural context and patronage, arguing that the Irish production of elaborate metalwork vessels in the early Middle Ages may have been intended to rival the great Church treasures of Rome that some Irish Churchmen would have known from their travels. Ryan suggests, further, that the manufacture of spectacular metalwork may have allowed Irish patrons to define a sphere in which they could compete with their Continental colleagues, something that they were hard pressed to do in the architectural sphere. For most medieval worshippers, after all, the sacred contents of the church building doubtless mattered more than the building itself, at least from a strictly devotional perspective.

The spread of the cult of saints in the latter half of the first millennium fostered the creation of elaborate reliquaries, which joined liturgical vessels as prime foci for the visual interest of the faithful. Metal reliquaries were produced in many forms: as simple boxes, with a greater or lesser degree of decorative elaboration; in the form of body parts, often echoing the character of the relic inside; or occasionally, as in the famous reliquary of Saint Foy from Conques, as complete

⁵ See Brigitte Meles, ed., *Der Basler Münsterschatz* (Basel: Historisches Museum Basle, 2001); and Timothy Husband, with Julian Chapuis, *The Treasury of Basel Cathedral* (New Haven, 2001).

⁶ Lawrence Nees, *Early Medieval Art* (Oxford, 2002), 50–51.

figurines.⁷ By the year 1000, a well-equipped church could possess an impressive variety of metalwork reliquary shrines and furnishings. At the Abbey of Essen, discussed by Karen Blough in Chapter 9, the tenth-century Abbess Mathilde commissioned at least one of two processional crosses bearing her portrait, as well as the church's large bronze candelabra, the now-destroyed reliquary of Saints Marsus and Lugtrudis, and the gilded figurine known as the Virgin of Essen, the oldest surviving freestanding image of the Madonna and Child. As Blough demonstrates, these objects express not just Mathilde's piety, but also her high status and her connections with the ruling Ottonian dynasty; the similar metalwork commissions undertaken by her successor Theophanu seem to have been intended as deliberate evocations of this golden age. Above and beyond their political and religious significations, though, the Essen artifacts, especially the statuette of the Virgin, occupy a pivotal position in the history of medieval art. It was in the Ottonian era that sculpture began to re-emerge as a major art form, after roughly six centuries of relative dormancy. Many of the most impressive sculptural productions of the era, including the Essen Virgin and the bronze doors and column commissioned by Hildesheim's Bishop Bernward, were executed in metal. The legacy of Ottonian metalwork contributed significantly to the flowering of architectural sculpture in the Romanesque era, informing the stylistic choices of Romanesque stone carvers as well as later metalworkers.⁸

Even Italy, with its strong connections to the antique tradition, was strongly influenced by the Ottonian metalworking achievement. The sculptor Willigelmo, who carved a noteworthy series of stone relief panels at Modena Cathedral, may originally have been trained in the northern metalworking tradition. An even more direct line can be drawn between the bronze doors of Hildesheim, those of Pisa Cathedral, and those of the Baptistery in Florence. Andrea Pisano created the Baptistery's first set of bronze doors beginning around 1300; his successor Lorenzo Ghiberti added the second and third sets in the first half of the fifteenth century. Ghiberti's doors are usually celebrated as seminal monuments of the early Italian Renaissance, but their obvious ties to medieval metalworking tradition deserve emphasis nevertheless. The prestige of these door projects may help to explain Ghiberti's surprising decision to work in bronze rather than gold or silver when crafting the reliquary shrine of the Three Martyrs for the Florentine church of Santa Maria degli Angeli, as Sally Cornelison explains in Chapter 10. This

⁷ Interestingly, however, many reliquaries are shaped as arms rather than as the body parts they actually contain. See Cynthia Hahn, "The Voices of the Saints: Speaking Reliquaries," *Gesta* 36 (1997), 20–31. This issue of *Gesta* also includes valuable articles on body-part reliquaries by Barbara Boehm, Ellen Shortell, Scott Montgomery, Thomas Head, and the team of Caroline Walker Bynum and Paula Gerson. On church furnishings more generally, see Anton Legner, ed., *Ornamenta Ecclesiae: Kunst und Künstler der Romanik*, 3 vols (Cologne, 1985).

⁸ This thesis has been advanced especially by M. F. Hearn, in *Romanesque Sculpture: The Revival of Monumental Stone Sculpture in the Eleventh and Twelfth Centuries* (Ithaca, NY, 1981).

shrine, jointly commissioned by Cosimo and Lorenzo de' Medici as a sign of Medici piety and power, was likely modeled at least in part on an antique tomb from Lucca, as Cornelison further demonstrates. It thus epitomizes the complex hybridization of ancient and medieval traditions that gave the Italian Renaissance its flavor and significance.

Silver, gold, copper and bronze may have been the key metals in the adornment of both elite individuals and their great churches, but many more practical facets of medieval life depended on the exploitation of less glamorous metals, including lead, tin, and especially iron. The three papers gathered here in the *Mundane Metals* section explore ways in which objects made from these materials were produced and used in both war and peace. Because of the incredible variety of such everyday metal use, it is even more difficult to briefly synopsise this subfield than that of sacred metalwork. Indeed, the first paper in this section, Chapter 11 by Kevin Smith, underlines the extent to which metal extraction and use practices depended on specific regional circumstances. Smith discusses how metalworkers in Viking Age Iceland were able to smelt iron from local bog ore, a rare but easily accessible source of the metal that obviated the need for complex hard-rock mining operations. Significantly, though, Smith shows that iron production even in this relatively provincial context involved far more than the “craft activities” of individual farmsteads and hamlets; instead, it was a large-scale and at least intermittently centralized industry. This Icelandic bog iron industry died out in the later Middle Ages, both because of local resource depletion and because the expansion of trade with larger centers made local iron production increasingly superfluous.

David Starley, in Chapter 12, considers the morphology and microstructure of arrowheads, demonstrating that practically minded medieval metalworkers knew very well how to match materials to functions, even if they lacked the analytical tools available to modern materials scientists. Using metallography, the visual analysis of crystalline structure in metal, he shows that late medieval arrow makers developed “high-tech” steel-enhanced arrowheads to counter the advance from mail to plate armor. This specialization is particularly noteworthy in view of the vast number of arrows produced, given that steel was some five times as expensive as iron in the period. As Starley notes, though, surprisingly little detailed metallurgical work has been done to date on medieval weapons.

On a more peaceful note, in Chapter 13 Julian Lea-Jones provides a detailed description and analysis of a lead conduit water pipe system that is still functioning in Bristol, more than seven centuries after it was first established by the city's Carmelite monks. By adopting a multi-faceted approach drawing on geological, archaeological and documentary evidence, he shows that medieval hydraulic engineering was more sophisticated, and more metal-dependent, than popular stereotypes of medieval squalor might suggest.

“Mundane metals” such as lead and iron helped medieval builders to create architecture that was anything but mundane, as the six papers in the *Strengthening*

Structures section demonstrate. The crucial role of metal in medieval architecture has often been overlooked by modern scholars, for a variety of reasons. From the perspective of nineteenth- or twentieth-century observers accustomed to seeing truly metal-framed buildings such as train sheds and skyscrapers, the use of metal in pre-industrial architecture can seem cautious or negligible, at least at first glance. Both the Greeks and the Romans reinforced their masonry buildings with metal components, however, and the Romans especially often used metal brackets to help mount the decorative columns and marble paneling that gave their buildings such splendor. With the end of the Roman Empire in western Europe, such metal use became far rarer, but occasional elite projects show that the technology was not completely forgotten. The upper cupola walls of the Carolingian Palace Chapel at Aachen, for instance, were held together by a large and carefully crafted armature of iron links. The growth of stone sculpture in the Romanesque era, meanwhile, depended on the availability of metal tools such as chisels.

In the Gothic era, the expansion of metal production allowed builders to exploit metals in new ways. Iron reinforcements helped to strengthen not only stained glass windows, but also the delicate armatures of stone tracery that framed them. Iron dowels in lead rust-proofing jackets, similarly, were used to pin together the components of slender pinnacles, like stone shish-kebabs, whose construction would have been impossible otherwise. By roughly 1300, the extension of these techniques permitted Gothic builders to conceive remarkable structures such as the openwork spire of Freiburg im Breisgau, a skeletal pyramid of iron-reinforced stone tracery that soars more than 350 feet above the town's main square. In a technical as well as visual sense, such spires were the distant antecedents of the Eiffel Tower and the modern skyscraper.

It is impossible to draw a straight line of descent between these structures and their modern successors, though, because the craft details of Gothic metal use were largely forgotten at the end of the Middle Ages. Since the rusting of iron clamps can cause splitting of the surrounding stones, many early modern builders unfamiliar with medieval rust-proofing techniques concluded, too hastily, that iron components should not be integrated into masonry structures. Medieval builders, of course, had used metal components in a variety of other ways – lead, for example, was frequently used to make drainage pipes, to clad timber roofs and spires, and to seal the joints between stones, while nails and other iron fixtures were increasingly used in the later Middle Ages to assemble timber structures – but these applications, too, were often neglected in post-medieval account of medieval building practice. In the nineteenth century, the romanticized idea of the Middle Ages as a pure and natural foil to the industrial age led many architectural theorists to emphasize the medieval use of stereotypically pre-modern materials such as wood and stone, and to champion the use of similarly traditional materials in neo-medieval building projects. In the twentieth century, too, the close identification of metal with modernity tended to obscure the various important

roles of metal in medieval architecture. It is only fairly recently, therefore, that scholars have begun to inquire systematically into this subject.⁹

The papers gathered in this section provide a wide range of perspectives on the use of metal by medieval builders. The first paper, Chapter 14 by Carl Barnes, opens the discussion on a cautionary note, explaining that nothing in the famous portfolio of Villard de Honnecourt suggests that its creator had any interest in architectural metal use. This, of course, reveals more about Villard de Honnecourt than it does about medieval architecture, since Villard, as Barnes points out, was probably not an architect. In recent government parlance, one might thus observe that absence of evidence is not evidence of absence. In fact, there is good evidence that metal was being widely used in architectural contexts by Villard's day, even if Villard himself was more interested in the precious metalwork in liturgical furnishings and sculptures, as Barnes suggests.

The next two papers, written respectively by Jennifer Alexander and by the team of Sabine Lepsky and Norbert Nussbaum, discuss various ways in which metal components were used in the masonry fabrics of northern Gothic churches. In Chapter 15, Alexander explores the use of lead joints in English buildings, with emphasis on their presence in high vaults, in window tracery, and in between the sections of *en délit* shafts. As Alexander notes, lead joints offered many advantages in terms of both flexibility and speed of construction, but they could be successfully poured only by careful teams of skilled workers. In Chapter 16, meanwhile, Lepsky and Nussbaum consider the use of metal at the Cistercian church of Altenberg, near Cologne. They discuss iron clamps, ties, window bars and mounting brackets, lead joints, pipes and gutters, and a complex system of wind bracing on the church's large west window.

In Chapter 17, A. Richard Jones investigates a far more singular set of iron components, those that link the capstone of the Salisbury Cathedral spire to the wooden scaffolding on the spire's interior. Jones sketches a plausible scenario for how these elements could have been assembled at the completion of the spire construction process, and he demonstrates that the linkage between the spire tip and the scaffold was far less structurally consequential than previous scholars had assumed. Ultimately, though, the rationale behind the installation of this unique jointing mechanism remains enigmatic.

More readily comprehensible uses of metalwork can be traced in many later medieval building projects, especially those for which extensive contemporary documentation survives, as the final two papers in this section attest. The team of

⁹ Recent studies on the subject include: Walter Haas, "Hölzerne und eiserne Anker an mittelalterlichen Kirchenbauten," *Architectura* 13 (1983), pp. 136–51; Arnold Wolff, "Stein, Blei, und Eisen," in *Festschrift Martin Grassnick aus Anlass der Vollendung seines 70. Geburtstages* (Kaiserlautern, 1987), pp. 161–5; Alain Erlande-Brandenburg, "L'Architecture rayonnante et le métal," in *Les Bâisseurs du Moyen Âge, Les Dossiers d'archéologie*, no. 219 (Dijon, 1996), pp. 46–55; Jean-Louis Taupin, "Le Fer des cathédrales," *Monumental* 13 (1996), pp. 18–27, and Paul Benoit and Odette Chapelot, eds, *Pierre et métal dans le bâtiment au Moyen Âge* (Paris, 2002).

Philippe Bernardi and Philippe Dillmann uses a combination of archaeological, archival and metallurgical approaches in Chapter 18 to investigate the medieval ironwork at the Papal Palace in Avignon. They show not only that the sheer quantity of iron in this complex was impressive, but also that its builders – like the arrowhead makers discussed by David Starley – carefully matched particular metal types to their appropriate functions. Thus, while many of the small cramps used to link individual stones were made of fairly poor iron, the large tie rods used to ensure the overall stability of the great audience hall and chapel were made of high-grade steely iron. The use of such components, they argue, was integral to the very conception of the edifice. Charles Morscheck, in Chapter 19, is able to make a similar argument about the use of iron at Milan Cathedral, whose design was so extensively and famously debated in the late Middle Ages. Taking advantage of previously unexploited documentary sources, Morscheck also shows that the installation of the truly vast number of metal components in the cathedral can be traced literally day by day and workman by workman, providing a strikingly precise picture of the construction process.

Architecture was by no means the only sphere in which late medieval documents describe the use of metal. The growth of technical knowledge in the late Middle Ages, together with the spread of literacy and the invention of the printing press, created newly favorable circumstances for the production and dissemination of technical literature of all kinds, including that on metal use. The final section of this book, *Technical Texts*, therefore discusses this emergent tradition, which set the stage for the flowering of technical writing in the early modern era.¹⁰ In Chapter 20, Ricardo Córdoba de la Llave considers a Spanish manuscript containing two related manuals: one on commercial arithmetic, and the other on techniques for assaying silver coins – that is, determining their purity and silver content. Córdoba demonstrates that the original text of the assaying treatise must date from the early fourteenth century, even though the present manuscript is a sixteenth-century copy. The detailed descriptions of both calculating methods and fire assaying procedures in this manuscript attest to a high level of intellectual and practical sophistication on the part of late medieval assayers.

The intellectualization of metalworking lore and practical wisdom was even more obvious in the Germanic Empire of the sixteenth century, especially in eastern territories such as Bohemia and Saxony that had flourishing mining industries. While it might be argued that this phenomenon belongs more properly to the Renaissance than to the late Middle Ages, it is worth noting that the material and visual culture of the region remained preponderantly medieval well into the sixteenth century. Indeed, it was the wealth from the Saxon silver mines in this period that made possible the final dramatic flurry of Gothic church construction,

¹⁰ For a discussion of these developments in a broad context, see Pamela Long, *Openness, Secrecy, Authorship: Technical Arts and the Culture of Knowledge from Antiquity to the Renaissance* (Baltimore, 2001).

which featured vaulting systems more complex than any seen before. Many of the substantial achievements of this dynamic era, more generally, built directly on the medieval legacy, even as they paved the way for new developments.

On these bases, it seems appropriate to conclude this book with three contributions that document the state of metal-related studies and social practices at the dawn of the early modern era. In the first of these, Chapter 21, David Connolly discusses the treatise on mining written by Ulrich Rülein von Kalbe, which enjoyed widespread circulation in the decades following its original publication in Saxony around 1500. Connolly emphasizes that this treatise was not only the first printed book on mining and metallurgy, and an important precursor of Agricola's monumental *De Re Metallica*, but also that it was a work of great rhetorical sophistication in its own right. In particular, Connolly explores the ways in which Rülein used co-ordinating conjunctions such as "and" and "or" to create a dense system of self-reinforcing and self-clarifying glosses within his text. In Chapter 22, Peter Siems considers the impact of the 1548 mining law promulgated by King Ferdinand I to govern the tin mines in Schlackenwald, Bohemia. His analysis shows that the royal administration was attempting to impose a new degree of centralized control over mining communities that had formerly enjoyed substantial autonomy. The results of this intervention were mixed; mine working conditions were improved in some cases, but the miners came to resent centralized control, especially when their wages failed to keep pace with inflation in the latter half of the sixteenth century, and changes in the international metals market kept the Crown from realizing the profits that had been expected when the Schlackenwald law was formulated. As Siems briefly notes, Agricola may well have visited the Schlackenwald mines when he was compiling his *De Re Metallica*. The present volume, although very different than its namesake, concludes with Chapter 23, a research bibliography that Agricola himself would probably have appreciated. This bibliography, compiled by David Connolly, has three principal parts: a list of all the primary texts relating to mining, metallurgy and mining law composed through the 1550s in German-speaking lands; a list of all the editions of Ulrich von Rülein's widely published mining treatise, and a large but selective listing of publications on early modern Germanic mining that have appeared in the latter half of the twentieth century.

Since the Middle Ages in Western Europe lasted for well over a millennium, from roughly 300 to 1500, no single volume can provide a comprehensive overview of a broad cultural practice like metal use over that full span of time and territory. The 23 contributions to this volume, however, together begin to suggest the outlines of this subject matter, while providing a series of thematic axes that may prove helpful in navigating it. This volume, in short, should be understood as part of an emerging scholarly discourse, rather than as a definitive monument in its own right. It will have accomplished its mission if it encourages readers and researchers to reconsider the substantial but unappreciated extent to which the Middle Ages were metal ages.