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Building The Medieval Trebuchet

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BUILDING THE MEDIEVAL TREBUCHET

by

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Abstract

The counterweight trebuchet was the heavy artillery of the Middle Ages, using gravity to hurl projectiles and destroy fortifications. In use from the mid-12th century until the mid-15th century, trebuchets became huge machines. Some were more than 60 feet tall and threw stones weighing more than 300lbs farther than 300 yards. These weapons changed the landscape of Europe until being replaced by later gunpowder cannons.

It is unclear how trebuchets were conceived or constructed. While replica historical machines have been made in modern times, the methods of building and assembling trebuchets have not been widely published. Learning how these machines were built can tell us about the logistical difficulties of sieges and the sophistication of medieval engineering and technology.

Although technical details are scarce, there are several extant drawings that are useful, like those from the Bellifortis, Elegant Book of Trebuchets, and the Anonymous of the Hussite Wars. Building techniques are also seen in the timber joinery of surviving buildings. The information gleaned from these sources can be used in conjunction with methods of traditional woodworking and experimental history to reproduce a machine.

Here, I argue that a master engineer would design an engine with geometry and experience, and that something so large can be assembled with traditional hoisting equipment that dates back to ancient times. My research examined these methods firsthand by building a half-scale trebuchet (33 feet tall). This project highlights the technological expertise of the high-late medieval period and shows that craftsmen of the Middle Ages knew how to use simple machines to accomplish the complex task of assembling a large trebuchet.
Acknowledgements

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Thanks also to community sponsors for donating or lending materials. Thanks especially to Mt. Naomi Farms for pumpkins, and to Preston and Morgan from Goodfellers Tree Service for our tree. And to Paul Anderson, local woodturner, for kindly and expertly turning wooden axles on his lathe even at last minute notice. And many thanks to the gracious landowners, Kenton and Barta Reese, who have happily allowed me to use their property as a testing field.

Thanks to my project mentor, Dr. Susan Cogan, for always pushing me to conduct my research, writing, and presentations to a higher standard, and for guidance through hard decisions and for her support of the project from its beginning. And thanks to Dr. Tammy Proctor and Dr. James Sanders for supporting the project as Department Heads, and to Dr. Danielle Ross for translating relevant sections of Arabic text from the Elegant Book for this project.

Thanks to the many friends, students, and community volunteers who have helped to construct the machine, in any aspect, some of whom have never even seen it launch in person. For my sake, and for the sake of space and avoiding playing favorites, I will not attempt to name them all. You know who you are – if you have interacted with the project in any manner over the last two and half years, thank you! This project could not have happened without you.

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Introduction

In 1304, engineers and craftsmen under the English king, Edward I, constructed one of the largest and most famous pieces of mechanical artillery ever used. Named the “Warwolf,” this monstrous machine was a trebuchet, designed to use the power of a falling counterweight to launch projectiles and destroy Stirling Castle, held by the Scots. Although we cannot know exactly how large this machine was, contemporary sources suggest that it was probably more than 60 feet tall and used more than 15 metric tons of counterweight. Building it required a team of 5 master carpenters and 49 other workers and took more than three months to complete. Among them, we know from administrative records, was Thomas of Houghton, an engineer and carpenter, who directed the construction of engines at Stirling and probably oversaw the building of Warwolf. The Scots, watching the machine being assembled, and at the mercy of bombardment by twelve other similar trebuchets, offered to surrender, but Edward refused to let anyone leave the castle until his prized engine had bombarded it. This machine launched stones weighing 300lbs and it broke down an entire wall of the castle.

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1 Several sources describe machines of immense size, and Warwolf was certainly one of these machines. Villard de Honnecourt draws a machine that was probably 20 meters tall with a counterweight box that could hold an estimated 25 to 30 tons of earth, according to Historian Roland Bechmann. See Bechmann, “Engins de guerre medieauxxa balancier: Le trebuchet de Villard de Honnecourt,” Historica 501 (Sept. 1988): 52-62. And Bechmann, “Le trebuchet de Villard,” Pour la Science 119 (Sept. 1987): 11-12. Thus 60 feet tall is a reasonable estimate for Warwolf and also the approximate size of the reconstructed machine currently at Warwick Castle in England.


3 Prestwich, Armies and Warfare, 286.

4 Ibid., 300.

These machines were certainly one of the greatest feats of medieval engineering and military technology. At scale, they were capable of destroying castles and fortifications, which were the keys to controlling the landscape. And Warwolf was not alone, for counterweight trebuchets were the heavy artillery of the Middle Ages, dominating siege warfare for almost 300 years. Trebuchets were ubiquitous across the whole of Eurasia, spread through the Crusades, and notably adopted later by the Mongols. Several of these machines were enormous and destructive engines, perhaps even larger than Warwolf, such as “Victorious,” used in the Siege of Acre in 1291.

In light of few technical sources, experimental history helps modern scholars to understand how large trebuchets were built. Most scholars and trebuchet enthusiasts have heard of Warwolf, but the construction of the machine is often overlooked or taken for granted. Assembling something so large and heavy presents many obstacles and challenges. Learning hands-on how medieval craftsmen solved these challenges and assembled trebuchets at scale lets us better understand the elegant sophistication of their technology and the logistical difficulties of siege warfare.

In the fall of 2017, I began answering these questions through the experimental construction of a half-scale machine, which is 33 feet tall. Guided by research and trial-and-error, this prototype was redesigned, rebuilt, and more successfully tested in the fall of 2018. It was built using as many historical techniques as feasible and provided a new lens with which to

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7 Counterweight trebuchets appear to have been in prime use from their invention in the mid-12th century until the middle of the Hundred Years War in the early 15th century.
8 If carts required for transportation are a sign of the size of a machine, Victorious took 100 carts to transport. Michael Fulton, “Development of Prefabricated Artillery during the Crusades,” *Journal of Medieval Military History* 13, no. 1 (2015): 51-72; see page 70.
9 The details of constructing a large trebuchet are often so ignored that the scale of Warwolf is dramatically over-exaggerated on the internet currently, to the point where many online sources claim that the machine was 300-400 feet tall. These claims are preposterous and unsubstantiated.
examine the building techniques of the period. Here, I aim to document this experiment, discuss the sources and methods behind it, and posit a general construction process that was used for trebuchets during their primacy.

**Trebuchet Principles**

A counterweight trebuchet is a mechanical artillery engine that operates mainly on the principles of leverage and gravity. A long lever, called the throwing arm, is suspended in the air by the main axle of the machine. This axle rotates in blocks on either side, which are held in place with a framework of support called the bents. The throwing arm is usually offset on the main axle such that the long side is anywhere from three to six times longer than the short side. On the short side is attached a counterweight, which is sometimes fixed onto the arm, but is often suspended or hung from the arm in the form of a box filled with weight. The latter type is called a hinged counterweight machine and will be the focus of this paper. This type of machine usually has two axles piercing the throwing arm: a main axle for the arm itself, and a secondary axle, or box axle. The latter allows the counterweight box to rotate in relation to the throwing arm during the throw, making the machine more efficient. This can be seen in figure 1 below.

The machine is operated by pulling down the long side of the arm, which in turn raises the counterweight on the short side. The arm is latched in place while the machine is loaded. A sling for the projectile has two cords on either side of a pouch, and one of these cords is fixed to the tip of the long side of the arm. The projectile is loaded in the pouch and placed in a trough underneath the machine while the second cord of the sling is made ready to slip off a pin on the tip of the arm during the throw. When the setup is released, the counterweight falls on the short side, and this rotates the long side of the arm around quickly, which in turn whips around the
sling, and when the second sling cord slips off the pin, the pouch opens and releases the projectile. Essentially, the machine uses the energy of a large falling weight, multiplied by leverage from the arm and sling, to accelerate a projectile through an arc.  

Figure 1: A frame sequence of a launch from the Black Widow, the author’s trebuchet, showing its function. These frames are separated by different time intervals, but the entire sequence takes hardly more than one second. As the counterweight falls, the long side of the arm whips around the sling, which slips off a pin and throws the projectile. This shot used 1,350lbs of counterweight and threw a 16lb bowling ball 887 feet. Note the fourth picture, with the angle of the sling in relation to the throwing arm. In the fourth picture, the arm has just returned to vertical position and the tail end of the sling has just slipped off the pin.

However, early trebuchets in history did not use counterweights but were instead powered by men violently pulling on ropes from the short side of the arm; these are called traction trebuchets.
Historiography

The history of the trebuchet has been thoroughly examined and its development debated. The focus of much of this work has been the separate inventions of traction and counterweight machines and their introduction and spread throughout Europe.¹¹ This scholarship has also tried to tackle the problems of primary source terminology, since historical accounts refer to trebuchets with a variety of generic terms in a multitude of languages, which makes evaluating the design of machines difficult.¹² Terminology in the sources is often so obtuse and unhelpful as to the function of the machine that a myth persists for the continued existence of Roman style torsion machines in the Middle Ages.¹³ Scholars have also debated the existence of “hybrid” trebuchets, and contested the response of defensive architecture to trebuchet technology.¹⁴ Some scholars have also examined the administration and logistics of trebuchet artillery, particularly in England, where sources are most prolific.¹⁵


The mechanics of trebuchets have also been discussed by physicists and historians. Physicist Donald Siano has done calculations on the mechanics of the machine, which have produced several useful conclusions that would have also applied to machines in history. First, Siano concludes that the sling should be the same length as the long side of the arm, and second, that the arm should be cocked at 45 degrees before firing. Third, that the counterweight should be allowed to hang as far down as possible before hitting the ground (or the machine itself), and fourth, that a counterweight to projectile weight ratio of 100 to 1 should be observed. Historian Donald Hill has also discussed the absolute importance of the trebuchet’s sling and the effectiveness of various arm ratios in throwing different weight projectiles. Historian D.J. Cathcart King has also produced model trebuchets and documented their ranges and the effects of changing several machine variables. King established that the trebuchet’s performance could be altered by changing the shape and angle of the pin on the tip of the arm, the weight of the projectile, the weight of the counterweight, the arm ratio, and the length of the sling. And historian Michael Fulton has analyzed the mechanics and mathematics of trebuchets, offering perhaps the best examination yet of traction machines.

Reconstructions of trebuchets have been made by several historians, archaeologists, and engineers. The first known reconstruction was by Napoleon III of France in the 19th century, and the attempt was led by his captain, Fave. This machine, considering its size and counterweight,
performed very poorly, apparently due to an extreme arm ratio and bad design. Reportedly, the first shot threw backwards, and the machine broke down after several launches.\textsuperscript{21} For more than a hundred years afterward, trebuchet reconstructions seem to have been scarce.\textsuperscript{22} Much of the focus in the early twentieth century was on torsion machines of Greek and Roman design.\textsuperscript{23} In the 1990s, archaeologist Peter Hansen built several machines in Denmark, and his designs are still used widely as reconstructions at museums and castles, particularly in England.\textsuperscript{24} W. T. S. Tarver, then graduate student at the University of Toronto, made and tested a traction machine in 1991.\textsuperscript{25} Engineer Wayne Neel led the reconstruction of a machine at the Virginia Military Institute in 1997.\textsuperscript{26} Craftsman Renaud Beffeyte has built dozens of reconstructed machines in France through his company, Armedieval, founded in 1984.\textsuperscript{27} Neel and Beffeyte both designed separate full-scale machines at Loch Ness in Scotland for the NOVA episode, \textit{Secrets of Lost Empires: Medieval Siege}, which aired in 2001; this has been a great inspiration for many people interested in trebuchets.\textsuperscript{28} Archaeologist Tanel Saimre has also constructed an engine in 2002 in Estonia.\textsuperscript{29} Reconstructions like these help us to understand the operation of trebuchets and to evaluate the performance and capabilities of medieval artillery.

\textsuperscript{22} I am not sure why this is – it could be that there are works or reasons I have not discovered yet. Also, many of these works in the early 20\textsuperscript{th} century remain in German, which I cannot read.
\textsuperscript{23} See particularly the work of Eric Marsden, note 51, below.
\textsuperscript{27} Renaud Beffeyte, \textit{War Machines in the Middle Ages} (Editions Ouest-France, 2008).
\textsuperscript{28} \textit{Nova}. “Secrets of Lost Empires: Medieval Siege.” Directed by Michael Barnes. Aired Feb. 1, 2000 on PBS, WGBH.
Many of these trebuchet reconstructions have been excellent projects in experimental archaeology and history and have discovered much about trebuchets. Experimental archaeology is the process of recreating methods or technologies from the past to gain an understanding of their form or function that cannot be gathered from the available sources alone. Neel, Hansen, and Beffeyte in particular have all overseen machines based on historical sources and built with traditional woodworking methods.\textsuperscript{30} Much of what has already been done will be built upon here. However, the actual process of assembling and raising the machine on site has not been discussed in detail in literature. My work has focused more on the assembly process and will examine techniques used to erect the structure of a trebuchet by looking at sources like the \textit{Elegant Book of Trebuchets} and the \textit{Anonymous of the Hussite Wars}. I argue that to construct a large trebuchet, the assembly process must be broken down into key steps, and that these steps would be quite similar across cultures due to the nature of the machine.

\textbf{Scale of this Project}

The size of the machine built was determined by contest limitations and maintained by balancing ambition with practicality. My interest in trebuchets began with the pumpkin toss hosted every year by the American Society of Mechanical Engineers at Utah State. This competition requires that the main axle of a machine be no more than 15 feet off the ground.\textsuperscript{31} It was necessary to stay within this restriction to allow the History Department to enter the machine.

\textsuperscript{30} Neel was assisted by the Timber Framers Guild, and Hansen credits his machines to Millwrights, while Beffeyte himself is experienced in medieval woodworking.

\textsuperscript{31} We were, however, breaking the previous width and length requirements for the machine’s base, but successfully lobbied the competition coordinator for these exceptions given that it made the machine more stable without adding undue advantages in performance.
in the contest. Moreover, this limit already serves to produce a machine of large scale. With an axle height of 15 feet, the machine was 35 feet tall at first construction in 2017.\textsuperscript{32}

In order to understand the problems of lifting and positioning heavy pieces, it is necessary to build at large scale. Certainly, building a 60-foot machine would reveal all the difficulties of assembling a trebuchet in full.\textsuperscript{33} But it would also require an exorbitant amount of money and other resources, such as heavy transportation equipment and sources of large timber. And, of course, building a full scale machine was completely unreasonable considering my lack of experience.\textsuperscript{34} On the other hand, building a small model is easiest and least expensive, but this makes it difficult to see the realities of full construction since pieces can be easily handled.

I have deemed the resulting machine half-scale, and the size served the project well. At this size, the difficulties of assembly must be tackled in much the same way as they would at full. But the scale does not make things so difficult as to dismay a determined novice or make assembly impossible without a large crew of experienced workers and heavy tools and ropes. In cases where this scale allows “cheating,” or assembly methods that would not be possible with larger pieces, I will mention this and examine how it could be attempted at full. The resultant machine was admittedly underbuilt for its height, meaning that it is tall but skinny,\textsuperscript{35} but this kept the cost of lumber within budget.\textsuperscript{36} I have named the machine the Black Widow.

\textsuperscript{32} The arm here was 25 feet long and designed to have a ratio of 1:4 originally, with the short side 5 feet and the long side 20 feet. This was later cut down, so the long side was 18 ½ feet. The machine now stands 33 ½ feet tall.\textsuperscript{33} The drawing from the Innsbruck version of Kyeser’s Bellifortis, standing at 84 feet, is the largest machine I have found evidence for, but there is no way of knowing if it was ever built. See Chevedden, “Invention of the counterweight trebuchet,” plate 4. See also figure 5 in this paper.\textsuperscript{34} If a full machine had been attempted, the logistical difficulties of assembly would have defeated me. In fact, the difficulties of assembly at half-scale almost did. It took 3 days of beating heats together to assemble the machine for the first time in 2017. Now it can be done in 3 hours. Much of what was learned here was learned the hard way.\textsuperscript{35} See in comparison the Lexington Bellifortis built at VMI, which stands the same height as my machine, but is constructed more substantially. Its main uprights are 10x8s, while the uprights on my machine are 6x4s, and the Lexington Belle holds more than 12 times the counterweight. Ed Levin, “Building the Lexington Bellifortis,” \textit{Timber Framing} 44, (1997): 10-11.\textsuperscript{36} The budget for this project has been through several requests and awards from half a dozen departments and programs and comes to almost $4,000 over the last two years.
Given project resources, my experience, and safety concerns, function was prioritized over pure historical accuracy. For example, I decided to construct the counterweight box with modern tie plates and lag screws due to my limited experience in timber framing. For sake of time, power saws and drills were used throughout. However, the larger pieces of the frame are indeed connected with mortice and tenon joints, and these are pegged with straight-grained dowels. Other historical elements of the machine will be discussed throughout, and in many cases, it is easy to see how certain elements could have been made with more historical methods.

The machine was built in 2017 and rebuilt in 2018, and both seasons consisted of more than 200 hours of labor on my part, with the help of several student volunteers, totaling more than 500 labor-hours per season. This work ranged from arranging logistics and transport to fabrication in the workshop and then assembly and testing on the field. It also included taking the machine to the pumpkin toss competition, and unforeseen tasks, like filling a ton's worth of sandbags at the city gravel lot and driving a backcountry road for the tree destined to become the throwing arm.

Figure 2: The author, 6'2", stands on the bottom rung of the ladder of the Black Widow, briefly displayed on the main campus of Utah State University in March 2019.

37 I confess that dowels are not the first choice for pegs when timber framing. Instead, pegs are usually made from scratch by splitting wood.
Sources and Methods

The most reliable sources about constructing trebuchets come from engineering drawings, technical manuscripts, and military manuals. These include the *Elegant Book of Trebuchets*, several versions of the *Bellifortis*, the *Anonymous of the Hussite Wars*, and the engineering notebook of Villard de Honnecourt. These sources were written and illustrated by people who had direct experience with trebuchets during their period of use, and they formed the basis of this study. They were supplemented by a variety of common manuscript illustrations, a handful of narrative accounts, and previous reconstructions and experiments.

An excellent source is from the thirteenth-century notebook of Villard de Honnecourt, a French engineer or architect. Villard draws a ground plan for a large trebuchet and describes it with a few sentences, which have been translated into English from the old French. Unfortunately, it seems there was also an elevation plan or sideview of this machine, but the page has been lost. Regardless, the base plan is enlightening. Its framework is clearly pieced together in a traditional style of woodworking, and the machine features at the rear two attachment points for capstans to haul down the arm and load the machine. Honnecourt’s machine also features labeled dimensions, and he describes the counterweight box itself as being 12 feet long, 9 feet wide, and 12 feet deep. Although there has been contention as to Villard’s background, he seems to have had useful knowledge of trebuchets and construction techniques.

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Figure 3: The plan of Honnecourt's trebuchet, taken from the Facsimile by Robert Willis, 1859 (see note 38). The rear of the machine is at the top of the page. The loop of rope would be wrapped around the throwing arm of the machine during the reloading process. The axles of the two capstans are represented by the round dots that the rope terminates in. Note how the plan only makes visual sense if all the pieces are lapped together to form one vertical level. See figure 9 in this paper for a drawing of the half-lap joint.

The *Bellifortis*, by Conrad Kyeser, is a military manual written in Germany around 1405. It depicts a wide variety of siege weaponry and machines, some of which are quite strange. There are several versions of the text that each feature different illustrations, and the Innsbruck and Gottingen printings are commonly referred to by trebuchet researchers. Each contains a single drawing of a trebuchet which is of interest. These are among the most detailed trebuchet

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41 Conrad Kyeser of Eichstatt, *Bellifortis* (ca. 1405), Gottingen, Niedersachsische Staats- und Universitätsbibliothek, Cod. MS philos. 63, fol. 30r; and Conrad Kyeser of Eichstatt, *Bellifortis*, Innsbruck, Tiroler Landesmuseum Ferdinandeum, MS 16.0.7, fol. 21r. These are figures 4 and 5 in this paper below. I am referencing these images as seen in Chevedden, “The Invention of the Counterweight Trebuchet,” plates 3 and 4 respectively.
drawings available and key features are able to be discerned from each which hint at their construction. Both drawings have parts labeled with dimensions which give the machines astounding size. The Innsbruck trebuchet would stand at over 84 feet tall.\textsuperscript{42} To my knowledge there is not original text, in German, that goes specifically with these drawings and describes the machines in any technical detail.

\textbf{Figure 4:} The trebuchet from the Gottingen version of the \textit{Bellifortis}. Note the windlass design, which I used on my machine. Also, the heavy timber joinery and the ladders on the side of the machine. However, the mounting of the windlass itself does not seem to be sturdy. Image from: https://www.michael-kirchschlager.de/category/blide-steinschleuder-trebuchet/

\textsuperscript{42} Innsbruck \textit{Bellifortis}, via Chevedden, “Invention of the Counterweight Trebuchet,” plate 4. See figure 5 below.
Figure 5: The trebuchet from the Innsbruck version of the *Bellifortis*. From Chevedden, “Invention of the Counterweight Trebuchet,” plate 4. Note the prop for the counterweight, and the heavy banding on the throwing arm. Also, the square hole at the top of the main uprights, potentially for using a header bar during the assembly of the machine.

The *Elegant Book of Trebuchets* is a Mamluk technical manuscript written by Yusuf ibn Urnbugha al-Zaradkash in 1462-63. It is the most detailed source about trebuchets that has been found, and the only source that depicts trebuchets in various stages of construction. The work features only a short introduction by Zaradkash before it turns to a series of drawings with scantily labeled parts. These drawings range from traditional trebuchets to gunpowder weapons, flammable projectiles, fortress designs, and other siege weaponry. The book depicts trebuchets of the couillard type, as well as a strange type of trebuchet that is not fully understood and has not yet been recreated: the Black Camel trebuchet. Zaradkash was clearly experienced with

*Chevedden, “Black Camels and Blazing Bolts,” 233-38.*
siege weapons and trebuchets, and this work represents the height of trebuchet technology. Even the traditional counterweight trebuchet depicted features an iron weight on the throwing arm to counterbalance the beam, and the counterweight box appears to be propped forward; both are advanced features. The original manuscript is located in the Topkapi Palace in Istanbul; however, I have worked with a published version by Ihsan Hindi. Although I cannot read Arabic, the original work itself is mostly a matter of interpreting the drawings. For the purposes of this writing, I have only focused on the short section of the book that deals with constructing a traditional trebuchet, called by Zaradkash a war trebuchet. This is the section that depicts a trebuchet in stages of construction and the section of most relevance to this study.

Figure 6: The “War Trebuchet” as drawn by Zaradkash in the Elegant Book. Picture taken from Hindi, page 67 (see note 44). Note that the counterweight box seems to be propped forward almost perpendicular to the arm. Also note the iron weight to counterbalance the throwing arm. The wheel at the front of the machine is the windlass used to reload the arm.

44 Aranbughā Zaradkāsh, al-Anāq fi al-manājanāq, ed. Ihsān Hindi (Aleppo: Jami‘at Halab, Ma‘had al-Turāth al-‘Ilmī al-‘Arabī, 1985). Unfortunately, Hindi’s edition is published in black and white and the original manuscript is in color. Hereafter referenced as “Hindi.”

45 The labels on these drawings, as well as some of Hindi’s commentary, have been kindly translated for me in rough form by Dr. Danielle Ross at Utah State University. The only primary source text accompanying the images are the short introduction and the labels on the drawings.
The *Anonymous of the Hussite Wars* is a technical treatise from the late-15th century in central Europe that features detailed drawings of many machines both military and civil in nature. The work contains two drawings of trebuchets which have some features that influenced my project. However, the most relevant drawings of this work depict shear leg cannon hoists, which will be described below. This work is contemporary with both cannons and trebuchets, and I will argue here that the hoists shown in this manuscript were similar to what was used to raise the throwing arms into position on trebuchets.

![Figure 7: The trebuchet from the *Anonymous of the Hussite Wars*. Scan taken from Bert S. Hall’s published edition (see note 46). Note the ratchet gear and the apparently laminated throwing arm, as well as the animal in the sling, about to be thrown.](image)

There are several other sources that feature trebuchets, but I have not thoroughly examined these. They are still useful but are not the main focus of this study. They include the many depictions of trebuchets and siege engines in Robert Valturio’s *De Re Militari*, and the drawings by Mariano di Jacopo Taccola and by Francesco di Giorgio Martini. Additionally, there are later military manuals like the Talhoffer Fechtbuch. There are dozens of illustrations and depictions, and the wealth of these has not been cohesively summarized and examined in the context of trebuchets.

Since there are no surviving trebuchets, sources like those mentioned above are the best available. Peter Hansen, citing Rathgen, mentions a trebuchet that was uncovered in 19th-century Prussia, but it was burned for firewood and no details of the machine were recorded. We do, however, find the stones that trebuchets threw, and some of these are quite massive, weighing up to 300kg. Nevertheless, there are no primary sources on trebuchets which are nearly as detailed as the treatises on Greco-Roman artillery. In that case, we have written technical descriptions by Heron, Biton, Vitruvius, and Philon, which give dimensions for machines and details on construction methods. These were translated and studied by Eric Marsden in the 1960s. In lieu of similar treatises on medieval artillery, we must turn to experimentation to learn about trebuchets in more detail.

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There are many written historical accounts that discuss trebuchets, but few are useful for learning technical details. It is common for a source to only mention that a machine was used at a siege, and even when sources mention features, we encounter the problem of non-standardized terminology. Essentially, every writer describes siege engines and their parts with different generic terms in his own language. Thus, it is usually difficult to determine via written sources if a machine was powered by traction or counterweight, let alone exactly how large the machine was or how it was constructed.

This leaves images from illustrated manuscripts, which are of controversial value among scholars. Many illustrations of trebuchets are secondary to the author’s purpose and merely serve as representations of the machines. These depictions are often not useful for noting technical details, and some of the illustrators had probably never seen a trebuchet in person. Most feature “Escheresque contradictions,” and draw the soldiers operating the machine taller than the machine itself. Several show a machine with physical impossibilities, which, upon launch, would destroy itself.

However, instead of entirely discarding illustrations as sources, key features can be discerned from careful examination. Some scholars would wholly discount many drawings when given these errors. But most of these drawings can still be useful, albeit subject to skepticism. Some of these artists, although getting a few details wrong, had probably seen a trebuchet in person, and depicted something that fits with the medieval aesthetic. Many of these drawings, although perhaps showing impossibilities, contain discernable and valuable features that could represent machines of the period. Even the trebuchet from the Gottingen Bellifortis is

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52 The non-standardization of trebuchet terminology is a problem even today, and I often refer to my construction as an engine, machine, trebuchet, or catapult.

drawn out of scale – it appears that the counterweight would not swing clear of the frame – but it still contains useful information.

Figure 8: The Milemete trebuchet, from Christ Church MS 92, folio 67r-1 (see note 54).

For example, take the trebuchet shown by Walter de Milemete, which contain features that are both unreliable and potentially useful. Here, the machine has an “x” bracing between the main supports that the counterweight would smash through upon launch. It also appears that the machine is attempting to throw a projectile around the same size as the counterweight, which would not be successful. And the relish or bottom end of the throwing arm would contact the counterweight basket on release. However, this drawing still contains useful information. The soldier standing by the winch is holding a large hammer, and it could be that this was used to trigger the machine. The machine was reloaded with an external windlass. And most glaringly,

the throwing arm is shown to be a tree through a knob or knot towards the tip. The artist went out of his way here to show a tree with its taper and character, and this can be taken to mean that at least some trebuchets in history used whole trees as throwing arms. The hinged counterweight machine at the Loch Ness trials also used a single piece tree for the arm which featured crooks and character.\textsuperscript{55} However, where skepticism must occur is in the extent to which this tree was processed. Although it cannot be discerned from the drawing, it is likely that the bark was removed and that the sides of the trunk were squared off to allow for parallel axle holes to be bored in the arm. Hence, any drawing has the potential to provide useful information when examined, but many features must be taken with a grain of salt, or else cannot be validated for certain.\textsuperscript{56} Even the technical sources are not exempt, and the same skepticism must be had of the sources outlined above which form the basis of this article.

Design and Construction

Trebuchets in the Middle Ages were designed by a master engineer using geometry, ratios, and expertise. The medieval craftsman had much experience with compass dividers and used this tool to lay out plans with ratios remembered through the figures of animals.\textsuperscript{57} The master engineer would design the machine and proportion the size and strength of pieces based on his experience, the quantity and quality of available lumber, and the size of projectile desired to be thrown.\textsuperscript{58} Ratios and geometry so dictated design that in many cases the entire machine


\textsuperscript{56} This process of careful examination would be aided by the ability to compare a wealth of trebuchet illustrations to each other. An excellent project waiting to happen is the creation of an electronic database containing as many of these illustrations as possible, with proper citations and sourcing. This would allow the visual study of the evolution of trebuchet construction and design and would make certain trends in depictions visible.


\textsuperscript{58} Neel, “Design Considerations for a Large Trebuchet,” 12.
could be proportioned from one or two pieces, such as the main throwing arm.\textsuperscript{59} The master engineer would also coordinate the majority of the project’s logistics, comparable to a modern contractor who oversees sub-contractors.\textsuperscript{60}

The pieces of the machine were fabricated by carpenters working from scale plans or a model. Scaling up the proportions of an extant model of the machine would make it easy for workers to lay out and visualize large pieces while minimizing the need for measurements and calculations. Model machines are mentioned, although sometimes for different purposes. Jean de Joinville tells of a toy machine used by the Count Compte d’Eu, who enjoyed shooting stones into his tent and breaking his dinnerware.\textsuperscript{61} Surely some of the great trebuchet builders, like James I of Aragon, possessed similar working models.\textsuperscript{62} Working from scale models is still commonly done today and is often used in reconstructions and historical projects.\textsuperscript{63}

Parts of trebuchets were connected with wood joints in a style called timber framing. Wooden pieces are socketed and fitted into one another without nails or bolts using instead protrusions and cavities in the workpieces themselves.\textsuperscript{64} The most common of these joints is the mortice and tenon, where the tenon protrudes into the mortice cavity on the opposite piece. These joints are usually locked into place with wooden pegs, dovetails, or wedges to prevent the pieces from withdrawing.

\textsuperscript{59} Levin, “Building the Lexington Bellifortis,” 10. Wayne Neel also has a theory about designing trebuchets to fit the golden rectangle. Neel, personal correspondence.
\textsuperscript{60} Malcolm Hislop, \textit{Castle Builders: Approaches to Castle Design and Construction in the Middle Ages} (Barnsley, UK: Pen and Sword, 2016), 1-10. And Derek Renn, “Master Jordan, who made the King’s Trebuchet,” \textit{Arms and Armour} 1, no. 1 (2004), 25-32.
\textsuperscript{62} Paul Chevedden, “The Artillery of King James I The Conqueror.” See note 47 above.
\textsuperscript{63} Hansen built and experimented with several models, working up in scale. I neglected to do this and so the inevitable flaws required a full rebuild of the large machine. Hansen, “Reconstructing a Medieval Trebuchet.”
\textsuperscript{64} On timber framing, see Jack Sobon and Roger Schroeder, \textit{Timber Frame Construction: All About Post-And-Beam Building} (North Adams, MA: Storey Publishing, 1984). Many of the conventional nails and fasteners of today did not come into use until the 19\textsuperscript{th} century.
Figure 9: Three of the wood joints most discussed in this paper. Taken from *Timber Frame Construction*, by Sobon and Schroeder (see note 64).

Evidence for these practices abounds in surviving medieval buildings and wooden structures, and they were standard practice in all manner of construction. Scholar Cecil Hewett has examined historic buildings in England and discussed the evolution of these joinery techniques.\(^65\) There is also direct evidence for this style of construction in surviving trebuchet manuscripts, and the construction of trebuchets probably evolved likewise.\(^66\) Villard de Honnecourt's base plan of a trebuchet does not make visual sense unless it was connected with timber lap joints in many places to form one level, and the plan features many dots which represent pegs in the joinery.\(^67\) The trebuchet from the Gottingen *Bellifortis* shows heavy wooden joinery held in place with up to five pegs in some joints.\(^68\)

Wood for trebuchets was worked green, while it was still fresh and moist from being cut and felled. Often machines were made at the site of a running siege, and seasoning wood was

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\(^66\) The evolution of counterweight trebuchet design and construction in the Middle Ages has not been discussed in literature to my knowledge.

\(^67\) Rev. Robert Willis, *Facsimile of the Sketchbook of Wilars de Honecourt*, plate LVIII. See note 38 above.

\(^68\) Gottingen *Bellifortis*, Chevedden, "Invention," plate 3. See figure 4 in this paper above.
not an affordable luxury. Wood is softer and easier to work when green, but it also weighs a lot more than when seasoned, making lifting and positioning pieces more difficult; as in any case, there are tradeoffs. Regardless, green woodworking was the standard practice for regular building construction, and this would have also been done for machines that were pre-fabricated and then transported to sieges.\(^6^9\) Examining surviving pieces shows that trees were debarked and hand-hewn with axes.\(^7^0\) Moreover, the ship-building scene on the Bayeux tapestry shows a worker hewing a freshly-cut log with a broad-axe.

The majority of pieces for a trebuchet would be pre-made and readied before the machine was assembled in one sequence. As parts are completed, they are temporarily joined to their neighbors and tested for fit, then set aside and labeled for their specific place in the machine. Each fit was custom and parts were not interchangeable in the final product. A system of carving notches in the pieces was usually used, as is being revived today at Guedelon Castle.\(^7^1\)

The Black Widow is a composite of several sources and modern reconstructions. The ground level of the machine is roughly informed by Honnecourt’s drawing and the base used in Peter Hansen’s design.\(^7^2\) I have since realized that this design is hardly faithful to Honnecourt, since Honnecourt’s layout forms one vertical level, while my base is multi-tiered. The axle blocks were influenced by the fixed-counterweight machine at Loch Ness.\(^7^3\) This design puts the load from the main axle down into a block which then distributes that load to each of the three

\(^{6^9}\) Allan Gordon MacKay III, *Changes in the Design of Centrally-Planned Timber Frames During the Middle Ages, A.D. 1250-1350* (Department of Architectural History, University of Virginia, 2004), 41. And Fulton, “Prefabricated Artillery.”

\(^{7^0}\) Cecil Hewett, *English Historic Carpentry*, throughout.


\(^{7^2}\) Hansen, “Experimental Reconstruction of a Medieval Trebuchet,” 207.

\(^{7^3}\) Levin, “Highland Fling,” opening picture. Neel’s design of the axle blocks was originally taken from the trebuchet on a Spanish manuscript, *Las Cantigas de Santa Maria*, MS T.I. 1, folio 28, which can be seen here: http://warfare.gq/Cantiga/Cantigas_de_Santa_Maria-028.htm
supports on either side, as opposed to relying on the main uprights and merely bracing those with the other struts further down. Later, I discovered the trebuchet in the *Elegant Book*, which features identical axle block design, although Zaradkash joins five supports into the blocks and not just three.\textsuperscript{74} The shape of my hanging counterweight basket was influenced by the Loch Ness hanging-counterweight machine.\textsuperscript{75} This basket design, with a curved bottom, maximizes the leverage of the counterweight by allowing the weight to hang as far down as possible before interfering with the base of the machine. A flat-bottomed box, in comparison, must be hung higher up to avoid the corners striking the base of the machine, and thus flat boxes lose that extra edge. Since I was not sure how to make the bottom of the box curved with project resources, I settled on a diamond pattern. Thus, the resulting machine is not faithful to any one source. The dimensions for the machine were determined using trigonometry.\textsuperscript{76}

The side struts on my machine feature integral ladders, which I found to be absolutely necessary. Ladder steps on side struts are clearly seen in the Gottingen *Bellifortis*.\textsuperscript{77} The ladders on my machine are used to access the axle blocks. They were made much sturdier in 2018 by sinking the rungs slightly into the struts instead of relying purely on screws; now, they are reliable and sturdy. The ladders are climbed during assembly to unhook the tackle after raising the throwing arm and to address any problems on seating the axle. They are then used frequently to lubricate the main axle and drape the reloading rope over the axle before launch.\textsuperscript{78}

\textsuperscript{74} *Elegant Book*, Hindi, 54-55. See also figures 6, 14, 15, and 16 in this paper.

\textsuperscript{75} Renaud Beffeyte, “A Serious Challenge,” 13. A picture of one side of the counterweight basket can be seen.

\textsuperscript{76} Trebuchet Dimensions. The main uprights are 14 feet tall, so with the height of the blocks and the frame the main axle is supported about 15 feet in the air. The rails are 20 feet long, with the bents occupying the forward 15 feet and the rear 5 feet left to serve for latching down the arm. The A-frame supports join into the blocks at 65°, and side struts with ladders, about 12 feet long, join into the main uprights at 75°. The two bents have 3 feet of clearance, and the side struts join into the main ground crosspiece which gives the trebuchet a 12 foot width. The throwing arm is a remarkable Douglas Fir tree which was originally 25 feet long and 9 inches in diameter at the base.

\textsuperscript{77} Gottingen *Bellifortis*, Chevedden, “Invention,” plate 3. See figure 4 in this paper above.

\textsuperscript{78} Draping the main haul rope, used for reloading the machine, over the axle blocks before launching gets it out of the way of the sling and prevents it from snagging on the frame and fouling the launch.
ladders also facilitate close inspection of the main axle and the throwing arm and are used to untangle ropes when needed. Curiously, a majority of historical depictions of trebuchets do not feature ladders. This could be artistic oversight, or it could be that workers in the Middle Ages simply climbed the frame; the frame braces drawn on the trebuchets in the *Elegant Book* would be easy to climb. It is difficult to imagine constructing a full scale trebuchet without the ability to climb to the axle blocks.

**Assembly Process**

Once all the pieces are completed, the process of erecting the machine can begin. The process begins at the ground and works upward. The pieces that are destined to be in contact with the ground are laid out and joined together and the ground frame is leveled. Then each side structure is laid out sideways on the ground, and the axle blocks are slid onto the tenons and all the joints on these structures are pegged into place. These structures are referred to as bents, and once they are completed, they can be tipped up and raised into vertical position just like in a traditional barn-raising.79 These bents could also be referred to as crucks, as they are built in the same manner as the corresponding frames in a medieval cruck house.80 The side struts, which support the bents laterally, are joined into each as it is raised.81 With this system, “the work of cutting the joints might have taken months, but the actual raising could be done in hours.”82 On the Black Widow, the bents could be tipped up by hand, but on a larger or heavier machine, ropes, poles, or additional tackle would be needed to raise them, such as the shear legs discussed below.

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80 Hewett, *Historic English Carpentry*, 3.
81 These side struts are the aforementioned pieces with ladder rungs.
Raising the Throwing Arm

Once the frame of the machine is assembled, the throwing arm needs to be lifted into position and seated in the blocks with the main axle. This is a remarkable feat of medieval engineering and the core of the entire assembly process. On my machine, this meant that a tree weighing an estimated 400lbs needed to be somehow raised 15 feet in the air. On a full-size machine, this would be even more demanding, requiring that a tree or laminated arm, weighing sometimes over 11,000lbs, would need to be raised more than 30 feet into the air.\(^8^3\)

There are several ways to raise the throwing arm which are shown in historical sources, and these include shear legs, a header bar, or a ramp. I have determined the best candidate to be a set of shear legs. Shear legs in the plural are two poles lashed or mounted together at the apex

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\(^8^3\) Ed Levin, “Highland Fling,” 14.
and raised into the air, resembling an A-frame. A shear leg in the singular is one piece, often called a gin pole.\textsuperscript{84} Although both were used, shear legs are stronger and more stable than a single pole and need fewer guy lines, or stabilization ropes. The purpose of shears is to create a point in the air used to lift something up — in fact, it is one of the simplest and most stable ways to do so. When lifting, the shears transfer the load down each leg to the ground and function mainly under compression, staying vertical because of the guy lines which are tied off.

Shear legs would have been regularly utilized to hoist the throwing arm into position on trebuchets in the medieval period. As Bert Hall states, shear leg hoists “were engineering commonplaces,” used “throughout the middle ages as heavy duty lifters.”\textsuperscript{85} Although they were a main ingredient in many larger ancient cranes, shear legs were also used by themselves for smaller projects, and an entire crane is not needed to assemble a trebuchet. Shear legs are first described by the engineer Vitruvius in the late 1\textsuperscript{st} Century BC.\textsuperscript{86} They are also described by Hero of Alexandria in the next century.\textsuperscript{87} Shear hoists could feature between one and four legs, but the basic two-legged type is most useful for trebuchet building since it combines strength with mobility. The load can be moved forward and backward through leaning the guy lines, whereas a three or four-legged type cannot be adjusted to reposition the load.\textsuperscript{88} Shear legs were used to raise the hinged counterweight trebuchet at Loch Ness trials and for the assembly of the trebuchet at VMI.\textsuperscript{89}

\textsuperscript{84} Sobon and Schroder, *Timber Frame Construction*, 133-35.
\textsuperscript{85} Hall, *Hissite Wars*, 44.
\textsuperscript{88} However, it is best to lean as little as possible, since the force on the rear guy quickly surpasses the weight of the load itself on leans beyond 30 degrees. To achieve a farther travel for the load, the shears should be made taller. J.G. Landels, *Engineering in the Ancient World* (Berkeley, CA: University of California Press, 1978), 87-88.
\textsuperscript{89} Beffeyte, “A Serious Challenge.” An excellent picture of these shears can be seen there on the cover of *Timber Framing 50*. See also *Nova*, “Secrets of Lost Empires: Medieval Siege.” And Evan Hadingham, “Ready... Aim...
**Figure 11:** Three shear hoists from the *Hussite Wars* manuscript. From left to right, folios 2r, 25v, and 6r. Folio 2r is the most straightforward, shown lifting a cannon.

The *Anonymous of the Hussite Wars*, dated from the mid-fifteenth century, shows many great examples of independent shear leg hoists, with the most straightforward being folios 2r, 6r, and 25v. Each of these depicts a set of shears, with a block and tackle system suspended from the apex. The tag line of the tackle is directed into a windlass mounted on an inverted Y-bracket on one of the legs. Folio 2r features a block and tackle which is hooked onto one of the legs near the apex and could be easily unhooked and used for other applications. In other words, the tackle of this hoist is not integral. This is not the case with folio 25v, where the tackle system is worked into the hoist itself and would not function separately. The tackle in folio 6r is detachable but has been doubled-up for extra strength in the ropes. The shears in folio 6r also

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90 Hall, *Hussite Wars*, 43.
91 The block and tackle, or compound pulley system, is usually attributed to Archimedes, and extant pulleys have been found from ancient Greece. See J. W. Shaw, “A Double-Sheaved Pulley Block from Kenchreai,” *Hesperia* 36, no. 4 (1967): 389-401.
appear to have three legs and not two, but the hoist could have worked without the third leg.

The purpose of these hoists in the Hussite Wars manuscript is attributed by historian Bert Hall to raising cannons. The hoist in folio 2r is indeed raising a cannon, but the other two have no attached load. Certainly, these hoists served to raise cannons, usually to place them on carriages, but these hoists could have also served other tasks. Hall mentions that these shear leg hoists were designed to be broken down for transport with the supply train of an army.92 A set of shear legs could come in handy during a campaign, whether raising a trebuchet, fixing a cannon carriage, or building or dismantling structures and other siege engines. If these hoists could handle cannons, the weights of trebuchet arms would be generally similar if not lower.93 However, the task of assembling a large trebuchet would require shear legs that were significantly taller than those used for simply putting cannons onto carriages.

The shears for this project were assembled from pieces left over from the prototype trebuchet in 2017. Each side was designed to be long enough to let the legs completely straddle the trebuchet frame when spread open to 30 degrees.94 The pieces were joined at the apex with threaded rod, nuts, and washers. These nuts were only moderately tightened to allow the shears to be adjusted for use. The frame was asymmetrical at this joint, which is necessary to allow the shears to be spread open and closed, the former for use and the latter for setting aside and transportation. Many of the hoists in the Hussite Wars manuscript seem to be similarly constructed, and asymmetrical, to facilitate folding them up for transportation or storage. Historical shears could have been lashed together at the apex with rope, but metal fittings and

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92 Hall, *Hussite Wars*, 44.
93 The tree used for the reconstructed hinged machine at Loch Ness weighed around 11,000lbs, and Mons Meg, the famous bombard, extant, weighs over 15,000lbs. Presumably a similar type of cannon hoist was used to put Meg on a carriage. For the Loch Ness tree, see Levin, “Highland Fling,” 14. For the weight of Mons Meg, see Peter Purton, *A History of the Late Medieval Siege 1200-1500* (Woodbridge, UK: The Boydell Press, 2010), 276.
94 Each leg is about 26 feet long. Most of the length is composed of the old 4x6 20-foot rails for the 2017 machine, which are pocketed with sets of mortice holes. Additional 4x6s were bolted on to lengthen them.
iron were used to join the heavy-duty hoists shown in the Hussite Wars manuscript. Metal fittings are also mentioned by Vitruvius when he describes a shear leg style crane. Interestingly, however, Hero of Alexandria cautions against compromising the wood when lifting heavy loads and so recommends using just lashings on shear legs and not bolts.

The shears need to have no obstructions between the legs in order to cleanly straddle the frame of the trebuchet and allow for the raising of the arm. Shears for the purpose of raising a trebuchet could be as simple as two trees lashed at the apex. The feet of the shears in this case were also lashed together with a rope running between the frame just above ground level, preventing the legs from spreading open under load. No such connecting pieces are seen in the Hussite War hoists, indicating that this is usually not a concern when the legs have solid footing.

Raising and lowering the shears can be difficult and dangerous. The riskiest part of the process is when the legs are closest to the ground. The feet each need to be kept from sliding when the shears are at low angles, and this can be solved by driving in wooden stakes at angles at the base of them. The apex should be raised off the ground by hand as far as possible before the guy line, emanating from the apex, is pulled.

Raising the shears can be made much easier by utilizing a winch. Vitruvius describes how to raise a large shear crane by turning its own on-board winch. On our project, we utilized the trebuchet’s on-board windlass. Since the windlass is in the rear of the machine, the shears were laid out on the ground to the front of the machine. The main axle of the trebuchet was placed in the blocks, and then the front guy line for the shears was taken and passed over it,

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95 Hall, *Hussite Wars*, 44.
96 Vitruvius, *De Architectura*, 10.2.1.
98 You can see the process of using the shears in action here on my YouTube channel: https://www.youtube.com/watch?v=EktF5Gn9W8M
99 Vitruvius, *De Architectura*, 10.2.3-4.
Figure 12: The current preferred method for raising the shear legs. Two people are winding the front line, which is passed over the main axle, into the windlass of the trebuchet. One person is also walking up each leg. Note the block and tackle attached and extended.

and then redirected down into the windlass. Taking this line up and over the axle in the blocks made the initial angle for raising much more favorable, and this method made raising safe and easy. However, using the windlass as the fixed hold point for the front guy line results in a steep angle, since it goes straight from the windlass, at the back of the trebuchet, to the apex of the shears, towards the middle of the trebuchet, at beyond 45 degrees. It would be better practice to use another line, fixed farther out, for steadying the legs when actually raising the throwing arm, and to only use the windlass for raising and lowering the shears. On a larger machine, a similar mechanical system would be useful in raising shears. Perhaps the front guy line could be redirected with a pulley and wound into a capstan or winch. It is quite possible that the capstans

100 The ratchet gear on the windlass made raising the shears very safe. Unfortunately, the ratchet must be disengaged for unwinding, so more attention has to be given when lowering the shears.
drawn on Honnecourt's machine, as well as the windlasses featured on many other manuscript images, were not only used for reloading the machine, but also for assembly tasks.

Once the shears are raised and held fast, the throwing arm is placed inside the frame of the trebuchet. To avoid the windlass on the machine, the arm was moved in from the front. The arm on the Black Widow weighs enough to be freely carried by four or more people and was moved in place by hand. However, on a large machine this arm would need to be moved into position with rollers and levers. Leonardo da Vinci, in a drawing showing a four-legged shear hoist raising a cannon, also noted rollers to move things around on the ground.\textsuperscript{101} We were able to move the tree with two people using rollers. No doubt a crew with rollers and lever hooks could reposition a full throwing arm across relatively flat ground.

After the arm is placed inside the frame underneath the raised shears, the axles are inserted, and the block and tackle attached. Inserting the axles into the throwing arm while it was in the air would be difficult and dangerous, especially on a large machine. Seating the main axle in the arm before raising gives a place to lash rope for attaching the block and tackle. It is necessary to attach the block and tackle to the apex of the shears before raising them, because the apex cannot be reached by hand when in the air. The tackle must also be extended on the ground before raising to make sure the lower blocks can be reached by hand from the ground once the shears are standing. Therefore, on raising the shears, the lower tackle blocks also serve as a sort of plumb bob. On the shears for this project, the tackle was hung from a rope lashed between two eye-bolts near the apex.\textsuperscript{102} In the Hussite Wars manuscript, tackle is often shown similarly

\textsuperscript{101} These are seen in the foreground underneath what could be a carriage for a cannon. Marco Cianchi, \textit{Leonardo's Machines}, translated by Lisa Goldenberg Stoppato (Florence: Becocci Editore), 27. This drawing is called "The Foundry" and is cited by Cianchi as "Windsor B.R. n. 12647."

\textsuperscript{102} The diameter of these eye-bolts was underestimated and one of them opened dangerously when trying to disassemble the machine, since the axle seats itself solidly into the grooves during use and requires significant force to dislodge for disassembly. These have been replaced with larger ones 3/8" thick.
lash, or hung from metal hooks plated onto just one leg near the apex.103

Since the main axle is wide enough to span across the blocks, it therefore must be wider than the clearance between the bents, presenting a problem on raising. This means that the throwing arm must be positioned forward of the machine, so that the main axle is in front of the bents. Because of this, the arm is raised diagonally both upward and backward to the blocks. The arm was held from the tip and pushed forward as it went up so that the main axle would clear the lips on the axle blocks and any other obstructions on the frame. In this way, the arm was raised into position with the axle maintaining level and riding freely in front of the bents. Since the long side of the arm is heavier, it stays at ground level during the raising and the arm can be manipulated from the tip. Manipulating the arm in this manner was not found to be difficult at this scale since the tackle system is holding the weight. If necessary, this technique could be accomplished on a large machine with an additional rope allowing the arm to be pulled forward from the front instead of pushed forward from the back.

The actual process of lifting the arm with the block and tackle is straightforward. At this scale, it hardly required two people pulling on the tag end of the block and tackle used, which provided a 5:1 mechanical advantage. It is best to position these people near the foot of one of the shear legs and have them pull down from the top block in line with the leg. This directs the force of their heave down into that leg, whereas pulling from out in front works to pull the shears over and increases strain in the back guy line. On a large machine, working the block and tackle to lift the throwing arm may need to be done with the aid of a capstan. This could be achieved by lashing a pulley sheave to the base of one of the shear legs and using this to re-direct the line

103 See again Hall, *Hussite Wars*, folios 2r, 6r, and 25v.
from the block and tackle out away from the machine.\textsuperscript{104} The capstan, depending on the size of spokes and number of men working it, would then add enough advantage to allow a trebuchet arm, or cannon, of several tons to be raised.

\textbf{Figure 13:} The throwing arm is raised into position as the author, left, directs. Note the two people holding the tip of the arm, pushing it forward to allow it to clear the bents as it rides upward and backward. In recent raisings, the two main pullers have been placed closer to the far leg. Also note the ropes used to attach the blocks of the block and tackle - these are single strands - weak points that would need to be strengthened by additional wraps when raising a heavier load. The counterweight box was present because we had already assembled the machine and were only replacing the main axle. Also note the rope tied to the box axle hole, which is needed to attach the counterweight box as shown later in the paper.

\textit{Photo by John Zsiray, Herald Journal, used with permission.}

\textsuperscript{104} An example of a pulley used to redirect a line can be seen in Taccola’s drawing of a Bricola. Chevedden, “Invention,” plate 5. Also, in Giorgio Martini’s drawing of the same. Chevedden, “Artillery of King James,” plate 11. The traditional woodworker Mr. Chickadee has a demonstration of shear legs used with a capstan on his YouTube channel, and has separate videos on how to timber-frame a capstan and hand-make pulley sheaves. https://www.youtube.com/watch?v=NXrBFiGYsgk.
Once the arm is above the blocks, the entire assembly can be seated by lowering the main axle into the open-top axle grooves. On my machine, these grooves were semicircular, with the center of their radius positioned just half an inch down into the block. I found no need to enclose the top side of the axle grooves after the axle was seated, and the *Elegant Book* depicts axle blocks that are open in this manner. However, many manuscript images show the main axle being set directly into the two uprights, with the uprights extending higher than the main axle, therefore closing off the axle grooves. This obstructs this method of lowering the arm and axle into the blocks, and it is not clear how this was accomplished on these machines.

Another possible method for raising the arm involves the use of a header bar. This would be a piece of wood that spans the gap between the two main uprights and holds in the center an attachment point for the tackle system, serving the same purpose as the shear legs. Positioning a header bar would seem more difficult, perhaps requiring that two men carry it while climbing up each side of the trebuchet and place it in position by hand. Also, a header bar requires that the two uprights extend taller than the axle holes to support the bar. In most cases, this also means that the holes for the main axle are closed off. I am not certain how the axle would be seated in closed blocks, or how this would dictate the shape or composition of the axle. Regardless, extended uprights are shown on many manuscript illustrations, such as the Innsbruck *Bellifortis*, the *Hussite Wars*, and the de Milemete trebuchet. The Innsbruck depiction specifically features a square hole at the top of the upright, above the main axle, which could be a mortice, ready to receive the tenon of a header bar.

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105 Some volunteers were concerned that the main axle would jump up and out of this groove during a launch, but that does not happen. For the blocks in the *Elegant Book*, see Hindi, 54-55.
106 This could in fact suggest that axles were completely round, possibly even made of iron, and that they were hammered in sideways when the arm was lined up. I have not explored the details of how this could be done.
107 Innsbruck *Bellifortis*, via Chevedden, "Invention," plate 4. See figure 5 in this paper above. Hall, *Hussite Wars*, folio 32v-33r. Christ Church MS 92, Folio 67r-1.
The *Elegant Book of Trebuchets* depicts a variant of a header bar being used to raise the throwing arm. Instead of the bar spanning the raised frame of the trebuchet above the axle blocks, the bar raises itself above the axle blocks using its own vertical supports that sit on the topmost of four horizontal braces on both bents.\(^{108}\) This three-sided square frame is clearly separate from the final trebuchet since it is not seen in later illustrations in the book of the same machine.\(^{109}\) Positioning this device might seem yet more difficult than positioning a basic header bar, and it is uncertain how it was raised and attached onto the frame in the first place. The device shown has a clear purpose labeled by Zaradkash as the means for drawing up the arm. It would clearly work for its intended purpose, and it features, hanging from the center, a pulley for the lifting tackle. The open-topped axle blocks of the trebuchet depicted here would be ready to receive the machine axle and complete the lifting operation.

**Figure 14:** Raising the throwing arm with a header bar, as shown in the *Elegant Book*, Hindi, page 61. The hook in the center is labeled as a pulley. The three pieces on the right side are the windlass axle and the “hands” of the windlass, or the blocks that mount it to the trebuchet. It is unclear how the header bar is fixed to the frame, or how it was positioned.

The *Elegant Book* also depicts another method, entirely different, for raising the throwing arm. This involves moving the arm up a set of ramps to the axle blocks.\(^{110}\) This would require

\(^{108}\) *Elegant Book*, Hindi, 60-61. These braces are each called a jisr.

\(^{109}\) Ibid., 63-67.

\(^{110}\) *Elegant Book*, Hindi, 57-58. This ramp has been labeled by Zaradkash as the “channel,” which creates problems with interpreting the “channel” depicted on pages 60-61, drawn to the left of the machine. Both are labeled the same, but drawn differently, and the purpose of the second is unclear.
two sturdy timbers that were each both fixed to the axle blocks and firmly seated in the ground. Lifting the ends of these boards to position them against the axle blocks would not be straightforward. While not specifically shown, it can be assumed that the main axle has been inserted here, and that the rounded ends of the axle are what is actually riding up the ramps. In this case, friction of this operation would induce wear on the axle; perhaps a lubricant was used. This setup would also require rope tackle, looping around a point up near the blocks themselves, to pull the throwing arm up the ramp. It is unclear how this would be arranged since no tackle is depicted by Zaradkash. Although this method could serve the purpose, it seems that it would be more difficult to set up, especially on a large machine, and that these two timbers used for the ramp would be better off repurposed for a set of shear legs. Although the direct evidence here cannot be argued with, this method has not been attempted at scale and seems less advisable; perhaps it was only used with smaller machines, of a similar size to my own.

**Figure 15:** Raising the throwing arm into position by means of a ramp, as shown in the *Elegant Book*, Hindi, page 58. It is unclear how the two pieces of the ramp have been lifted and fixed into place, and the rope tackle for pulling the arm up the ramp is not shown. The appearance of the wheel could imply that a rope for pulling the arm was directed into the windlass, which is pictured at the front of the machine in figure 6 above. Note that the counterweight box is not attached to the arm at this stage but is set off to the side.
Attaching the Counterweight Box

It is unlikely that the throwing arm on a full-scale historical machine was ever raised into position with the counterweight box already attached. This would increase the demand of the lift by adding the weight of the box and would require an increased haul force by the crew as well as heavier equipment. It is better practice to instead break this operation into multiple steps that each require less weight to be lifted at one time. Furthermore, assembling a box onto the throwing arm would in many cases require that the arm be lifted at least partially off the ground anyway, and in this case, it might as well be fully hoisted into the blocks beforehand.

The technique of raising the throwing arm and attaching the counterweight box afterward is substantiated by the *Elegant Book*. The book illustrates the previously-mentioned technique of raising the throwing arm with a ramp (figure 15), and in both versions of the manuscript, the two halves of the counterweight box are depicted on this page but are placed off to the side. The box does not seem to have any involvement in the arm raising process, and the artist is probably implying that attaching the counterweight box is the next step in the process. And in showing the use of a header bar (figure 14), the box is not depicted; the arm is being raised by itself.

In addition to the arm-raising drawings, the *Elegant Book* also shows two depictions of the next step itself: attaching the box to the already-raised arm. In these drawings, the trebuchet frame is fully assembled, and the arm has been set in the blocks. The counterweight box, inscribed in a square by Zaradkash, is positioned as if ready to be attached to the arm. Attached to the tip of the throwing arm are two ropes, or Watara, and the arm has been brought to level with the horizon.

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112 Ibid., 60-61.
113 Ibid., 63-64.
114 The square this box is inscribed in clearly demonstrates the significance of geometrical design in the middle ages.
Figure 16: Attaching the counterweight box, as shown in the *Elegant Book*, Hindi, page 64. Note the square the box is inscribed in, and the two guy ropes attached to the tip of the throwing arm. It is unclear how the short side of the arm is being brought down - it could be that the weight on the end of the arm has in fact brought the center of gravity onto the shorter side.

To attach the box to the throwing arm, the short end of the arm must be brought down near its lowest point. Since the center of gravity of the throwing arm normally resides on the long side, this side rests on the ground, and as such the short end of the arm is hanging at its highest point; it would be unreasonably difficult to attach the box like this. Instead, the short end should be brought down, thus pointing the long end of the arm skyward. It appears that Zaradkash is in the middle of this process here, although, in light of the weight on the base of his throwing arm, it is unclear where the center of gravity rests in this case.

Hauling down the short arm can be accomplished in several ways. Regardless, it requires tying rope to the box axle before the throwing arm is raised.\textsuperscript{115} It also requires attaching two guy ropes.

\textsuperscript{115} To haul down the short end, ropes need to be attached to the short end. The choice for lashing here is the axle for the counterweight box. These need to be tied before the arm is raised, since reaching the box axle after raising would require climbing dangerously out onto the throwing arm.
lines to the tip of the arm. These guy lines are the same cords used for the shear legs on my machine, since the shears are not needed for attaching the counterweight box at this scale and are lowered and set aside before this step to get them out of the way.

The first method reminds a trebuchet builder of a traction machine. On the Black Widow, the short end was pulled down by heaving on ropes. In 2017, when the throwing arm was green, four people were required, since this operation is conducted at a leverage disadvantage. In 2018, after the arm had dried out, this could be done with two people.

Pulling down the short arm of a full-scale machine, however, would require mechanical assistance. Heaving from ropes on the short end would require a significant number of men, especially on a large trebuchet with a green throwing arm. In the later assemblies during 2018, I took to using the trebuchet’s on-board windlass to accomplish this step. This required one rope tied to the box axle before the arm was raised. It also required pushing up the tip of the arm by hand to get the operation started. This is because the angle on the rope, when directed into the windlass at the rear of the machine, was almost parallel with the arm itself when the tip was resting on the ground, also at the rear of the machine. We pushed the tip of the arm using a pike to the point where the arm was almost horizontal, and then the rest of the operation was handled by the windlass. Alternatively, the line could have been re-directed through a pulley positioned at the base of the machine towards the front. On a large machine, this operation could also be handled with a block and tackle and directed into any kind of medieval winch. A block and tackle was used for this step on the Loch Ness machine.

Once the short end is down, the arm is easily held vertical by the front and back guy lines.

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116 For example, if the top one-foot of the tree weighed 10 lbs., it would require almost 40 lbs. of force from the short end to move it, since it is hanging out almost four times farther from the fulcrum.
hitched to the tip. These are the two Watara depicted by Zaradkash. If the shear legs were tied off to stakes in the ground, the guy lines for the throwing arm can also be tied to the same stakes. Once the arm is held vertical by these lines, any ropes tied to the box axle can be removed so that the box can be attached.

Figure 17: Attaching the counterweight box on the Black Widow. The tip of the arm is started up by hand, then a rope from the short arm is wound into the windlass. As it comes up, control is transferred to the front guy line, which can be handled by one person at this scale. The line is fixed off and the box is rolled in from the front and the windlass rope removed. The box is chocked up to height and the axle is hammered in. Only once the box is attached are the side planks bolted on and the sandbags put in. Note that the windlass rope is slack in the third frame.

Once the arm is held vertical, the counterweight box is constructed onto the machine. On the Black Widow, the counterweight box was initially completely assembled in the shop with all the side boards and planks. The box axle hole was designed to be completely round in both the box arms and the throwing arm, and the plan was to move the box into position and then hammer in the box axle, also completely round, to hang the box on the machine. But it was quickly discovered that the full box was too heavy to move, and the planks on all sides had to be taken off to lighten it. The box, approximately seven feet long, ten feet tall, and two feet wide, could be moved by hand with four people once the extra weight of the side boards was shed, reducing it to its skeleton frame and the bottom planks. It was then walked into the frame of the trebuchet from the front and propped up to the correct height with scrap wood. Once the holes were
aligned by manipulating the positions of the box and the throwing arm, the axle was hammered in and the trebuchet assembly was completed by re-attaching the side boards and filling the box with sandbags.\footnote{To complete this operation, the box axle hole in the throwing arm had to be brought forward of the main upright, by leaning the tip of the arm slightly backward, to facilitate hammering in the axle.}

The method I used here to attach the box must be further broken down into steps on a larger machine. The skeleton of the box would simply be too bulky and heavy to move if it was completely constructed beforehand. Therefore, the box needs to be directly constructed onto the throwing arm from its side pieces, further complicating assembly. As seen in the *Elegant Book*, the box axle would also be square in the middle and rounded on the ends (see figure 19), as opposed to completely round.\footnote{See *Elegant Book*, Hindi, 69-70. The throwing arm is shown with square axle holes through it. It is generally accepted that the axle holes in a throwing arm on a historical machine would be square, since it is easier to chisel a large square hole accurately than a round one. The square midsection of the axle also helps to give stability and keep the axle in place. See Neel, “Design Considerations,” 13, and Hansen, “Experimental Reconstruction,” 197.}

What this means is that the box and throwing arm cannot be simply aligned and then the axle hammered in, because the larger square mid-section of the axle would not clear the round holes in the box arms. Thus, the axle would need to be placed in the throwing arm first, before its raising, and then the two side skeletons of the counterweight box would be mounted on the axle.\footnote{It seems that this would require enough clearance between the uprights of the trebuchet to allow the box sides to be slipped onto the axle. Thus, the clearance between the bents would equal the width of the whole box skeleton plus and additional width for the two side skeletons of the box. This could be a good practice, since it would serve as a rule of thumb to give the completed box enough clearance to swing freely in the frame. But alternatively, the box may have been placed on the axle while the arm was hanging out in front of the machine, clear of the bents. However, this would require lifting the pieces up higher to meet the axle.} These sides, once hanging on the box axle, would be connected together to give the box width, completing the skeleton, and then planking boards could be attached on the floor and sides. This method would only require moving by hand the skeletons of the left and right half of the box separately, thus handling as little weight as possible at one time. Perhaps these side skeletons for the box could be maneuvered into position with a
few people, rollers, and ramps, especially since the box usually hangs close to the ground.\textsuperscript{121} For constructing the hinged machine at Loch Ness, however, a modern powered lifting machine was used.\textsuperscript{122} It could be medieval engineers still needed lifting equipment at this stage for mounting the box onto a large machine.

**Figure 18:** Moving one side of the box with a power lift on the NOVA project. From Beffeyte, "Serious Challenge," page 13. The five main pieces here are what I refer to as a side skeleton of the box. This seems to be the smallest convenient unit of the box. In a medieval assembly, this would be moved into position without the planks. It could be that rollers or hoisting tackle was needed to position these.

The *Elegant Book* supports this method of assembling the box from its two side pieces. The Book details several pictures which seem to be layouts of parts required for the trebuchet, and the counterweight box is most often shown in two halves, representing the two side frames of the box.\textsuperscript{123} Although only one piece is shown during the attachment stage, this one piece lacks any definition of depth and perhaps does not represent the box as a whole.\textsuperscript{124} The frame of the trebuchet is drawn in perspective with the two different bents, but this piece of the box does not have similar perspective. This could be suggesting the attachment of just one side of the box at a time; alternatively, perhaps the drawing was not finished, or the perspective is inconsistent.

\textsuperscript{121} On machines with treadwheels mounted to the main uprights, the box hangs higher to clear the treadwheel axle. Here, mounting the box would be more difficult and require scaffolding and lifting equipment.

\textsuperscript{122} Beffeyte, "A Serious Challenge," 13. An orange power lift can be seen holding a side of the box. This section has the side planks already attached, but the skeleton frame of the box is clearly visible. I am not sure how much those five pieces of the skeleton weigh, or how reasonable it would be to mount that section onto the arm with manpower alone. Mounting that completed skeleton onto the axle would seem preferable to trying to connect angled mortice and tenon joints onto the main strut while it's hanging from the axle.

\textsuperscript{123} See *Elegant Book*, Hindi, 57-58, 69-70, 72-73.

\textsuperscript{124} Ibid., 63-64.
Figure 19: Pieces of a trebuchet, from the *Elegant Book*, Hindi, page 70. Note the two square holes for the axles in the throwing arm. Also, the two halves of the counterweight box, and the two wheels for turning the windlass. Although the sides of the counterweight box look different than the style on the Black Widow, the concept of assembling the box directly onto the throwing arm from its two sides is the same.

Once the box is mounted and finished, the trebuchet assembly is almost complete. The arm can now be drawn down with one of the guy lines, and these two lines can be replaced with a more substantial main rope to be used in reloading the machine. At this stage, all the remaining hardware and parts can be attached, like the sling release pin, the trigger latch, and the projectile sling. Then the box can be lowered back down and loaded with weight, and the machine is ready to commence a bombardment.
Disassembly

Large trebuchets in history were not only assembled, but they were also disassembled for transport and reused at later sieges. Michael Fulton discusses how this became a practice during later use, especially in the Middle East. I found that disassembly of the machine is generally straightforward, and that all the previously mentioned operations can be done in the reverse order. However, the main axle becomes heavily seated into the axle grooves with use and requires significant force to dislodge. Also, the machine’s parts must be stored properly to prevent warping, which can ruin pieces and prevent reassembly and reuse.

The largest hinderance to disassembly was found to be driving out the pegs in the joinery. We resorted to using ½” threaded rod to hammer out the ½” pegs, and then withdrawing the threaded rod by spinning it out using tightened nuts and a power drill. Regardless, some of the pegs had to be drilled out, chewing them to bits in the process, and many others split open or were otherwise rendered unusable. Perhaps medieval engineers had special tools for driving out pegs to disassemble joinery. However, many pegged joints are usually intended to be permanent, and the system of drawboring pegs does not take well to reuse and wear. The best solution when disassembly is required is to use a system of through-tenons and wedges. Here, instead of pegging the tenon into the mortice piece, the tenon comes out the back end of the mortice piece and a wedge is driven in the tenon, holding it against the outside of the mortice piece. To tighten this joint, the wedge can be driven in a bit farther, and to take this joint apart

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125 Fulton, “Pre-Fabricated Artillery.”
126 This is somewhat addressed by wiggling the tip of the arm up and down, attempting to loosen it while the crew pulls on the tackle that raises the arm out of the blocks. Regardless, this initial lift out of the axle blocks on disassembly requires more force than usual, and the equipment needs to be up to the task.
127 Generally, proper storage would provide a covering from sunlight and barriers from moisture and humidity. Simply placing a tarp over the machine’s parts while outside was not found to do enough to prevent much of the machine from being unusable after the winter of 2017.
128 Drawboring is the process of purposely drilling the peg holes misaligned so that the pieces are driven farther together when the peg is hammered in.
the wedge can simply be knocked loose and taken out (see figure 9, through mortice and extended tenon). This was the method chosen for the reconstructed trebuchets built in Denmark and Virginia, and it is also hinted at in the Innsbruck Bellifortis (see figure 5). The struts of the counterweight box on the Innsbruck trebuchet are joined with a piece that extends through all three of the struts and appears to be wedged on the outside.129 However, the connections on the Gottingen trebuchet and the machine drawn by Honneecourt seem to show pegs and not wedges. Perhaps properly-tapered handmade pegs are easier to hammer back out than dowels.130

The processes of assembly and disassembly take a considerable amount of time. A complete assembly of my half scale machine from the first arrival on site to the first projectile thrown takes about four hours, and a disassembly around three hours. Certainly, assembling a larger scale machine would take more time, especially since large pieces like the throwing arm need to be more carefully rolled and maneuvered into position, and the bents would be raised with lifting equipment, and the assembly of the counterweight box must be broken down into smaller steps. It seems that the majority of an entire day would be needed to assemble a full-scale counterweight machine after it arrives on site, even with an experienced crew. Loading the counterweight, addressing problems, and getting the machine throwing stones accurately might have to wait until the next day, and with poor conditions this could take longer. Once deployed, these machines cannot be repositioned without complete disassembly. They would also need to be defended from attack during construction and use, which would be a topic for another study. It is understandable that many commanders chose to simply burn and destroy these engines rather than disassemble and transport them at the conclusion of a siege.

130 See Sobon and Schroeder, Timber Frame Construction, 129-130.
Conclusion

Trebuchets are complex and powerful weapons, and the construction of a large machine is a testament to the complexity of medieval technology. This process requires a considerable amount of equipment and lumber and the hiring of experienced craftsmen. The end result is a significant feat of military engineering, standing more than 60 feet tall and dropping a counterweight of perhaps 30 tons. My half-scale machine was able to throw a 16lb bowling ball 300 yards, and a full-scale machine could easily throw projectiles heavier than a person this same distance. That Warwolf took more than 50 people 3 months to build is certainly reasonable, although much of this time was probably absorbed in the initial stages of sourcing materials and laying out geometric plans and designs. A trebuchet spends much of its early life as individual pieces of green lumber, which are each fabricated specifically for their place in the machine. Then, when everything is ready to come together, an amazing process of assembly could raise the machine together in less than a day. Lifting the throwing arm into the blocks is elegantly accomplished with a set of shear legs like those used to hoist cannons or build ancient temples. And after the arm is mounted, it must be stayed vertical and the counterweight box constructed onto the arm from its parts. The entire process makes use of dozens of mechanical aids such as rollers, levers, pulleys, ropes, and windlasses. Simply raising the shear legs themselves is a difficult and potentially dangerous task that must be done with care and technique. Attempting these tasks through experimentation makes it easy to see the sophistication of technology in the Middle Ages. Medieval engineers may have been working simple machines, but they knew how to combine these to accomplish complex tasks such as building the medieval trebuchet.
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This capstone has been the most difficult and rewarding project of my undergraduate career. It has forced me to grow, and during the process I have overcome challenges, achieved triumphs, and deepened my research and critical thinking skills. The project has broadened my exposure across disciplines and taught me about engaging in the community and upholding the motto of the Honors Program.

Building a large siege engine is full of challenges, but overcoming these has been a source of confidence. First has been acquiring funding, which required formal requests or interactions with several departments and securing an URCO grant. Second among these was timeframe. The construction of the machine needed to be completed by a deadline, whether the Pumpkin Toss or CHaSS Week. Sometimes there was not enough time to make all the details perfect, and I learned to prioritize the important pieces and schedule work diligently. A third challenge was the logistics of fabrication and transportation. For example, I recently decided, in repairing the machine for display on the Quad, to construct pieces on the field instead of in the shop to save transport. This required more careful work with hand tools. A fourth challenge has been paperwork, and through this I learned to work with Facilities and Risk Management and to plan ahead on time for procedures. A fifth challenge has been the recruitment of manpower, and I have practiced reaching out to new students and coordinating volunteers.

The most significant obstacle to the project has been the machine itself. Building at large scale, flaws in the design and fabrication show themselves mercilessly and require large scale fixes and additional time and funding. Chief among these flaws has been the mis-alignment of the counterweight box, which resulted in it smashing through a strut and destroying the machine.
over the winter of 2018. Although it might have been wise to work with a smaller model before beginning large scale work, much of this is part of the engineering process. Regardless, it makes the project a constant struggle to fix and improve the machine – the third complete design iteration, to be built summer 2019, has a chance at being the first to truly perform properly.

Overcoming these challenges has led to incredible triumphs and rewards. The Black Widow, as I am aware, is second to only one other machine for the title of “largest historical trebuchet reconstruction” in the Americas. It has thrown a 16lb projectile 300 yards using 1,500lbs of counterweight, which is equivalent to 2/3 the mass of my car. The historical windlass installed in 2018 allowed just two people to lift this weight safely. Mastering the techniques of constructing the machine a dozen times, I have dramatically reduced time required. It took 3 days to assemble it for the first time in 2017, but now the entire trebuchet can be built, utilizing more historical techniques, in less than 4 hours. I have accomplished what I set out to do in 2017: learn how to construct a large medieval trebuchet.

Through my experiences in the project I have gained wisdom which may be of use to future students. Start the process early, taking Honors 3900 at the start of Junior year. The capstone process cannot be done in one semester – a year or two is appropriate. In fact, it has taken me an entire semester to write the paper, after all the research and experimentation was completed. Find something you are interested in, a question that drives you. You must be motivated to solve this question of your own volition. Do not limit yourself by your major – if your interests lie elsewhere, pursue them anyway. Set timeframes for your project from the beginning. Plan for all major steps at least 3-6 months in advance and think through as many details as you can as early as possible. The sooner you confront all the details the sooner you realize that something important might be missing, and the more time you will have to remedy
that. If you ignore the small things, no one else will do them, and the project could stall in big
places. Do not be afraid to ask for help, or money, when you need it; consider URCO grants for
the latter. You do not need to become an expert on the entire topic – set a defined scope for the
project and stay focused on a reasonable amount of material. Take notes as you read or perform
research the first time, or else you will inevitably have to redo things a second time. Set a
weekly meeting with your mentor. Sitting in front of someone and explaining why you did not
get anything done pressures you to stay on track and make progress.

This capstone project has been the defining experience of my undergraduate education.
Never before in school have I tackled something in so much depth and stuck with a project so
far. Being able to explore this interest to these levels has allowed me to discover what I want to
do. I want to continue learning about ancient and medieval technology and reconstructing
machines. The paper written here is largest piece I have ever written and has forced me to tackle
writing at new levels. The complete experience sets me apart from my peers and will give me an
advantage in applying to graduate schools or careers. The project has allowed me to practice
team leadership and management skills. I have learned a few things, but I still have much to
learn regarding coordinating a team.

This capstone has deepened my research experience and created a positive mentor
relationship. It has allowed me to learn about things at an academic level that I would have
never gotten a chance to hear about in a classroom. I have practiced how to use the extent of
library resources to conduct historical research and studied a life-sized facsimile of a medieval
technical treatise. I have looked at manuscripts in foreign languages and dipped my feet into
working with language specialists to translate them. My relationship with Dr. Susan Cogan has
developed over the last three years and led me to places I could have never anticipated. Through
her guidance I have presented my research at the state and national levels and I will continue to value her guidance going forward.

The project has required exercising critical thinking and analytical skills. The core question: "how did medieval engineers build large trebuchets?" Has in of itself required tackling big problems, like lifting a tree 15 feet into the air. Building a concrete object forced me to tackle all the details. I put several sources together to solve these problems. It is telling that the best solutions I found to several of these problems were the ones I directly answered with historical sources. However, the project has also brought me to question sources in new ways. I discuss the questionable validity of illustrations above in the paper, and I have yet to reach a firm stance. Working from these pictures has resulted in devices that work well but has also revealed critical flaws in historical depictions.

The capstone project has contained work across disciplines and involvement in the community. I have teamed with engineering students to solve challenges, despite being a history major. In fact, I could not have completed the project without the suggestions of volunteers, and much of the process follows principles of engineering. I have also seen aspects of journalism from project members and the time-lapse filming of our first assembly in 2018 by a student in the Multimedia Minor. I have demonstrated the machine at two events I organized, hosted by the History Department, and taken the machine to the Pumpkin Toss, as well as displayed the machine on the USU Quad. These events have worked to inform the public about the sophistication of medieval technology and the complexity of ancient engineering. This has especially been the case with the history-department demonstration events where I discussed and operated the machine, both of which received articles in the Herald Journal. To this end, I also hosted a panel discussion at the Logan Library, featuring panelists Dr. Alexa Sand, Dr. Robert
Mueller, and Dr. Danielle Ross, and organized with the help of Dr. Rebecca Andersen. This was titled *Misconceptions of the Middle Ages*, and we discussed topics ranging from technology to religion, culture, and daily life. The project has found a unique niche in the community and captured the interest of the campus, as evidenced by the inter-departmental war between JCOM and History which resulted from standing the machine on the Quad, facing the JCOM studio. I have also taken a small scale trebuchet to STEM fairs and events at Lincoln Elementary, River Heights Elementary, and the CCID School, demonstrating the principles of trebuchet mechanics to elementary and middle school students in Cache Valley.

This project falls in step with the “Dare to Know” motto of the Honors Program. I have broken a dozen boundaries for what undergraduates are capable of doing at a university. I found something I wanted to learn and got stuck in and addressed it hands-on. Admittedly I bit off a lot more than I could chew at first, but my perseverance and continuation of the project, rebuilding the trebuchet in 2018, produced great results and solved many problems. Dare to know! Or rather, dare to dream big, fail, and try again.
Appendix: Video Documentation

Documenting my trebuchet adventures and experiments, I have posted several videos to YouTube. These videos document much of what has been discussed in this article and complement this paper. I will continue posting videos of the project as it continues, and as such I would encourage anyone that has read this far to visit my channel here,

https://www.youtube.com/channel/UCXIB2SLLkMPzr6BjajJe_DA

or to see these videos in particular:

Time-lapse of the first trebuchet assembly during the 2018 season:

https://www.youtube.com/watch?v=78fLMejgZqk

Launch videos from the best day of the year 2018:

https://www.youtube.com/watch?v=boE2dp3u1ss

Assembly highlights on the USU Quad 2019:

https://www.youtube.com/watch?v=StEl7pkttSg

All about shear legs and tackle blocks:

https://www.youtube.com/watch?v=EktF5Gn9W8M

Windlass, ratchet, and pawl:

https://www.youtube.com/watch?v=lV0VwhtGTjo
Author Bio

Daniel Bertrand is an undergraduate History major and member of the Honors Program at Utah State University. Originally an engineering student, he switched to history to learn more about the technology of the past instead of the present. Daniel is especially interested in the military history and technologies of the ancient and medieval worlds. To that end, he has researched and completed reconstructions of medieval trebuchets – large artillery machines used in medieval sieges. His work has been supported by grants from the Department of History, Honors Program, Office of Research, and the Student Association at Utah State University. In his spare time, he makes wooden longbows and arrows and practices archery and slinging. After graduation, he aims to fix up the Black Widow and take it to national Pumpkin Chunkin’. Daniel is considering pursuing graduate studies in military history or the history of technology, and perhaps joining onto a medieval reconstruction project in Europe. One day, he wants to build a full-scale trebuchet with historical methods.