Introduction and overview: The comprehensive goal of the "Digital Amati" project is to provide a usable, historically justifiable suite of software tools, and to experiment with them, in order to advance the understanding of the geometric structure inherent in the design and construction of classical string instruments. We want these tools, and creative work done with them, to be publicly accessible, and to be of use to historians, curators, restorers, and makers of these instruments. The proposed work integrates the further development of this software, its use in design, in analysis and acoustics, in manufacture, in education, and as a framework for continued research into the history and evolution of instrument forms. In the start-up phase of this project, and in ancillary efforts complementing this phase, we have already made progress in all of these directions.

Modern *luthiers*—the makers of classical string instruments—are necessarily and effectively applied art historians. Their success depends on the knowledge of artistic forms having roots in classical geometry, a synthesis of science and art with parallels in architecture, furniture making, and painting. Their *historical* task is not only to *understand*, but also to *create* in accord with that historical idiom, and to *extend* the tradition with appropriate and new ideas. Imagine, by analogy, studying Vermeer as an art historian would—but also in order to paint in confluence with his idiom, and to extend it artfully and with originality. This understanding and extension—of both learning, and of making—is part of the natural evolution of art, science, and humanities.

Even so, the art of lutherie has not profoundly changed since the seventeenth century. A modern-day *luthier* making pilgrimage to the Museo Stradivariano in Cremona, upon seeing the tools and templates from Antonio Stradivari's workshop, would immediately be struck by their familiarity. Concurrent and synonymous with this arrested development, significant knowledge has been lost over time. Social upheaval and epidemic contributed to degrade lutherie's institutional memory. New technologies made old understandings obsolete and then forgotten—an inevitable social process that surely transcends instrument making—even as vestiges of this past knowledge lingered in practice. Newly dominant notions of measurement and numeration pushed aside the geometric, proportional design methodology that formed the *lingua franca* not only in lutherie, but also in furniture making and architecture.[1]

This transition in lutherie could be described as one from the analytically classical to the romantic, the latter a *liuteria da capo* recapitulation of the work of Cremonese, Brescian, and Venetian masters, a sort of communication without understanding. At the same time, our notions of precision and accuracy have changed from the geometrically Euclidean to the numerically Cartesian—namely, that a circle isn't a geometric object, but rather a generic, algebraic equation, and that precision is achieved with graph paper, measured rulers, Vernier calipers, and protractors, not with straightedge, compass and dividers. The original rules of lutherie became obscured.

This absence of artistic comprehension is why Kevin Coates wrote in his groundbreaking book, **Geometry, Proportion, and the Art of Lutherie** (Oxford, 1985), *"No matter how illustrious the talents of its present-day practitioners, the art of lutherie will never again achieve the same grace of enlightenment, of genuine creativity, unless it can return to its true center, an understanding of the lost principles that nourished the genius we now mindlessly, or rather, soullessly, seek to replicate."* How can this "true center" be rediscovered and communicated, to both historians and to makers, with a greater understanding and facility of use?

It is self-evident that the violin in its most admired form, as exemplified by iconic instruments of Amati, Stradivari and Guarneri, presents a sophisticated and seemingly hermetic system of design and construction. With the original, underlying design principles obscured, the traditional approach of violin makers in recent centuries has been careful empirical documentation, with the goal of accurate copying. While this method has often been an effective strategy to create quality instruments, it has limited our ability to enable optimization, customization, or innovation.

[1] See George Walker and Jim Tolpin, **By Hand and Eye** (Lost Art Press, 2013); Lionel March, **Architectonics of Humanism: Essays on Number in Architecture** (Academy Editions, 1998); Rudolf Wittkower, **Architectural Principles in the Age of Humanism** (Norton, 1962).

Recent years have seen advances in understanding the history and techniques of lutherie[2], a suite of research efforts that resonate with unquestioned academic precision and standards of scholarship, even as they have taken place largely removed from the academy.

Coates's book was very significant in evoking where attention needed to be focused. In the context of design, the impact of François Denis's **Traité de Lutherie: The Violin and the Art of Measurement** (ALADFI, 2006) has been profound: a catalogue for the 2013 exhibit of Stradivari instruments at the Ashmolean Museum in Oxford included the following unmistakable homage to Denis's pioneering work: *"It is now recognized that what first distinguished Cremonese instruments from those made in other centres was a geometrical formality of design and proportion borrowed straight from the architects, painters and many other designers and craftsmen of the Renaissance."*[3]

These advances are important both in the worlds of scholarly understanding, and in artistic making. The increased quality and competitiveness of violin making in recent decades have demanded a more comprehensive and accurate approach. We have witnessed a dramatic increase in the quantity and accessibility of accurate documentation, with the widespread availability of quality publications, high-resolution digital photography, and more open sharing of this information and its analysis. Moreover, CT (computer axial tomography) brings to the modern luthier a comprehensive documentation of outlines, arches, internal contours, even density of materials, from canonical, iconic instruments made during the golden age of lutherie. CT data is the raw material for geometric reconstructions of form.

With this increased detailed knowledge of instruments, the clear challenge is to understand those first principles of design which gave rise to these classic instruments as examples of an aesthetic unity. An approach to this challenge, addressed in this proposal, is to take this recovered knowledge of design in lutherie, and to represent it in programming language software.

Digital technology and software methods provide lucid, coherent tools for facilitating and enhancing the understanding inherent in that tradition. They render that knowledge accessible, repeatable, and flexible, allowing rapid experimentation and communication. Algorithms encode methods, including those that are ubiquitious in lutherie. Programming languages don't exist simply to tell machines what to do. Well recognized as the engineering vernacular of software, they are more importantly the collective mother tongue of algorithmic ideas. *Computational thinking*[4] is an accepted way of understanding complex, constructional processes; programming languages—a form of writing—provide a medium for us to express *to each other* what we know how to do.[5] In this case, that knowledge is a description of the geometric constructions in the mind's eye of the luthier, which guided his skilled hand.

Geometric drawing has demonstrated value for drafting pleasing outlines for instruments, and questions of geometry in a musical instrument are quite naturally related to analogous issues of acoustics. While the cumulative details of outline, contour and construction give rise to the response and tone of an instrument, the underlying functions of vibration and movement have previously been invisible to our perceptions, just as critical aspects of tone and response until recently could only be evaluated subjectively. Advances in computer spectral analysis are giving us an equivalent ability to document and map the timbre of sound, compare and contrast various instruments, and track changes made to an instrument in the optimization process. Similarly, the actual vibration patterns of the instrument's surface which create these tonal variations can now be mapped with readily available modal analysis equipment and computer software.

[2] Apart from cited books by Coates and Denis, see the canonical book by Simone Sacconi, **The 'Secrets' of Stradivari** (Eric Blot, 1979).

[3] **Stradivari** (Ashmolean Museum, 2013).

[4] Jeannette Wing, *Computational thinking*, **Communications of the Association for Computing Machinery** 49:3 (March 2006), pp. 33–35.

[5] One of us [HM] was shown a drawing of a viola by a luthier. When asked "How did you do that?" the luthier responded, "Here, I have a couple of pages of notes." But when you have *code* to describe the drawing, the code *is* the notes, and by running the code, you have the drawing. The *challenge* is to develop a programming idiom that is as transparent and self-explanatory as possible. It's a writing style, like others (school essays, love letters, user's manuals) with their own form, which needs to be mastered to ensure good communication. And *coincidentally*, a machine can execute it.

Thus the combined approaches of enhanced empirical documentation, first-principle design concepts, and acoustic sound and vibration analysis help us understand the geometry of violin design, the anatomy of tone, and the physiology of the violin's movements and vibration. It is from the combined efforts of violin maker and musician, in applying these insights and tools, that we may create more personalized and effective new instruments. Here, as in other aspects of cultural evolution, technology is a crucial enabler of advances in the arts and humanities. Moreover in this case, technology does not serve as a means of mass production, but rather of individualization.

In synchrony with these efforts, and to facilitate them, our intention is to provide software tools that embody a new means for representing, synthesizing, and effectively communicating old knowledge, with the concurrent goal that they facilitate new ideas. Andrea Amati, regarded as the father of the violin, lived roughly a half-century before Galileo, and a century before Newton, during an era already endowed with a genuinely expressive and powerful scientific and mathematical language. What would Amati's ideas have looked like if he had had a programming language in which to express them? That representation would be an interesting intellectual history—what Amati's thought would look like in a modern idiom. The result would be neither historical nor science fiction: history gets written and rewritten, among other reasons, because we try to characterize what the past means to us. Moreover, software is an executable form of that expressed thought. It can be a prosthetic tool for the luthier.

History of the project and start-up phase results:[6] The beginning of the project saw the initial formulation of what we call the *geometry engine.* It is, in effect, a programmable straightedge and compass machine, where the user writes code describing geometric constructions. The programming "front end" of the user's *source code* is totally Euclidean, in the vernacular of the original knowledge, while the computational "back end" of the *target code* is entirely Cartesian, in the numeric, rectilinear language of computation. Like any good programming system, the goal is to let the user express what is viewed important (geometry), where the implementation hides unnecessary detail (numbers and ancillary calculations).

There are any number of lovely books that describe such Euclidean constructions in a colloquial language, which can then be programmed directly.[7] A central, core thesis of the Coates and Denis monographs (among others) is that string instruments were designed and drawn *proportionally*: keyed from one initial, physical distance, the geometric construction followed entirely from straightedge and compass constructions of points, lines, circles, arcs, and intersections between them.

What we initially did is formalize this idiom into a programming language, so that *describing* the construction is tantamount to *carrying it out.* The translation from a colloquial *mode d'emploi* to our more formal, geometric code is remarkably seamless. When you code precisely how to do something, you can then run the code—and unlike the 'wysiwyg' ("what you see is what you get") of so many software products, you can see *what you did to get what you got.* You can modify it easily and examine variants. You can share it with colleagues and work collaboratively. Most importantly, the software embodiment of knowledge transforms the "how to" of descriptions into executable algorithms.

The practical core of François Denis's **Traité de Lutherie** is a similar description of seven different string instrument models by famous makers; the language can then be used to embody the constructional knowledge expressed in these descriptions. It was an epiphany to recognize that a significant component of this book was, in essence, an informally written computer program. Moreover, the programming language can elide—with complete precision—common patterns of design, abstracting over them with appropriate parameterization.[8] As a consequence, the description of how to draw these instruments can be given with a kind of hierarchy that emphasizes salient aspects of the design. (Think of the programming language

[6]This proposal describes a collaborative, but "we" describes here work done by the principal investigator (Mairson) during the start-up phase supported by NEH ODH. A web site containing most all results and deliverables produced during the start-up phase is `www.cs.brandeis.edu/~mairson/TDL`.

[7]See, e.g., Andrew Sutton, **Ruler and Compass: Practical Geometric Constructions** (Bloomsbury, 2009), and Robert Vincent, **Geometry of the Golden Section** (Chalagam, 2014).

[8]This is revealed knowledge in courses on software design; see e.g., Harold Abelson and Gerald Sussman, **Structure and Interpretation of Computer Programs** (MIT Press, 1985), a course that Mairson has taught for years.

description as a kind of high-level instrument specification, and the underlying straightedge and compass constructions as a sort of low-level machine language.)

This software was used to code many of the designs described, in detail, in Denis's book.[9] We proceeded from following these "recipes" to a kind of "cooking" on our own: we took measurements from high-resolution, low-parallax photographs of several Stradivari violoncellos[10]: the *Mediceo*, the *Cristiani*, and *ex-Paganini, Countess of Stanlein*, reverse engineered the data following the Denis methodology, and produced geometry engine code for straightedge and compass constructions of these instruments.

The geometry engine was also used, in a kind of proof of concept, as an investigative tool to understand more about the history and evolution of instrument design, an inquiry we like to call "computational art history".[11] Our initial focus on Stradivari violoncellos was in part motivated by Denis's proposition that this maker marked a transition from the "classic" to "romantic" understanding of forms. What, then, could Stradivari have understood about classical, proportional design—could he have conceived of these forms purely through that geometrical approach? One way to address this possibility was to try ourselves. Earlier violoncello design, we thought, was likely to tend to be more traditional than violin design because making a cello takes so much longer than making a violin, and consumes more resources. Violins—smaller, cheaper, with more rapid production—are a more likely venue for experimentation with novel, alternative technology.

Stradivari violoncellos changed markedly over four decades, commensurate with the improvements in string technology that allowed shorter strings with greater resonance, and the transition of the violoncello from providing *basso ostinato* in church processionals to being a virtuoso instrument. His most celebrated, canonical model, and the one largely made today, was the *forma B*, played by Mstislav Rostropovich (the *Duport*), Yo-Yo Ma (the *Davidov*) Bernard Greenhouse (the *Countess of Stanlein*), etc. Where did the idea for the *forma B* come from?[12] We tried to explain the evolution of this form from principled modification of Stradivari's earlier *Mediceo* instrument: proportionally reduced but virtually identical in the upper two bouts, with an extension of the curves in the lower bout, and longer tangents at the lower corners of the bout.[13]

Data for these kinds of analytic reconstructions of instrument forms come from different sources, including measurement of instruments, photographs, and CT (computer axial tomography) imagery. Each source comes with its own challenges and risks of error. We focused particular attention on the *Cristiani*, a transitional instrument from larger models to the canonical *forma B*. We did several iterations of the drawing, finally with CT data. It became clear during this work that the *Cristiani* and the *Castelbarco* violoncello (now in the Library of Congress) had identical forms and were made from the same internal mold.

Much of this work was presented in conference at the Violin Society of America's annual meeting in 2014, and at the ACM International Conference on Functional Programming in 2013.[14] These presentations in front of (respectively) programming language and lutherie professionals were augmented with more practical workshop presentations on design, and how to use the software. In September 2014, we organized a visit by François Denis to the North Bennet Street School, a vocational arts institute, to present his drawing method

[9] See `www.traitedelutherie.com`.

[10] These renowned instruments are typically named after famous musicians who played them, e.g., the *Cristiani* after Lise Cristiani, for whom Felix Mendelssohn composed the *Song Without Words*.

[11] See e.g., Philip Steadman, **Vermeer's Camera** (Cambridge, 2002).

[12] When asked this question, a renowned violin expert smiled knowingly and pointed at the location of his brain. But even a genius has to get his ideas from *somewhere*.

[13] We completed an instrument drawing inspired by the *Stanlein* and based on this hypothesis; it was built by luthier Todd Goldenberg this year.

[14] See for example the review ("Fun in the afternoon" at `wadler.blogspot.com/2013_10_01_archive.html`) of our paper, *Functional Geometry and the Traité de Lutherie*, by Prof. Philip Wadler (U. Edinburgh). The paper was chosen as a research highlight by the Association for Computing Machinery see `www.sigplan.org/ Newsletters/CACM/Papers`. The project was highlighted in the **Atlantic Magazine** (`www.theatlantic.com/technology/archive/2014/04/how-high-frequency-trading-computers-see-new-york/359984/`), and presented also at seminars given at the Humanities Center at Brandeis, the University of Maryland, U.C. Berkeley, and NEH.

to students in the violin making program.[15] In January 2015, we organized a two-day workshop at Brandeis University for a dozen-odd luthiers on using the geometry engine.[16] This was a (largely successful!) exercise in seeing whether a group of luthiers could write code to design instruments; participants completed code for a drawing of a violin by Andrea Amati, interpreting directions from Denis's book in the formal language of the geometry engine. It was followed in the summer by a presentation at the Oberlin Violin Workshop[17], a remarkable two-week annual by-invitation gathering of 60 luthiers from around the world, which was followed with individual tutorials for luthiers who wanted to learn more.[18]

The Oberlin visit was particularly exciting: our drawing of the *Cristiani* interested many luthiers, not only because it has iconic status among the Stradivari violoncellos, but also because our analytic reconstruction of it was a proportional reduction in size to modern, quasi-*forma B* dimensions. As a consequence, there was renewed interest in building the model—which is why we [HM] did it in the first place.[19] Benjamin Ruth, a renowned American luthier, has mischievously referred to this reduced-size *Cristiani* as the Stradivari *forma P* violoncello, analogizing the *forma B* with the "long form" violins made by Stradivari, and the so-called "P-form" violins that followed them.

Two Oberlin attendees, luthiers Paul Crowley and David Polstein, took our PDF files, and used them together with the Rhino 3D modelling software to produce files that would direct a CNC (computer numerically controlled) router. An Oberlin-area shop with CNC equipment was found, and in the space of two days, roughly 40 internal molds and templates were produced for Oberlin workshop participants who paid $150 each to the shop for the instrument-making infrastructure. We expect to see numerous *Cristiani* models this spring.

This conclusion was a very satisfying summary to an ensemble of work: of François Denis's remarkable historical research, and its practical significance (namely, *here's how to draw violin forms*), of the software development that allowed this knowledge to be automated, embodied, and transmitted, of the focus on the *Cristiani*, long thought of as a prescient design move towards the *forma B* model, and to the final step where practical, historically appropriate artifacts could be provided to instrument makers.

Digital humanities is, at its core, about building things.[20] These luthiers could appreciate the essential features of the chain of interrelated constructions: of theories, of historical methods, of software, of luthier infrastructure. They clearly realized that the software component was essential in expediting a new approach to the understanding, design, and making of string instruments.

Our intention is that this digital humanities project can provide an analytic, computational foundation for studying aspects of this design tradition and its associated art history—not simply as a form of automation, but through an ensemble of intellectually precise, linguistically articulate descriptive tools, with examples of their use. The Renaissance quadrivium of arithmetic, geometry, music, and astronomy was anticipated by Pythagoras and immortalized by Plato. Replacing astronomy with computation results in a new quartet of complementary analytical and creative disciplines, spanning the humanities and sciences, and forming together an integrated subject.

Environmental scan: Lutherie, in a variety of ways, has not changed since the seventeenth century. This project integrates what was done during the NEH-supported startup phase with approaches to design taken by others, notably Kevin Kelly and his "four circles" methodology, and the `Strad3d` project led by Sam Zygmuntowicz. CAD/CAM methods are familiar in design, but the markup language (versus 'wysiwyg')

[15] We [HM] sponsored his visit to take the course and learn more about the method ourselves. We also visited him for a week in July 2014 to learn more about his methods.

[16] `www.cs.brandeis.edu/?p=618`.

[17] `www.oberlinviolinmakers.org`, and especially the video `https://vimeo.com/70135675`.

[18] Next summer, we (Mairson) are invited as a regular participant, to learn more about violoncello making, and to teach luthiers more about coding and design.

[19] The redesigned *Cristiani* has a body length of 740mm, shorter than the *forma B* models (typically around 755mm), but the reduction is principally in the lower bout; dimensions and relative proportions in the upper bouts resemble the *forma B* models very closely.

[20] See the essay by Steve Ramsay, *On building*, at `stephenramsay.us/text/2011/01/11/on-building/`, following his presentation at the "History and Future of Digital Humanities" panel at the 2011 MLA.

here is not, and of some significance: the design works, like a skeleton, of shapes connected by articulated points. For example, moving one circle, like riders jostled on the subway, causes connected changes in the design, not a disconnected circle, with a breakdown only of the various geometric constraints cannot be satisfied. Remarkably, we don't know of significant competing digitally-enhanced and methodologically traditional design methods for classical string instruments.

Work plan: The start-up phase of this project involved initial development and use of the geometry engine. The next, obvious, and deliberately chosen question is: what can we really do with it? The work plan encompasses five basic directions: *further software development of the tool and digital archives*, *design*, *acoustics*, *education*, and *history*. The related and complementary projects build on use of the geometry engine, in order to show how it, and software artifacts like it, could change the understanding and practice of lutherie.

Software development: (Harry Mairson, Eden Zik[21]) The geometry engine was designed to *do something*, not to have a beautiful user interface. Mairson wanted to recapitulate Denis's drafting prose in programming syntax. Now it is time to make the interface better. We are in the process of porting the software so that it will run entirely inside a web browser using a Javascript intepreter for the Racket language, in which the geometry engine is coded. Moreover, we want the graphics to be running automatically in realtime with the programming environment. Error messaging needs a lot of improving. As the language for using the geometry engine converges on a steady state, we need to write more documentation, which is presaged in material that was prepared for the Brandeis minicourse and Oberlin presentation in 2014. We plan a combination user's manual (programming straightedge and compass constructions) together with elements of Denis's **Traité de Lutherie**.

We want to build a website, likely constructed at or based on the Github model, where there is a repository of designs (i.e., code), drawings (PDF of run code), and data (CT files or imagery related to the code), which can be modified and returned to the repository. In this way, users can collaborate on the design of instruments. Finally, we want to build more facility into the geometry engine. A fair amount of Denis's methodology for reverse engineering CT and related data to Euclidean constructions in the design idiom of the Renaissance should be automated.

Education: (Harry Mairson, Roman Barnas) We intend to run courses for using the geometry engine and related design of instrument forms: at the Oberlin Violin Workshop, and at the North Bennet Street School. Mairson gave an initial presentation of the software project at Oberlin in June 2014, and is invited back as a participant in Summer 2015, where he intends to integrate instrument making and teaching. Denis gave his drawing course at NBSS in September 2014; we want to follow it with a similar course that is software based. Curriculum materials under development will reiterate many of the constructions and principles of Denis's **Traité de Lutherie** but in the form of code.

Among the differences (and we hope, advantages) is that when you make a mistake in the drawing and have to debug it, you have to determine what was done correctly before the error, and what steps following the error need correcting. With software, you simply *debug the code*: find the error (e.g., "no, it was one third the distance from X to P, not one half"), fix it, and run the code again.[22]

History and design: (François Denis, Harry Mairson) Much of the Denis and Kelly design methodology is directed towards that of internal forms for rib structures, which is for the most part a two-dimensional problem. In an article by Denis[23], he sketches an approach to the arching of the belly and back of instruments using locating points, taking inspiration from architecture, namely the design of vaults in cathedrals. We want to elaborate and implement these ideas in software for three-dimensional design using similar geometric primitives. A plausible case study is the arching of the *Cristiani* and *Castelbarco* violoncellos,

[21] Brandeis undergraduate, who helped with the Brandeis minicourse and is working on the browser implementation.

[22] Mairson took Denis's course, and redrew the same viola three times on the same day before he got it correctly. There was only time to make three mistakes. When luthier Marco Coppiardi took Mairson's short course, and his code had bugs, Mairson told him, "By hand, I could only make three mistakes a day. But with software, you can make fifty mistakes a day. That means that you can learn more."

[23] *Golden Arches*, **Strad**, Feb. 2010.

for which we have detailed CT scans provided by museums housing these instruments, and the radiology software (Osirix[24]) to manipulate this data. This collaboration will mostly consist of Denis explaining to Mairson what he's done up to now, and Mairson trying to resolve this information with CT data and in a simple enough coding scheme.

History and foundations:(François Denis) The invention of the violin is not, like outdated biological hypotheses, a case of spontaneous generation. Any profound cultural evolution is the consequence of complex processes, requiring an understanding of the political and and religious ambience that engendered them. The violin family is, consequently, the result of a general movement that literally *reformed* medieval instruments, beginning in the fifteenth century, unfolding throughout the sixteenth-, and coming to conclusion in the seventeenth century.[25] Understanding the violin, therefore, requires a concurrent interest in the forces and ideas that surrounded its emergence, in order to appreciate the moment of its creation.

In the **Traité de Lutherie**, we demonstrated that the violin is dependent on both a Greco-Latin and Greco-Arab theoretical heritage.[26] Violin design—an artifact of this ancient world, perhaps among the last of its type—follows principles that provided admirable service in both art and architecture, whose underlying meaning of its language had been rendered obscure. In other words, the principles of the *language of design* were no longer understood: not simply proportions, but the almost algebraic kind of geometric poetry that related these proportions to one another.[27] The echoes of this revolutionary reform of knowledge is understood by us as a conflict of the ancient and modern. The paradigmatic change is reflected an abandonment of a mathematical and philosophical essence—a kind of industrial revolution, with the introduction of a *numerical, digital* environment in place of a *geometric, proportional* one.[28]

The bygone notion of number and proportion has the structure of a language with its own syntax, semantics, and logic. Once this language of measure is decrypted, our understanding of works of the past can be elaborated to a profound degree. String instruments, organs, architecture, urban design would lend themselves to a common interpretation, and a hidden, common story would unfold.

Part of the challenge of this possibility is that the reliability of its conclusions is limited by the precision of available data.[29]The more that the image and analysis is vague, the more difficult it becomes to make valid interpretations. It is for this reason that the combined tools of the geometry engine and of CT scan are valuable in overcoming these obstacles. The CT data allows the construction of a trustworthy data set; the geometry engine is a complementary (and self-documenting) analytical tool. Together, they provide an approach to surmounting what has been, up to now, a quandary[30] in the cataloging of the initial form of the violin, as well as other musical instruments, and other cultural artifacts defined by their partitions of surface and area.

History and design: (Kevin Kelly) We want to to experiment with the software and the knowledge of past instruments to inspire new modes of design, and see how the software can facilitate each of these processes.

The elegant model composed by Andrea Amati in the mid-sixteenth century became the dominant form of stringed instrument of its type, and was wholeheartedly adopted by makers all across Europe. It was also, by all appearances, adopted by successive generations of makers in Cremona for almost two centuries. It is very important to note that the forms composed by the next generations of Cremonese makers show not only a close imitation of the character of the original Amati design, but also a singular personality—a divergence of form that varies in ways that nonetheles maintains a clear fidelity to the original.

Two important qualities of classical Cremonese forms stand out. First, they are visually compelling, possessing a natural beauty comparable to plant or animal forms (seashells, ferns, and humans). Second,

[24]`www.osirix-viewer.com`.

[25]William Monical, *Shapes of the Baroque*, `www.williammonical.com`.

[26]The word *lute*, and its derivative, *lutherie*, derive from the Arabic *oud*.

[27]See, in the context of architecture, works such as that by Wittkower (note 1).

[28]Denis, p. 17-18

[29]For example, reverse engineering of data is constrained in different ways by physical tracing of an instrument, by photographs, and by CT data.

[30]Denis's French characterization of this impasse is *aporie* (Greek, απορια), a logical impasse seemingly without resolution.

this "family resemblance" enables a trained observer to identify a classic Cremonese instrument, even when that individual form has not been encountered earlier.

The Amati forms are closely related to other designs composed in neighboring regions before and during his lifetime. It is a plausible conjecture that the Amati designs are the derivative of a design system used across northern Europe, and that this design system includes *a fixed number of elements which are related to each other in a limited number of allowable ways to generate instrument forms.* Understanding that the people who designed and built these instruments were craftsmen, it would follow that if such a system existed, it should be reasonable easy to understand and accessible using familiar workshop tools and techniques. If it is too complicated, it is not historically or physically plausible.

We want to investigate if such a system existed and if so, to determine the elements and relationships of the system: the formulaic "DNA" of the Amati violin[31]. After many years of work, Kelly believes that he has made progress toward that goal, and has a workable design system to establish this hypothesis.

The geometry engine software, developed in the start-up phase of this proposal, is a significant investigative tool to facilitate this research. One can imagine a sufficiently generic program in which one could incorporate potential elements and relationships of a violin design system in a parameterized form, making it much faster and easier to compare to actual instruments. In this way it could be possible, and moreover feasible, to determine whether or not such a system exists, and if so what its component parts and relationships are.

Underlying this approach is Kelly's "four circles" methodology for drawing Amati-style violin forms. The system has been adopted by numerous colleagues as a *design methodology.* Its distinguishing feature is a framework of four tangent arcs related in simple ratio relationships to provide the underlying design. Layout lines and smaller arcs which make up the particular design details of each instrument are then established on this framework, in a limited number of prescribed ways. This leads to a significant—but limited—number of possible outcomes.

The practical goal of developing this system is to have a straightforward process to develop new forms of instruments that belong to the same esthetic tradition as the classic instruments that are normally copied, so that it is possible to modify the instruments to better meet the demands of modern playing without sacrificing the qualities of the instruments that make them special.

Design: (Sam Zygmuntowicz) Zygmuntowicz will be making a new viola for the principal violist of a major orchestra. The goal is to create a customized instrument that will be well suited to active use by this individual. As part of the discovery process, this player tried a viola that he made, copying the *Primrose* Guarneri viola. We have agreed to base his new viola on that concept, but plan to incorporate significant changes in design, for tonal and ergonomic reasons. He plans to use the geometry engine to reverse engineer the original design, and also to alter the design to suit the needs of the player. Finally he plans to construct this newly designed instrument, and evaluate the result with the proposed player.

Individual specimens of Cremonese instruments have often been associated with a prominent player, and have come to exemplify a particular type of sound and response. These well-known examples can be an easy way to discuss elusive aspects of sound with a musician, and thus are often the jumping-off point for a new instrument, either as a copy, or a basis for interpretation.

A canonical example is the Andrea Guarneri viola formerly played by William Primrose (1904-1982), a prominent soloist. The most striking tonal aspects are its very penetrating intense sound, very resilient under the bow, allowing a wide dynamic range, quite suited to solo work. Also its moderate size and rounded outline make it very easy to play. Key aspects of this instrument are a moderate length, somewhat narrow middle bouts, and high arching, full in the upper and lower bouts, but quite scooped in the middle bouts. We have extensive documentation of this instrument, including photos, measurements, tracings and CT scans.

[31] **The DNA of Amati: A Dynasty of Stringed Instrument Makers in Cremona** (ed. F. Cacciatori, B. Carlson, C. Chiesa), Consorzio liutai e archettai Stradivari, Cremona, 2006.

Working from a CT scan view of the rib outline, we seek to recreate the original design, with proportional drawing technics, using the geometry engine software, in collaboration with François Denis and Harry Mairson. With the design drawn within the software platform, we will be able to generate multiple variations of the outline, to incorporate desired changes, including a somewhat wider outline, especially in the middle bouts, for increased bass response, and a shortened string length, for greater ease of fingering in technical passages. In the construction stages, I will also consider changes to the arching, thickness and f-hole placement. When the viola is completed we will evaluate the instrument in performance, and document the tone using spectral analysis. We expect to consider consider further modifications at the player's request.

Geometry and acoustics: (Sam Zygmuntowicz) Instruments sharing design and construction styles often share basic tonal characteristics. To understand this causal linkage, accurate and repeatable descriptors of sound are needed. Computer aided analysis of sound is now practical, using Fast Fourier Transform algorithms, which create a graphic display of the full resonance profile. This imaging enhances traditional subjective judgments. Psychoacoustic study has shown how the harmonic content of a played violin is processed by the human brain into our perception of tone color. This sound analysis is useful for comparing disparate instruments, but finds its fullest use in documenting the effect of modifications on one specific instrument in before/after comparisons. This enables a useful dynamic feedback loop for optimization.

We want to enhance the optimization of violin sound, utilizing digital technology, in an interactive process with the performing musician. This work will be a continuation of the ongoing "Gluey" experiments, drawing on resources and software developed during the `Strad3D.org` project (see website of that name). The focus will be on enabling more expressive musical performance, and on insights that can be transferred to general violinmaking.

This process will begin with selection of a study instrument, with a performer having experience in judging violin sound as a collaborator. Player and maker will test the instrument to form an initial subjective judgment of the sound and response, reevaluating the instrument after successive modifications. Spectral analysis will be used to document and display the specific resonance potential of the instrument. This combination of subjective playing and objective testing can establish a baseline judgment of the violin, tracking and quantifying changes caused by successive modifications. The graphs and data thus acquired will be correlated with our subjective judgments, identifying weakness or excess in the violin's spectral output.

Each of the many resonances of a violin is caused by one idiosyncratic vibration pattern of that violin's surface, called a vibration *mode*. The frequency and amplitude of each mode is a product of the underlying structure. The causal linkage becomes apparent: if you change the violin's structure, you change the vibration pattern, which changes the resonances, which changes the sound we hear. Modal analysis software developed by `Strad3D.org` allows us to track these patterns, and to extract a comprehensible guide to action. The toolkit for possible modifications is extensive, but here we will focus on the "gluey" technique, which involves the rapid adhesion of stiffening strips to targeted points on the exterior of a study violin, which can selectively influence the stiffness, mass and damping of targeted areas of the surface. The rapid adhesion and easy detachment of these strips allows easy and virtually unlimited alterations and combinations, and quick and reliable before/after subjective judgments of sound, which are much more difficult after the passage of time.

Risks and challenges: The Oberlin Violin Workshop has the rubric, "Where violin makers come to share." This is in marked contrast to practices of secrecy that have pervaded lutherie for many generations. The workshop is remarkable. But what happens when this sharing is extended on the Internet?

There are two difficulties, both of which emanate from a similar source: that the knowledge we are discussing encompasses the development of artefacts that are both artistic and proprietary. If a famous instrument is subject to analysis, do the owners of that instrument was that information publicly available? If a luthier is working on a design, does this mean that everyone should see it? If templates, outlines, etc. are publicly available, are they then subject to mass production, 'disrupting' a challenging existence for artisans?

These questions are going to take more thinking and working out. In the interim, we have two temporary solutions: one, that only the geometry engine and ancillary tools will be completely publicly available, and that access to the website will be login-keyed, where users have to identify themselves.

Staff:

Harry Mairson (project director) is professor of computer science at Brandeis University, and an amateur violoncello maker. He received the B.A. in mathematics from Yale University in 1978 and the Ph.D. in computer science from Stanford University in 1984. The only non-professional luthier on the staff, he recently finished a violoncello after a 1740 Montagnana, and is now working on the *"forma P"* Stradivari, based on the *Cristiani*, also described in the proposal. He has a long interest in making musical instruments, and worked as an apprentice to harpsichord maker Mark Stevenson in Cambridge, England during the late 1970s.

Roman Barnas (project director) is director of the violin making program at the North Bennet Street School. He attended the violin making program in Zakopane, Poland at the Kenar School, also studying sculpture, drawing and painting. He continued his education at the Ignacy Paderewski Academy of Music in Poznan, graduating with honors. He then worked in Detroit for a decade as a violin restorer, before joining NBSS. He is a prizewinner from instrument making competitions sponsored by the Violin Society of America. Most recently, he collaborated with mechanical engineering faculty at MIT on analyzing f-holes of Cremonese instruments, and how they optimized acoustic power.[32]

François Denis is a luthier in Angers, France, the author of **Traité de Lutherie: The Violin and the Art of Measurement**, and numerous articles on instrument design from historical principles. He is the preeminent historian of classical string instrument design, and has lectured worldwide on his investigations into design. He won the Musicora Prize in 2000 for his research on string instruments. It is Denis's work that has in large part made the subject and the foundations of string instrument design feasible to the modern generation of luthiers.

Kevin Kelly is a luthier in Boston, Massachusetts.[33] A maker and restorer, he has made significant contributions to geometric methods for violin design. He received the Distinguished Alumni Award from the North Bennet Street School in 2015, where he is on the board of advisors, and is a consultant for the Department of Musical Instruments at the Museum of Fine Arts, Boston.

Sam Zygmuntowicz is a luthier in Brooklyn, New York, and is one of the leading violin makers in the world, having made instruments by commission for Joshua Bell, David Finckel, Yo-Yo Ma, Isaac Stern, and many other famous musicians. He was the subject of John Marchese's book, **The Violin Maker** (Harper, 2007), detailing his making a violin for Eugene Drucker of the Emerson String Quartet. Winner of numerous prizes for lutherie, he is *hors concours* at competitions of the Violin Society of America. He was also creative director of the *Strad 3D* project (`strad3d.org`), a comprehensive artistic and acoustic study of three canonical instruments: the *Plowden* of Guarneri, and the *Willemotte* and *Titian* of Stradivari.

Advisory board

Ras Bodik Professor of Computer Science, University of Washington, Seattle.
Curtis Bryant Luthier and restorer, Boston.
Darcy Kuronen Curator, Collection of Musical Instruments, Museum of Fine Arts, Boston.
Christopher Reuning Reuning and Sons Violins, Boston.
Benjamin Ruth Luthier, Swampscott, Massachusetts.
Robert Brewer Young Luthier, Montfa (Ariège), France.

Final product and dissemination: Dissemination will occur through the teaching enterprise at the North Bennet Street School and at Oberlin, and through presentations at the Violin Society of America as well as publications in the VSA journal and in the **Strad**. Open source software and a dynamic library of designs will be available through the project website.

[32] *Power efficiency in the violin: new study identifies key design features that boost violins' acoustic power*, MIT News, February 2015, `https://news.mit.edu/2015/violin-acoustic-power-0210`.

[33] `www.kellyviolins.com`

Sustainability plan:

Data management plan:

Budget:

Resumés:

Letters of commitment and support:

Philip Steadman Professor of Architecture (emeritus), University College, London. (Author of *Vermeer's Camera*, Cambridge, 2002.)
Christopher Germain, President of the Violin Society of America (2013-2014), Director of the Oberlin Violin Workshop (1997-), Luthier, Philadelphia, Pennsylvania.
John Unsworth Professor of English, Chief Information Officer, and University Librarian, Brandeis University, Waltham, Massachusetts.

Appendices: (up to 10 pages)