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In most technology today, small, efficient solid-state components have replaced the large, fragile, high-voltage vacuum tubes of the past. Transistors, integrated circuits, and microprocessors make up the core of modern circuitry, and typically, substituting smaller components for larger ones is the natural progression of technology and design. However, in the audio industry, vacuum tubes are still irreplaceable, and they continue to be an integral part of recording technology to this day. When transistors were first invented, many industries were excited about the possibility of smaller and more efficient devices, but the problem of finding compact modes of audio amplification without losing the sound quality of vacuum tubes was not fully solved. Since then, many attempts have been made to remedy the issue, but there still isn't a best option for vacuum tube enthusiasts. By revisiting these technologies and applying modern human-centered design practices, a new, user-centered solution that combines efficiency and useability is possible. The purpose of this study is to examine the ways in which audio amplification technology arose historically, use this information to critique and examine current design issues, and apply modern design thinking toward a solution that centers the musician and audio engineer. Sources range from engineering logs at the onset of tube technology and transistor technology, historical papers describing the development and significance of these technologies, psychoacoustics and spectral analysis of both tube-dependent and solid-state audio devices, scientific papers on mathematics and acoustics modeling processes, writings by world-renowned designer Don Norman, and a field guide for design thinking by the human-centered design firm, IDEO.

The invention of the vacuum tube, or thermionic valve, at the turn of the twentieth century sparked a revolution in electronics design. With the two-electrode tube, invented by Thomas Edison and John Ambrose Fleming, detection of wireless telegraph signals was possible, but it wasn't until the three-electrode tube, or audion, designed by Lee De Forest in 1906, that the breadth of applications of this new technology was fully understood.[1] The three-electrode tube, which now had an added grid between the filament and plate, was used as a voltage rectifier and detector, modulator of AC current, oscillator, and most importantly, as a voltage amplifier.[2] This revolutionized electronics across many fields including radio broadcasting, telephone communication, audio recording and playback, television, radar, flight navigation, and eventually, computing.[3]

Although vacuum tubes made many new technologies possible, they had some major flaws that hindered further development. One issue with vacuum tubes was their large size, making many new technologies cumbersome and some impossible. Another was the high power demands and heat runoff which required meticulous management of power supplies and cooling devices.[4] Additionally, vacuum tubes tended to have a short lifespan and either burned out or cracked, making the technologies that used them difficult to depend on.[5] Large, unwieldy technologies that required high voltages and complex cooling devices became more of a hindrance than an asset in many fields, and designers started to search for solutions.

In 1947, John Bardeen and Walter Brattain at Bell Labs produced the first transistor which was made from germanium, and in 1954, Morris Tanenbaum, also at Bell Labs, created

[1] Hong, *Wireless,* 119; King, "Thermionic Vacuum Tubes," 38.
[2] King, "Thermionic Vacuum Tubes," 40.
[3] Guarnieri, "Seventy Years," 33; Guarnieri, "The Age of Vacuum Tubes," 52.
[4] Barbour, "The Cool Sound of Tubes," 28.
[5] Fink, "Transistors Versus Vacuum Tubes," 480.

the first silicon transistor.[6] Bardeen and Brattain state in their Bell Labs report, that this new component "may be employed as an amplifier, oscillator, and for other purposes for which vacuum tubes are ordinarily used," and it wasn't long before many industries caught on and did just that.[7] The small size, low heat production and voltage requirements, and comparatively robust nature of transistors solved many of the problems designers had been experiencing with vacuum tubes. The transistor sparked a second electronics revolution, and now technologies could get smaller, more efficient, and more portable than ever before. Watches, radios, hearing aids, pacemakers, and computers were some of the products that were affected directly and immediately by this new technology, but as time passed, scientists and engineers discovered some technologies were still better suited to using vacuum tube technology even with their known disadvantages.[8]

Although solid-state devices are superior to tube technology in low-power circuitry because of their low voltage, high current capabilities, vacuum tubes are still integral to technologies in some fields today that require support for high-powered, high-frequency devices. Some of these technologies include microwave ovens, high energy particle accelerators, commercial satellites, compact radio frequency accelerators, nuclear polarization experiments, and audio amplification technology.[9] Many brands of amplifiers, microphones, equalizers, and direct boxes are still designed with vacuum tubes but, unlike the former applications, are used for aesthetic purposes rather than practical ones. Audio engineers and musicians agree that tube preamps and amplifiers typically have a fuller and clearer sound than transistorized gear which can sound muffled or muddy at certain levels.[10] The key to this phenomenon is that vacuum tube

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6 Guarnieri, "Seventy Years," 33; Guarnieri, "Solidifying Power Electronics," 37.
7 Bardeen and Brattain, "The Transistor," 230.
8 Fink, "Transistors Versus Vacuum Tubes," 479; Guarnieri, "Seventy Years," 36.
9 Symons, "Tubes: Still Vital," 54; Qiu et al., "Vacuum Tube Amplifiers," 39.
10 Hamm, "Tubes Versus Transistors," 268.

amplifiers can operate with an overloaded signal without unwanted distortion.[11] This is because when a tube amplifier is overloaded, it generates a wider range of harmonics than transistor amplifiers which gives tube amplifiers a full, roomier sound without pushing the decibel levels out of range.[12] Unfortunately, these aspects of tube technology have proven difficult to replicate both digitally or with solid-state components, but many engineers, mathematicians, and computer scientists continue to try new methods.

With the onset of digital technology and modeling capabilities, engineers, acousticians, and mathematicians have been attempting to find a solution that eliminates the disadvantages of tube technology while retaining the desired audio effects. There are two main modes of digital modeling, digital signal processing and complete virtual circuit model, and many companies have designed both hardware and software with these techniques.[13] Some early examples include Yamaha's guitar effect for waveshaping nonlinear distortion in 1996, Digidesign's waveshaping table lookup for their Turbosynth software in 1989, Line 6's oversampling process they called "TubeTone Modeling," and Korg's tube-DSP (digital signal processing) hybrid.[14] There are advantages and disadvantages to all modeling techniques, and some considerations include the correlation between computational expense and accuracy as the complex nonlinear nature of tube modeling makes digital replication difficult.[15] In fact, it is because of these complex nonlinearities that most modeling devices typically focus on the most noticeable aspects of signal processing while some of the outlying effects are not included.[16] As a result, the full capacity of tube technology has yet to be encompassed in solid state devices or digital modeling processes.

11 Hamm, "Tubes Versus Transistors," 272.
12 Hamm, "Tubes Versus Transistors," 272.
13 Sapp, Jörg, and Claas, "Simulation of Vacuum-Tube Amplifiers," 1.
14 Pakarinen and Yeh, "A Review of Digital Techniques," 90-7.
15 Pakarinen and Yeh, "A Review of Digital Techniques," 98.
16 Pakarinen and Yeh, "A Review of Digital Techniques," 88.

Although there are some viable tube modeling options for musicians and recording engineers to choose from, there is still no definitive, non-compromising solution. However, with the application of modern design processes, there could be other solutions that have not been considered. The design community has made strides toward solving large-scale problems via a process called human-centered design. According to designer and author Don Norman, “Human-centered design is the process of ensuring that people’s needs are met, that the resulting product is understandable and useable, that it accomplishes the desired tasks, and that the experience of use is positive and enjoyable.”[17] The idea is that through getting rough prototypes into the hands of users as soon as possible, designers can design products or systems that are specifically tailored to serve the potential user. The design process has been broken down into four main categories: observation, generation, prototyping, and testing which typically get revisited multiple times throughout the design process.[18] Design firm IDEO calls these processes inspiration, ideation, and implementation, but the basic structure remains the same and relies heavily on observing and interviewing potential users.[19] This is how modern designers get to the root of an issue and then build a solution from the ground up to create a robust, user-centered design. Historically, designers and developers solve issues based on preexisting designs, which is why revisiting the root of an issue, even a very old issue, can be beneficial, especially when new technology has the potential to change the design significantly. Otherwise, designs can piggyback on technology that no longer serves the user. Implementing aspects of human-centered design by observing, interviewing, and gathering information from musicians and audio engineers could illuminate new information and allow designers to move forward with a modern, elegant solution to a long-term problem.

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[17] Norman, *The Design of Everyday Things,* 219.
[18] Norman, *The Design of Everyday Things,* 220.
[19] IDEO*, The Field Guide to Human-Centered Design: Design Kit,* 11-12.