Whirlwind:
Blowing Down Barriers for Modern Computers

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Senior Division
Individual Documentary
Documentary Length: 10:00
Process Paper: 500

YouTube Link: https://youtu.be/Py74a_RaMeA

My National History Day project is about Jay Forrester and his contributions to modern computer technology. I decided to research this topic, because I am interested in computer technology and wanted a Nebraska topic. In the late 1940s, as the U.S. transitioned from post World War II into the new era of the Cold War, technology became increasingly important. Two barriers prevented widespread computer use: analog computers were too slow to process information for “real time” interaction, and the cost and limitations of memory storage. These barriers threatened to prevent the development of computer technology. Jay Forrester, a Nebraska farm boy, was the unlikely hero who broke both barriers. His solutions, digital computing in “real time” and core memory, were so important that the innovations changed two industries: computer technology and national security. I decided a documentary would be the best way to present my research because it allowed for a visually moving representation of Jay Forrester’s innovations.

One of the challenges in the research process was that Jay Forrester is more well known for his work in system dynamics. Many sources dealt only with that aspect of his career. While interesting, I wanted to focus on his computer innovations. The MIT archives had an extensive collection of records, documents, pictures and notes from Jay Forrester. In addition, I wrote to the Air Force for information on SAGE. They sent official files from the SAGE development process. Both of these sources were very technical and took time to go through them. The MITRE Corporation and IBM were helpful in finding appropriate information and images. In addition, there were many oral

histories available online. Whirlwind had a long list of firsts and became the predecessor to many computer advances. I could not cover all of them in this documentary. I focused on the two innovations that had the biggest impact on history. Other firsts made by Whirlwind included the light gun, graphics and computer music. Therefore, my background music was entirely composed and played by a computer using artificial intelligence.

I thought this project would be easy, but I ended up struggling to develop moving images to demonstrate how his inventions worked. I put my entry together using Final Cut Pro, GarageBand, and Keynote. I needed patience in order to line up my words, pictures, and effects.

It is important to study Jay Forrester and his inventions. By 1956, Jay Forrester had broken two barriers in computer technology that affected the growth of the computer industry and national security. His inventions led to “real time” computer transactions such as air traffic control, banking and online reservations. Core memory affected the way data was read, written, and stored, making computers faster and more reliable. The barriers broken by Jay Forrester provided the bridge between early analog computers and today’s digital computers. This National History Day project has been a valuable experience. I enjoyed going through the archives at MIT, learning the research process. These skills will help me in the future.

Bibliography

Primary Sources

Army Liaison Office of the Lincoln Laboratory. "Monthly Progress Report." 1953-1955, US Air Force Archives, Montgomery, Reel 24843. Typescript.

Early in my research I wrote to the US Air Force for information. I was sent copies of monthly progress reports from 1953-1955. The narrative was very technical and often difficult to read. However, there were also block diagrams that helped clarify the information. I found it interesting as I followed the progression. Some of the information did not apply to Whirlwind but dealt with the connection between the military and Lincoln Laboratories. As a result, other projects were mentioned. This affirmed that there was a strong connection between MIT and the military.

"Electronics: Magnetic Cores I: Properties 1961 US Army Training Film TF11-3131." *Vimeo*, uploaded by Jeff Quitney, 27 Sept. 2018, vimeo.com/292244109. Accessed 9 Feb. 2020.

This is a U.S. Army training film from 1961. In the film, magnetic core memory is explained in detail. Although the film was created almost 10 years after Jay Forrester invented core memory, the concepts were unchanged. The film was extremely detailed but followed exactly how Jay Forrester described his method and design. This film helped me visualize how core memory worked. I used it as a basis for how to demonstrate core memory in my documentary.

Everett, R. R., compiler. *Whirlwind I Computer Block Diagrams*. Report no. R-127, 4 Sept. 1947. *MIT*, www.bitsavers.org/pdf/mit/whirlwind/R-series/R-127_Whirlwind_I_Computer_Block_Diagrams_Volume_2_Sep47.pdf. Accessed 24 Jan. 2020.

This is one of the original reports when Whirlwind was first beginning. It contains the block diagrams for the prototype computer. It includes both the math and physical building of the computer. The report included mostly diagrams of how the computer worked and would be put together. I used several pages in my documentary to show that the project was well thought out. This is before many of the changes that occurred with digital computing and memory storage.

Everett, R.R., and F.E. Swain, compilers. *Whirlwind I Computer Block Diagrams*. Cambridge, Servomechanisms Laboratory, 4 Sept. 1947. *Computer History Museum*, www.bitsavers.org/pdf/mit/whirlwind/R-series/R-127_Whirlwind_I_Computer_Block_Diagrams_Volume_2_Sep47.pdf.

This is a technical report that was submitted by the Servomechanisms Lab to the Special Devices Center, Office of Naval Research. It contained the block diagrams and drawings for Whirlwind. The report is dated 1947. This was the beginning of the Whirlwind project and demonstrated the starting point for Jay Forrester and the Whirlwind project team. It was interesting to compare some of these drawings to drawings made later in the project development.

"The Explosion of the First Soviet Nuclear Bomb." *YouTube*, uploaded by Radiation Hazard, 1 Nov. 2014, www.youtube.com/watch?v=tTrzu32XorA&feature=emb_logo. Accessed 23 Mar. 2020.

This is a Russian clip of the first Soviet atomic bomb. The test was carried out at 7:00 local time on August 29, 1949. The power was 22KT, at the Semipalatinsk test site. This was a shock to the United States. Most American officials thought the Soviets would not have an atomic bomb until the mid-1950s. As a result, the U.S. felt threatened and needed a way to protect Americans at home. This prompted the Air Force to find solutions that were new or in development. They became interested in Whirlwind because of its ability to do "real time" computations. I used part of this clip in my documentary to show the urgency of a national air defense system.

Fedorkow, Guy. "Whirlwind Computer Jingle Bells." *Internet Archive*, 12 Dec. 2018, archive.org/details/jingle-1k-rolloff. Accessed 11 Sept. 2019.

This is an audio clip of the song Jingle Bells. This song was programed into the Whirlwind computer. This is significant because Whirlwind is one of the first computers to have a loudspeaker for auditory maintenance and monitoring and early computer music. The clip is available due to a software restoration and output recreation project. This technology allows us to recover software from the Whirlwind paper tapes and run it on computers today.

Forrester, Jay W. "16th Annual Killian Award Lecture—Jay W. Forrester." 20 Mar. 1988. *MIT Infinite History*, MIT, 20 Mar. 1988, infinitehistory.mit.edu/video/16th-annual-killian-award-lecture%E2%80%94jay-w-forrester-1988-lect-1. Accessed 17 Dec. 2019. Speech.

Jay Forrester received the Killian Award from MIT in 1988. As a result, he presented a lecture series on his work at MIT. In his first lecture, he discusses his background and time working on Whirlwind. Throughout the lecture he mentions breakthroughs in computer science involving creating the first high-speed computer and magnetic storage system. He also discusses the design of SAGE air defense system. His lecture regarding his work helped me see that his innovations broke barriers that advance both computer science and national security. It also gave me background information about what he did after Whirlwind in the area of system dynamics.

---. "The Beginning of System Dynamics." 13 July 1989. *MIT*, web.mit.edu/sysdyn/sd-intro/D-4165-1.pdf. Accessed 18 Dec. 2019.

This paper is written by Jay Forrester. It is actually the transcript of a banquet talk at the international meeting of the System Dynamics Society in Germany. Jay Forrester is best known for his work in system dynamics. Much of the information I found was about this portion of his career. I used this article to learn about the beginnings of system dynamics. It seemed like a natural progression from Computer development to computer application. Digital computers developed by Forrester were know able to calculate the information needed to make system dynamics possible.

---. "Data Storage in Three Dimensions." Received by 6345 Staff Members, 29 Apr. 1947. *MIT*, dome.mit.edu/bitstream/handle/1721.3/38920/MC665_r04_M-70.pdf?sequence=1. Accessed 12 Jan. 2020. Memo.

This memo is on data storage. Even at the beginning of the project, Jay Forrester realized that one of the biggest problems with large-scale digital computers would be storage. This memo showed that early in the project development, Forrester was already working on the storage issue, including three dimensional storage. He states that vacuum tubes are insufficient and using electrostatic still falls short of what is needed. The memo includes diagrams and graphs of three dimensional storage concepts.

---. *Forecast for Military Systems Using Electronic Digital Computers*. Report no. L-3, 17 Sept. 1948. *MIT Archives*, dome.mit.edu/bitstream/handle/1721.3/45963/MC665_r28_L-3.pdf?sequence=1. Accessed 28 Feb. 2020.

This report, written by Jay Forrester, details different ways the military could use digital computers. At the time of the report, Whirlwind had been designed and was under construction. However, there was no sense of urgency regarding military use because the Soviets did not have the atomic bomb and it was not expected for them to have the bomb until the mid-1950s. The report describes different military applications and cost. He estimates that Whirlwind would be able to apply military functions within 4 years. After 1949, the timetable was moved up because of Soviet threats and Whirlwind was fully operational with "real time" computations and core memory by 1951.

---. "Infinite History Project Jay Forrester Interview." Interview conducted by Toby A. Smith. *MIT Infinite History*, MIT, 26 Jan. 2009, infinitehistory.mit.edu/video/jay-forrester-sm-%E2%80%9945-part-1. Accessed 17 Dec. 2019.

This is was an interview with Jay Forrester conducted by Toby A. Smith for MIT's Infinite History Project. Jay Forrester recounts his time at MIT while working on Whirlwind. He explained the process of how he developed the first digital computer that was capable of real time interactions. He also explained how magnetic core memory works. His explanations were important in helping me to understand how he broke technology barriers that changed both computer science and national security. I also used parts of the interview in my documentary.

---. Letter to Nathaniel McLean Sage. 12 Apr. 1951. *MIT*, dome.mit.edu/bitstream/handle/1721.3/45959/MC665_r28_L-26.pdf?sequence=. Accessed 17 Feb. 2020.

This is a letter from Jay Forrester to Nathaniel McLean Sage. It details the funds needed to extend the capacity of the Whirlwind computer to demonstrate its capabilities for handling low flying aircraft requiring the processing of information from many radar sets. This letter was written just days before Whirlwind went online and discovered that core memory would work. There is a paragraph requesting money for experimental testing on a storage device that would make SAGE possible. The overall budget is to gain more funding to extend the capacity of the computer to demonstrate its capabilities.

---. Multicoordinate Digital Information Storage Device. US Patent 2,736,880, United States Patent and Trademark Office, 28 Feb. 1956. *US Patent and Trademark Office*, history-computer.com/Library/US2736880.pdf. Accessed 5 Jan. 2020.

This is a copy of Jay Forrester's patent application. Although the patent was not issued until February, 1956, Forrester originally filed the patent in May, 1951. His application was the first for core memory. He filed for the patent immediately after Whirlwind went online and successfully demonstrated core memory. In the years following he continued to improve and expand his concept. Jay Forrester is the man who created and developed core memory. However, after filing his patent and officially being issued the patent there were many lawsuits involving core memory. Jay Forrester had the documentation necessary to prove he was the first successful innovator of core memory. I also found his drawings included in his patent application to be very interesting and clearly shows how core memory developed.

---. "Project Lincoln, Division VI Program." 7 Jan. 1952. *MIT Archives*, dome.mit.edu/bitstream/handle/1721.3/45966/MC665_r28_L-32.pdf?sequence=. Accessed 26 Mar. 2020. Memo.

This is a three page memo from Jay Forrester regarding improvements that could be made to Whirlwind. In this memo he discusses how to make Whirlwind smaller, and faster. The results of the memo will be the improvements made in 1953. The improvements made the computer, faster, more reliable and cheaper to run. These improvements made the computer more appealing to commercial industries as well as the Air Force.

---. "Proposal for the Study of Digital Computation for Naval Fire Control." Received by Office of Naval Research, 2 Mar. 1950. *MIT*, dome.mit.edu/bitstream/handle/1721.3/45953/MC665_r28_L-20.pdf?sequence=. Accessed 12 Feb. 2020. Memo.

This is a memo written from Jay Forrester to the Office of Naval Research. It is dated January 5, 1950. It follows discussions with technical representatives of the Office of Naval Research. There is reference to a letter from Forrester to Commander Gilbert H. Mitchell of the Armament Branch of the Navy, dated November 25, 1949. This memo replies to some of the issues discussed. It states that MIT is completing the assembly of a high-speed electronic digital computer. A proposal could be integrated for an anti-aircraft land-based fire control system. This showed me that even when the Navy was funding Whirlwind there were considerations for other applications.

---. "Staff Organization." Received by All Personnel, 11 Dec. 1950. *MIT Libraries*, dome.mit.edu/bitstream/handle/1721.3/38989/MC665_r04_A-111.pdf?sequence=1. Accessed 10 Mar. 2020. Memo.

This is a memo that Jay Forrester sent out regarding the reassignment of responsibilities. It also outlines the objectives these reassignments should accomplish. This memo demonstrates the logistics of scheduling computer time between maintenance, testing new equipment, and use of the machine by the application groups. This memo demonstrates the leadership ability of Jay Forrester and the details necessary to successfully accomplish the project goals.

---. "Visit to University of Illinois and Engineering Research Associates." Received by E. S. Rich, 22 Jan. 1951. *MIT*, dome.mit.edu/bitstream/handle/1721.3/39017/MC665_r04_M-1152.pdf?sequence=1. Accessed 24 Feb. 2020. Memo.

This is a memo written by Jay Forrester that outlines his visit to both the University of Illinois and Engineering Research Associates. The Whirlwind research team that visited saw a demonstration of the IAS computer. They also discussed ERA's computer experience and its relation to future work in the field. There was an evaluation of the magnetic drum as a reliable element in computing systems, and discussion of electrostatic storage and possible use of the RCA Selectron. This is before the success of core memory. This showed me that Jay Forrester was aware of developments others were making in the field. He was very thorough and considered new research when creating Whirlwind.

Gilmore, Jack. "Whirlwind Before Core Reminiscences of Jack Gilmore." *Gallery Talk*, 16 June 1982, tcm.computerhistory.org/exhibits/WhirlwindFall1982.pdf. Accessed 24 Jan. 2020.

This is an article written by Jack Gilmore. He joined the Whirlwind team in October, 1950. It was his job to write the assembly program first. When Whirlwind was going to appear on television Gilmore wrote the program to show the trajectory of a Viking rocket on the display and a program that played Jingle Bells. He also felt that a computer museum should be built to document the first computers and the quickly changing technology. This included Whirlwind and the barriers it broke.

IBM Corporation, editor. "IBM Chronology." *IBM Archives*, www.ibm.com/ibm/history/history/decade_1950.html. Accessed 26 Jan. 2020.

This is IBM's online archive site. Forrester chose IBM as the contractor for Whirlwind once it was fully developed. The IBM archives had a collection of primary source information about Whirlwind and the various components that IBM used to further advance the commercial aspects of Whirlwind's innovations. IBM used Forrester's core memory and "real time" interaction concepts to make computers appealing in a commercial environment. I was able to go through IBM documents to see how the technology progressed. There were many diagrams and photographs that I was able to use.

"IBM SAGE Computer Commercial." *YouTube*, uploaded by IBM, 30 Dec. 2018, www.youtube.com/watch?v=LfdcZFzmNvs. Accessed 19 Feb. 2020.

This commercial was created in 1960 by IBM. The purpose was to explain the SAGE system to the American people. It focuses on the advancing technology that is used to keep America safe from enemy attacks. It explains how the air defense system tracks enemy aircraft, calculates interception points and can launch a counter-attack before a missile reaches the U.S. I used a clip from this commercial in my documentary to show how Whirlwind broke barriers for national security.

"In Your Defense." *YouTube*, uploaded by Computer History Museum, Mar. 2008, www.youtube.com/watch?v=06drBN8nlWg&t=901s. Accessed 3 Mar. 2020.

This video was created for the U.S. Air Force by the Western Electric Company sometime in the late 1950s or early 1960s. It is primarily a propaganda film to show the significance of SAGE and how it keeps America safe. The film walks the viewer through a scenario in which Sage makes calculations and the Air Force officer must make a decision. It then finishes with a computer guided missile. I used part of this video to show the locations of radars, control centers and command centers.

Jacobs, John F. *The SAGE Air Defense System, A Personal History by John F. Jacobs*. MITRE Corporation, 1986. *MITRE Corporation*, www.mitre.org/sites/default/files/pdf/SAGE-Air-Defense-System.pdf. Accessed Mar. 2020.

John F. Jacobs worked on Project Whirlwind. He stayed with the project from its beginning at MIT through its transfer to IBM as a computer contractor and the MITRE Corporation. This paper was very detailed and outlined not only the computer components but also budgeting and political aspects of the project. There was one section devoted exclusively to Jay Forrester. This helped me understand Jay Forrester as the project designer and a co-worker.

"Jay Forrester on the Whirlwind Computer." *YouTube*, uploaded by Computer History Museum, 19 Apr. 2011, www.youtube.com/watch?v=JZLpbhsE72I. Accessed 11 Sept. 2019.

This video was recorded in June 1980 at The Computer Museum in Boston. Jay Forrester describes the 1946-1953 development of the Whirlwind computer, its purpose, and influence on subsequent designs. He explains the problems that led to the development of magnetic core memory. He also discusses the transition of Whirlwind from an aircraft simulator to a real-time control computer that led to the SAGE air-defense system. This video helped my understand the transformation and different stages of development of the Whirlwind computer and how it influenced future technology. Since Jay Forrester is giving the lecture, I used clips in my documentary.

"Jay W. Forrester and the WHIRLWIND Computer." Hosted by Edward R. Murrow. *See It Now*, season 1, episode 5, CBS, 16 Dec. 1951. *YouTube*, www.youtube.com/watch?v=5ZQP4G3Qwb4. Accessed 10 Sept. 2019.

This is a clip of the *See It Now* television program which aired in 1951. Jay Forrester was a guest and demonstrated the Whirlwind computer. Although this program was filmed early in the Whirlwind's development it does show some of the first computer graphics. I was able to see what the Whirlwind computer looked like and how it worked with Jay Forrester demonstrating different problems, for example, the flight path of a rocket and its fuel consumption along the path. I also used clips from this video in my documentary.

Loeb, Arthur L., and Norman Menyuk. "Group 63 Seminar On Magnetism." Received by Group 63 Staff, Mar. 1953. *MIT*, dome.mit.edu/bitstream/handle/1721.3/39267/MC665_r05_M-1902.pdf?sequence=1. Accessed 21 Nov. 2019. Memo.

This is a memo that was sent at MIT. It is in regards to a seminar on magnetism. Core memory is based on the concept of magnetism. This memo discusses the molecular components of magnetism. There are drawings and diagrams that helped me understand how magnetism works. This concept is critical to how core memory carries bits of information on a grid that allows for randomly accessing each bit.

Making Electrons Count. Screenplay by Edwin S. Kopley, directed by Lloyd C. Sanford, Office of Naval Research, 1950. *MIT Infinite History*, MIT, infinitehistory.mit.edu/video/making-electrons-count-c-1950. Accessed 17 Dec. 2019.

This film was created in 1950 to demonstrate the capabilities of Whirlwind in solving problems. It is filmed inside the Whirlwind I computer facilities. This was very helpful in understanding the large size and capabilities of Whirlwind. The film shows a few examples of the types of problems in which computers can be useful. It then described efforts of a typical user in programming a problem for Whirlwind. It also covered background information and the history of computers. I used this information to further my research on historical context. I used parts of these images in my documentary.

"1957 SAGE Early Warning Defense Radar Computer System." *YouTube*, uploaded by IBM, 3 Dec. 2007, www.youtube.com/watch?v=tf1h6aGE5Zo. Accessed 24 Feb. 2020.

This film was made in 1957 by IBM. The purpose is to explain the advancements made by SAGE to keep America safe. The focus is on IBM's technological advancements. This is 20 years before mass-market production of computers. It is clear that computers are advancing and being applied in new and different ways such as commercial air traffic and weather.

Olsen, Ken. "Transcript of an Oral History Interview with Ken Olsen." Interview conducted by David Allison. *National Museum of American History, Smithsonian Institution*, 29 Sept. 1988, americanhistory.si.edu/comphist/olsen.html#tc10. Accessed 18 Mar. 2020.

This is a transcript of an interview with Ken Olsen. Ken Olsen was at MIT and worked on Project Whirlwind. He often worked at night and was involved in the modular design of the computer. He was also involved in making test equipment. His information on core memory verified that Jay Forrester was truly breaking barriers in computer technology. It was valuable to read information from someone who worked on the project and was able to give a perspective that was different from the designer.

On Guard! The Story of SAGE. Produced by Department of Defense, U.S. Air Force, and Boeing Airplane Company, IBM, 1957.

This is a 12 minute video that discusses SAGE and its importance to national security. IBM released the film after having government agencies help produce it. The purpose was to assure the public that the US was safe from enemy aircraft. The end of the video covers how technology based on SAGE/Whirlwind was further developed for onboard computers in bombers. I used clips from this film to show the size and improvements made in the late 1950s.

Reflections on the Sage Project. Performance by Jay Forrester, 2018. *Lincoln Laboratories, MIT*, www.ll.mit.edu/about/history/reflections-sage. Accessed 16 Nov. 2019.

This website contained several videos of Jay Forrester. They were his reflections on Whirlwind. He discussed the start-up, core memory, working with IBM and its transition to SAGE. He also discusses the many different inventions that came from Project Whirlwind. It was very interesting to hear about the computer from the developer himself. His attitudes and beliefs about the process were clearly stated. He helped me to understand how complicated the development process can be including creating Whirlwind and working with businesses to ensure the work continues.

"SAGE Air Defense." *YouTube*, uploaded by Bruce Gordon, 2 Feb. 2017, www.youtube.com/watch?v=cWPZwaD_M7M&t=20s. Accessed 9 Jan. 2020.

Bruce Gordon explained the SAGE system, how it worked and why the U.S. needed it for National Defense. While in the military, he was very familiar with SAGE and used it a number of times while flying. Bruce Gordon flew an F-106 in 1968. He gave a first hand account of one incident where SAGE was critical to achieving his mission. At one point during the incident, the mission was called off because the computer was down but Gordon's computer was still working and he was able to accomplish the mission. This verified the concept of tandem operation for zero down time. It was interesting to hear an account from a military pilot who used the system and verified its value for national security.

SAGE System Training Program. Produced by System Development Corporation. *Periscope Film's Operation Archive*, stock.periscopefilm.com/78864-sage-system-training-program-cold-war-early-warning-system/. Accessed 3 Mar. 2020.

This video explains the SAGE computer system. Although there was no production year, it seems to be around the early 1960s based on the aircraft. It details the functions needed and processed by the computer to get flight details. It also walks through a training simulation. I found the end very interesting as the participants analyzed what worked and what did not work. There were also suggestions about changes and upgrades that would make SAGE more accurate. This video helped me understand how the computer was continually changing and stayed a vital piece of national security through the 1980s.

Thompson, Joe. Interview. Conducted by David C. Brock. *Computer History Museum*, 19 Feb. 2018, www.youtube.com/watch?v=nZhj9vCrg3U&feature=emb_logo. Accessed 24 Jan. 2020.

This is an oral history in which Joe Thompson discusses his time working on Whirlwind. He was a software engineer who operated Whirlwind. He worked 4 ½ years on Whirlwind while attending evening classes at MIT. Whirlwind was his first exposure to computers. He continued working on Whirlwind as it developed into SAGE. Afterwards, Thompson was recruited as a programmer at RAND. He describes the work environment at MIT, and his experiences with other employees. Thompson, who had high level security clearance, also describes his interactions with the military in support of national defense projects.

Tobey, J. R. Memo to J. D. Porter. Mar. 1959. *MITRE Corporation*, sage.mitre.org/wp-content/uploads/2019/02/TM15.pdf. Accessed 7 Jan. 2020.

This is a memo dealing with the SAGE system development. It outlines the entire program from the mission to the functions and descriptions of the project. It also included the XD-1 instructions. XD-1 is hardware and software that would pass information from one direction center to another. This showed that work on Whirlwind/SAGE was continually advanced and modified.

U.S. Navy. *80-G-K-15097 Naval Aviation Cadet Training*. 1943. *Naval History and Heritage Command*, www.history.navy.mil/content/history/nhhc/our-collections/photography/numerical-list-of-images/nhhc-series/nh-series/80-G-K-15000/80-G-K-15097.html. Accessed Feb. 2020.

This is a photograph showing flight simulators that were used during World War II. Aviation cadets are shown receiving instrument flying instruction in "link trainer" flight simulators. Simulator operators are women. These were mechanical. The Navy wanted more realistic simulators so that pilots could receive "real time" flight instruction. The Navy wanted flight simulators to more closely mimic the actual plane while flying. I used this photograph in my documentary to show Jay Forrester's starting point when developing a flight simulator for the Navy.

Walquist, R. L. "Utilization of Magnetic Drum and High Speed Random Access Storage." Received by WWII Planning Group, 2 May 1952. *MIT*, dome.mit.edu/bitstream/handle/1721.3/39211/MC665_r05_M-1473.pdf?sequence=1. Accessed 24 Jan. 2020. Memo.

This is a memo that was sent in 1952. It discusses how a combination of a large magnetic drum memory and random access memory could be used. Forrester successfully demonstrated core memory, which uses random access in 1951. This document verified that his idea was initially of interest to the military rather than commercial groups. However, the combination suggests there was some hesitation about using core memory only.

Secondary Sources

AI/AVIA. *Guiding Light*. 2019. AVIA Technologies. *YouTube*, www.youtube.com/watch?v=q6-u_--3hJQ. Accessed 2 Mar. 2020.

This is the background music for my documentary. I chose this music because it was composed and played by a computer using artificial intelligence. Whirlwind was the first computer to play music (Jingle Bells) on a computer. This marked the beginning of computer generated music. I felt it was appropriate that the background music also be a result of the progression of computer technology from Whirlwind.

"Animation of Serial vs Parallel Transmission." *YouTube*, uploaded by HowTo, Oct. 2015, www.youtube.com/watch?v=PJ_bS7meE7s. Accessed 14 Jan. 2020.

This was a simple animation showing the difference between serial and parallel transmission. This concept was used by Jay Forrester to make the first high-speed interactive computer. Parallel transmission is still used in modern computers today. I used this clip because it clearly demonstrates this significant concept in a way that can be understood. The visual makes it clear that serial transmission is much slower than parallel transmission.

Barbour, Eric. "The Strange World of Memory Tubes." *Ed-Thelen*, ed-thelen.org/comp-hist/TubeCollector-.pdf. Accessed 15 Feb. 2020.

This is an article that was posted about the history of memory tubes. It starts with the Williams Tube. This is the tube that Jay Forrester originally used. Due to its weaknesses, he altered the tube. The altered tubes were expensive and failed. This article details some other tubes Forrester tried. It showed the progression of development. There were also pictures.

Brock, David C., and Guy Fedorkow. "Jinglebits: Auditory Maintenance, Whirlwind Holiday Songs and the Dawn of Computer Music." *Computer History Museum*, 16 Dec. 2018, computerhistory.org/blog/jingle-bits-auditory-maintenance-whirlwind-holiday-songs-the-dawn-of-computer-music/. Accessed 13 Dec. 2019.

This article dealt with the auditory maintenance and monitoring of Whirlwind. It also dealt with the creation of the first electronic computer music. A loudspeaker was attached to Whirlwind and deliberate sounds were made by the computer through programming. Although this information was of secondary importance to my research, it helped me to see that there were many other ways in which Whirlwind affected the computer technology industry.

Computer History Museum, editor. "Revolution: The First 2000 Years of Computing." *Computer History Museum*, 2020, computerhistory.org/collections/. Accessed 29 Dec. 2019.

This is an online museum about the history of computers. There were many different collections that I was able to explore, starting with early computers and following the progression through modern computers. The timelines were interactive and helped me make connections between the different key events. There were also oral histories that I allowed me to hear first hand accounts from those who worked on computers and helped develop them. I was particularly interested in the sections on analog computers, real time computing, and memory and storage. There were many high quality pictures including hand written notes and diagrams that I was able to use in my documentary.

The Cornhusker 1939. 1939. *University of Nebraska*, yearbooks.unl.edu/yearbook.php?year=1939,440#page/311/mode/transcription. Accessed 26 Jan. 2020.

This is the 1939 yearbook for the University of Nebraska, Lincoln. Jay Forrester received a scholarship and attended the university from 1936-1939. While at the university, Forrester was active in the Rifle Club, Council for Religious Welfare, “N” Club, and Sigma Tau (honorary engineering fraternity). He was also a member of Sigma Chi fraternity. Although his scholarship was for the department of agriculture, once he got to the university he switched to engineering. He speaks very highly of his time at UNL. I used a picture of Forrester with the Sigma Tau fraternity in my documentary.

Dizikes, Peter. "The Many Careers of Jay Forrester." *MIT Technology Review*, June 2015, www.technologyreview.com/s/538561/the-many-careers-of-jay-forrester/. Accessed 23 Nov. 2019.

This article chronicles Jay Forrester's life. It is divided into different stages which made it easy to understand how his career path developed and changed. This article also emphasizes the influences that growing up in Nebraska had on his career and work ethic. I found it interesting that he feels there should be more "hands-on" education today. There was also a slideshow that contained several photographs, including some of his family and the ranch where he grew up in Nebraska. I used these in my documentary.

Eckstein, P. "The Childhood of a Computer Pioneer -- Jay Forrester." *Talent Development*, vol. II, 1992, pp. 405-08. *Davidson Institute*, www.davidsongifted.org/search-database/entry/a10015. Accessed 12 Nov. 2019.

This article focused on the childhood of Jay Forrester. Jay Forrester grew up in Nebraska. The article focused on how living in a rural area helped him develop skills he would need later. The author interviewed Jay Forrester. As a result, there were several quotes from Forrester about how his "tinkering" on a Nebraska ranch taught him persistence - how to fail and try again. I found it interesting that he created several things as a young boy. In a shop class he created a cap for the roof of the ranch house. While growing up, his house did not have electrical power. In high school, he created a wind generator that provided his family ranch with power. He won a scholarship to the University of Nebraska as a result of his wind generator. This put him on the path to MIT and Whirlwind.

Electrical Concepts, editor. "Basics of Servomechanism and Servo Motor." *Electrical Concepts*, 2019, electricalbaba.com/basics-of-servomechanism-and-servo-motor/. Accessed 2 Dec. 2019.

I used this website to learn about servomechanisms. Jay Forrester went to MIT to study servomechanisms. He was working within the servomechanism department when he was approached about the Whirlwind project. I wanted to understand the connection between servomechanisms, analog computers and digital computers. This article explained servomechanism nicely and I could understand how those were initially used in flight simulators. There was also a flowchart diagram that I used in my documentary.

"Evolution of Computers 1936-2020." *YouTube*, uploaded by Evo Of, Nov. 2019, www.youtube.com/watch?v=hfjMtKfZmUs. Accessed 28 Feb. 2020.

This is a short video on the evolution of computers. It showed the development of computers visually. I used a clip from this in my documentary to show how computers developed. I reversed the clip to get the effect of going back in history.

Fedorkow, Guy. "The Whirlwind Computer at CHM." *Computer History Museum*, 13 Nov. 2018, computerhistory.org/blog/the-whirlwind-computer-at-chm/. Accessed 18 Oct. 2020.

This article contained a very detailed description of the Whirlwind components and how it worked. There was also a floor plan of the computer and each of its sections which gave me an idea of how much room this computer took inside the Barta Building at MIT. I used some of the pictures and diagrams in my documentary. There was also an interesting section comparing Whirlwind (1951) to Arduino (2018). Of course there are striking differences, however, it is clear that Whirlwind was the forerunner to modern ‘real-time’ interactive computers. The final section of the site clearly outlined the legacy of Whirlwind and its impact on the developments in computer science.

Fine, Morton S. "Engineering Registration and the Law." Oct. 1977. Institute of Electrical and Electronics Engineers, US Air Force Archives, Montgomery, Reel 39797. Typescript.

This article was sent to me by the US Air Force after I wrote for information. The article gave details on the project and the barriers that were broken by Whirlwind. It included the challenges of funding and legal issues. There was also a section outlining the lessons learned from Whirlwind. This was helpful to establish that the barriers broken by Whirlwind were significant to the development of both computer science and national defense.

Fried, Gavi, and Jon Sweitzer-Lamme. "History of Mechanized Thought." *Bit by Bit*, Haverford College, 2012, ds-wordpress.haverford.edu/bitbybit/bit-by-bit-contents/chapter-seven/. Accessed 7 Dec. 2019.

This is a site that was developed for Professor Steven Lindell's c*omputer science class History of Mechanized Thought* at Haverford College. It included nine chapters and the lecture slides for each. I was particularly interested in chapter seven. This chapter covered early flight simulators and Whirlwind as well as the progression to SAGE for national security. There were several pictures that I used in my documentary

Gallager, Robert G., and Sanjoy K. Mitter. *From Servo Loops to Fiber Nets*. MIT, 1990. *MIT*, lids.mit.edu/sites/default/files/servo_loops_to_fiber_nets.pdf. Accessed 16 Jan. 2020.

This is a research paper written to document the fiftieth anniversary of the MIT Laboratory for Information and Decision Systems. It included the research projects that were carried out in the lab, including, Whirlwind. The focus was on the lab's contribution to science and the technology of communication and control. I was interested in the section that outlined the progress from servomechanisms to electronic systems. Whirlwind is what bridged the two concepts.

Garfinkel, Simson, and Rachel H. Grunspan. *The Computer Book: From the Abacus to Artificial Intelligence, 250 Milestones in the History of Computer Science*. New York, Sterling, 2018.

This book covers the landmark inventions in computers. It begins with the abacus and ends with artificial intelligence. Although the descriptions of each machine is brief, there are cross-references to other machines that developed from the machine or were inspired by the machine. This book made it easy to follow the development progression of Whirlwind especially when it was developing at a rapid rate during 1946-1956. It also covered the significance of each machine in society at the time. This book had nice quality pictures that I used in my documentary.

Goodner, Stanley. "The RAM Types That Run Today's Computers." *Lifewire*, 9 Nov. 2019, www.lifewire.com/types-of-ram-4150713. Accessed 17 Dec. 2019.

This is an article that explains the types of RAM used in today's computers. Although they are different than core memory, core memory made their development possible. Digital computers that use "real time" interactions must have random access memory in order to manage information and solve problems quickly. Whirlwind broke this barrier allowing for computer technology to be used in everyday life. I used a picture from this site in my documentary to show how memory has changed from Forrester's core memory to today's RAM memory.

Hicks, Joy. "Benefits of Integrating an Electronic Health Record System." *Very Well Health*, 18 Aug. 2019, www.verywellhealth.com/benefits-of-integrating-electronic-health-records-2317142. Accessed Feb. 2020.

This website contained an article about the benefits of moving from paper medical records to electronic records. Although it mentions the concern for patient confidentiality, it promotes the idea of unlimited access, physicians being able to track issues in "real time". This is an example of "real time" interaction that Forrester made possible with the Whirlwind. I used a picture of a records page in my documentary to show the significance of this development of "real time" interaction from the Whirlwind to today.

IProgrammer, editor. "An Wang - The Man Who Might Have Invented the Personal Computer." *iProgrammer*, 3 Mar. 2016, www.i-programmer.info/history/people/550-an-wang-wang-laboratories.html. Accessed Dec. 2019.

This article is a brief biography of An Wang. Wang was also a computer scientist. Forrester was familiar with his work and studied Wang's array. Wang could not get core memory to work as he focused exclusively on the core itself. Forrester used his information as a reference to develop core memory by using a grid of cores. Afterwards, Wang commented that the idea was brilliant. I used a picture of Wang and his original diagram in my documentary to show where Forrester started with his idea of core memory.

"Jay Forrester." *PBS Online*, 1998, www.pbs.org/wgbh/aso/databank/entries/btforr.html. Accessed 8 Nov. 2019.

This is one of the first articles I read about Jay Forrester. It was very brief and only gave the big concepts of Whirlwind and core memory. It gave me information (names, organizations and dates) to further research. I primarily used this site to get started and to verify that a significant barrier was broken.

"Jay Forrester and Whirlwind." *iProgrammer*, 18 Nov. 2016, www.i-programmer.info/history/people/439-jay-forrester.html?start=1. Accessed 28 Jan. 2020.

This article was divided into two parts. The first part covered the life of Jay Forrester and the development of the Whirlwind computer while the second part focused on core memory. This article was of particular interest because it focused on overcoming the problems encountered during the design and development of both Whirlwind and core memory. There were several of Jay Forrester's drawings and pictures that I used in my documentary. There was also the patent diagram of the Williams Tube that was helpful in understanding how Forrester modified the tube and how it still did not work. Eventually, these failures will lead to core memory.

Kilbane, Doris. "RAM Innovator Took a New Career—and Education—by the Horns." *Electronic Design*, vol. 56, no. 1, Dec. 2008, p. 46. *EBSCOhost*, EBSCOhost, search.ebscohost.com/login.aspx?direct=true&db=brb&AN=501352492&site=ehost-live. Accessed 23 Jan. 2020.

This was a brief article about the contributions of Jay Forrester to the computer industry. It also covers his work after he left the Whirlwind project. The section of the article I was most interested in was how his childhood on a Nebraska ranch influenced his actions and ideas later in life. He believes that young people should get into the real world and do things with their hands. He uses his development of wind power to generate electricity on his boyhood ranch as an example.

Long, F. "An Algorithm of Enemy Aircraft and Missile Threat Zone in Surface Warship Air Defense." *IOP Conference*, 2018. *IOP Science*, iopscience.iop.org/article/10.1088/1757-899X/392/6/062062. Accessed 9 Dec. 2019.

This document discusses the algorithm of the enemy aircraft and missile threat zones when the enemy launches air-to-ship missiles in surface warship air defense. The mathematics considers the position situation of both parties. The paper defines the regional shape of the threat zone. I used the formulas and a diagram in my documentary to show the complexity of the math required. Whirlwind would be able to do the computations quickly and accurately making it the choice for an air defense system. I understood why the Air Force was interested in Whirlwind as a computer for its new SAGE program.

"Magnetic Core Memory." *Today's Engineer*, Aug. 2003, ethw.org/Magnetic-Core_Memoryl. Accessed 22 Nov. 2019.

This article was about how core memory worked. It was helpful in verifying the design of core memory. In addition to the basic information regarding core memory, this article also discussed how core memory developed and affected our modern machines. The line of technology progression detailed, confirmed that the barrier broken by Jay Forrester was significant in the development computer science. Without core memory, the industry had stalled and many did not see a use for computers in daily life. Jay Forrester's contribution to "real-time" interaction is used every day for banking and making reservations. The article also discussed limitations of core memory and the development of integrated circuitry.

"Memory and Storage: Crash Course Computer Science #19." *YouTube*, uploaded by CrashCourse, PBS Digital Studios, 5 July 2017, www.youtube.com/watch?v=TQCr9RV7twk. Accessed 20 Dec. 2019.

This is a video in which memory and storage are explained. It gives the historic background of both and the difference between the two. This clip makes it easy to understand the difference and how they apply to the development of computer science. There was a section in the video on Whirlwind because it was the first to develop fast interactive computer storage and core memory. I used a clip from this video to demonstrate how storage and memory work. This video also gave me some background on the history of the development. In addition, it also showed the progression to modern computers.

MITRE Corporation, editor. "Our History." *MITRE Corporation*, 2020, www.mitre.org/about/our-history. Accessed 23 Feb. 2020.

The MITRE Corporation was founded by those involved with the SAGE project. Many of MIT's Lincoln Laboratory employees were transferred to MITRE. This website provided the history of MITRE, including the development on Whirlwind/SAGE. There were many documents, photos and videos that I used to learn about Whirlwind. MITRE is still in existence today. They primarily focus on issues of national security and safety.

---, editor. "SAGE: Semi-Automatic Ground Environment Story." *MITRE Corporation*, 2020, sage.mitre.org/. Accessed 8 Jan. 2020.

This website is dedicated to the history of the SAGE. It contained background information, links to primary sources and several slideshows. There were also several oral histories from those who worked on SAGE. I used a diagram of the command centers in my documentary to show that SAGE was a nation-wide system.

National Academy of Engineering. 2019. *Memorial Tributes: Volume 22*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25543.

This section of the National Academy of Engineering's Memorial Tributes had a chapter on Jay Forrester. The chapter was a biography of his life, including his significant contributions to computer science. This was a good source for basic information. It listed many other people, equipment and dates to further my research.

Office of Air Force History, compiler. *The United States Air Force and the Culture of Innovation, 1945-1965*. CreateSpace Independent Publishing Platform, 2015.

This book is about the rapid technological growth that followed World War II. The Army Air Forces, later Air Force, was the driving force behind some of this development. Whirlwind is mentioned in the book. Whirlwind/SAGE is the air defense effort that evolved into large-scale, real-time computers. It discusses the reasons the Navy lost interest, the biggest factor being cost. It also discusses how the Air Force pushed to get Whirlwind. After the Soviets detonated an atomic bomb, it became critical for the U.S. to develop an air defense system that required rapid computation and reliability. Whirlwind was the only computer capable of providing this.

Pugh, Emerson W. *Memories That Shaped an Industry: Decisions Leading to IBM System/360*. 3rd ed., Cambridge, MIT Pr., 1986.

This book focuses on IBM. IBM was the company Jay Forrester chose to be the contractor for Whirlwind after its development. The book looks at a 25 year period during which IBM evolved from the position of leading supplier of electromechanical equipment to dominating the field of electronic computers. Jay Forrester was in the book as the developer for core memory. It is because of Forrester's innovation that computers became a commercial reality.

Redmond, Kent C., and T. M. Smith. *Project Whirlwind: The History of a Pioneer Computer*. Bedford - Mass, Digital Press, 1980.

This book details the trials and tribulations Jay Forrester experienced while developing Whirlwind. It outlines the development of Whirlwind from the beginning with Navy backing through its end and transfer from MIT to the private sector. It also covers the period in which the Air Force was funding the project for SAGE. Much of its focus is on the challenges that Jay Forrester confronted regarding government funding. Funding was outside the focus of my research but it was interesting to see how the funding was handled in the 1950s.

Rogoway, Tyler. "The Futuristic Cold War Era SAGE Air Defense Bunkers Looked Right Out of a Kubrick Film." *The Drive*, 14 Mar. 2019, www.thedrive.com/the-war-zone/26959/the-futuristic-cold-war-era-sage-air-defense-bunkers-looked-right-out-of-a-kubrick-film. Accessed Jan. 2020.

This was an interesting article on the SAGE air defense system. The focus of the article was the bunkers that were spread throughout the U.S. The system was tied into master Combat Centers that could direct North America's entire air defense system during a conflict. It also discussed the consoles that included light pens. SAGE had a duplex arrangement that one of the computers was always double checking the primary one and would instantly take over full functionality if the lead computer had any sort of technical difficulties. This tandem access was another barrier broken by Whirlwind. It prevented "down time" critical to national security. There were also pictures that I used in my documentary to show that the computer was continually updated into the 1980s.

"SAGE (Semi-Automatic Ground Environment)." *YouTube*, uploaded by NORADCOC, Apr. 2011, www.youtube.com/watch?v=dF75jHfawtM&t=71s. Accessed 24 Jan. 2020.

This video was a computer generated graphic of how SAGE operated. The Semi-Automatic Ground Environment (SAGE) was an automated control system for tracking and intercepting enemy bomber aircraft used by NORAD from the late 1950s into the 1980s. In later versions, the system could automatically direct aircraft to an interception by sending instructions directly to the aircraft's autopilot.The graphics were clear and mixed with actual photographs which helped me understand how the air defense system worked.

"SAGE: Semi-Automatic Ground Environment Air Defense System." *Lincoln Laboratory Massachusetts Institute of Technology*, MIT, www.ll.mit.edu/about/history/sage-semi-automatic-ground-environment-air-defense-system. Accessed 22 Jan. 2020.

This is MIT's website for the Lincoln Laboratory. There is a section on this site that details SAGE. The information started with background information about why SAGE was needed and how it worked. It also included technological updates and reflections of those involved in the project. There were links to videos in which Jay Forrester gave his account of SAGE. I used this site to further my research. I also used pictures and video from this site in my documentary.

"Smart Technology for a Smart Society." *YouTube*, uploaded by SmartSocietyFP7, 10 Jan. 2017, www.youtube.com/watch?v=AR4MU-P9gvY. Accessed 2 Mar. 2020.

This is a short video that deals with technology in today's society. It covers how technology is driving life today, how it can help improve quality of life, and build a smarter society in the future. I used a clip from this video in my documentary to show that technology is all around us and affects our everyday lives. Jay Forrester is responsible for making this technology commercially viable through his innovations.

Tekwalker, editor. "White Label Booking System." *Tekwalker*, 2018, tekwalker.com/white-lable-booking-sysytem/. Accessed 2 Mar. 2020.

This is a website from Tekwalker. Tekwalker sells software for travel agencies and businesses that need to book online reservations. This is an example of "real time" interaction that Forrester made possible with Whirlwind. I used a picture of their online reservation page in my documentary to show the significance of this development of "real time" interaction from Whirlwind to today.

Vincent. "Visio Stencils for Server HP." *Techbast*, 17 July 2019, techbast.com/2019/07/visio-stencils-for-server-hp-update-2019.html. Accessed 26 Feb. 2020.

This page explained modern HP servers available today. These servers have tandem qualities to eliminate down time. I used a picture of the servers in my documentary to show how computers have evolved from Whirlwind into the “real time” interactive computers we have today.

Waltman, Gene L. *Black Magic and Gremlins: Analog Flight Simulations at NASA's Flight Research Center*. NASA History Division, 2000. Monographs in Aerospace History 20. *NASA*, www.nasa.gov/centers/dryden/pdf/88787main_Black_Magic.pdf. Accessed 28 Jan. 2020.

This is a research paper written by NASA on the history of flight simulators used by NASA. I was interested in this report because it focused on analog flight simulators. Jay Forrester started project Whirlwind by trying to develop an analog computer simulator. He found it was too slow to do the calculations necessary for "real time" interaction. This report covers the time period from 1955-1975. It discusses some of the same issues with speed regarding analog computers.

Warren, James A. *Cold War: The American Crusade against World Communism, 1945-1991*. New York, Lothrop, Lee & Shepard Books, 1996.

This book covered the Cold War from the beginning to the end. Each chapter focused on a particular time period or event. While I reviewed most of the chapters, I was most interested in the chapters covering the beginning of the Cold War. This book was a basic overview but it helped me understand the tensions between the Soviets and the Americans which prompted the necessity of Whirlwind/SAGE for national defense.

Williams, Brad D. "Emerging 'Hyperwar' signals 'AI-Fueled, Machine-Waged' Future of Conflict." *Fifth Domain*, 7 Aug. 2007, www.fifthdomain.com/dod/2017/08/07/emerging-hyperwar-signals-ai-fueled-machine-waged-future-of-conflict/. Accessed 8 Dec. 2019.

This is an article about the future of warfare using artificial intelligence. This discusses the possibility of fighting unmanned wars and the logistics that go along with that. Both the Navy and Marines have conducted studies and simulations, stating this is the next transformative move in offensive and defensive cyber capabilities. I used a picture from this site in my documentary to show the future of technology in national security.

"Working in the Office of the Future." *YouTube*, uploaded by Fw:Thinking, 23 Oct. 2013, www.youtube.com/watch?v=QnUztQc3TTA. Accessed Feb. 2020.

This video dealt with future technology in office spaces. I used a piece of this video that dealt with touch screens and light pens in my documentary to show the progression from screen interaction and light pens developed for the Whirlwind to today's touch screen and light pen technology.

Wurster, Christian. *Computers, an Illustrated History*. Köln, Taschen, 2002.

This book contained a brief history of computers. There were many pictures that I was unable to find in other sources that document the evolution of computers through 2002. The section on Whirlwind was short and brief. However, the source gave an overview of how computers developed. It started with scientific and military computers. Initially, computers were primarily used for military tasks. They were the only ones interested in developing computers, primarily for national security. Whirlwind falls into this category. The book continues to show how breakthroughs in military computers such as SAGE led to the development of computers for business and personal use. It concludes with microcomputers and desktop computers.