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NES in HD: Porting the Nintendo Entertainment System to Modern Displays

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Problem

The Nintendo Entertainment System (NES) is a 8-bit video gaming console developed by Nintendo and released internationally in the early 1980’s. It captured the imagination of an entire generation by pushing the limits of what was possible with the available display technologies. While there remains a large user base for the NES, it relies on outdated RGB video technology through composite and RF connectors that are not supported by the displays currently on the market.

Figure 1. The Nintendo Entertainment System as released in the United States.

This presents a problem to the users of the NES, as they must retain outdated displays in order to continuing playing their original, classic games. Consequently, there exists a need for a system which is compatible with more recent display standards, such as HDMI, that can play the original Nintendo game cartridges.

Objective Statement

There are a number of existing methods to play the original Nintendo games on modern display technology. One popular method is through the use of emulators - pieces of software that use the ROM (read-only memory) from NES games to recreate the system. There are multiple issues associated with this approach.

Figure 2. An example of a Nintendo emulator running on Mac OS.

One primary concern is the legality of the system - these ROM files are easily obtainable online, so people can use them despite whether or not they have paid for them. Next, many families and enthusiasts still have the original Nintendo cartridges, and seek a solution that gets as close to the original gaming experience as possible.

Another issue is the lag involved. Although it may seem small, software interrupts which handle the controller input are not as quick to respond as a pure hardware alternative. This can be frustrating for users of emulators.

In this document, we propose a recreation of the NES, built with a field-programmable gate array (FPGA). We aim to retain all functionality of the original NES, but also to produce an HDMI output signal that will allow the system to be used on modern displays. We would like this system to be in an aesthetically pleasing enclosure to match modern styles. Finally, we hope to acquire experience with large-scale system development, by breathing new life into a device that helped foster our interest in engineering.

Objective Tree

The project will be broken down into three primary components. First and foremost, the functionality of the system is pivotal to its success. Also considered are the enhancements to input and output, as well as the system casing and documentation.

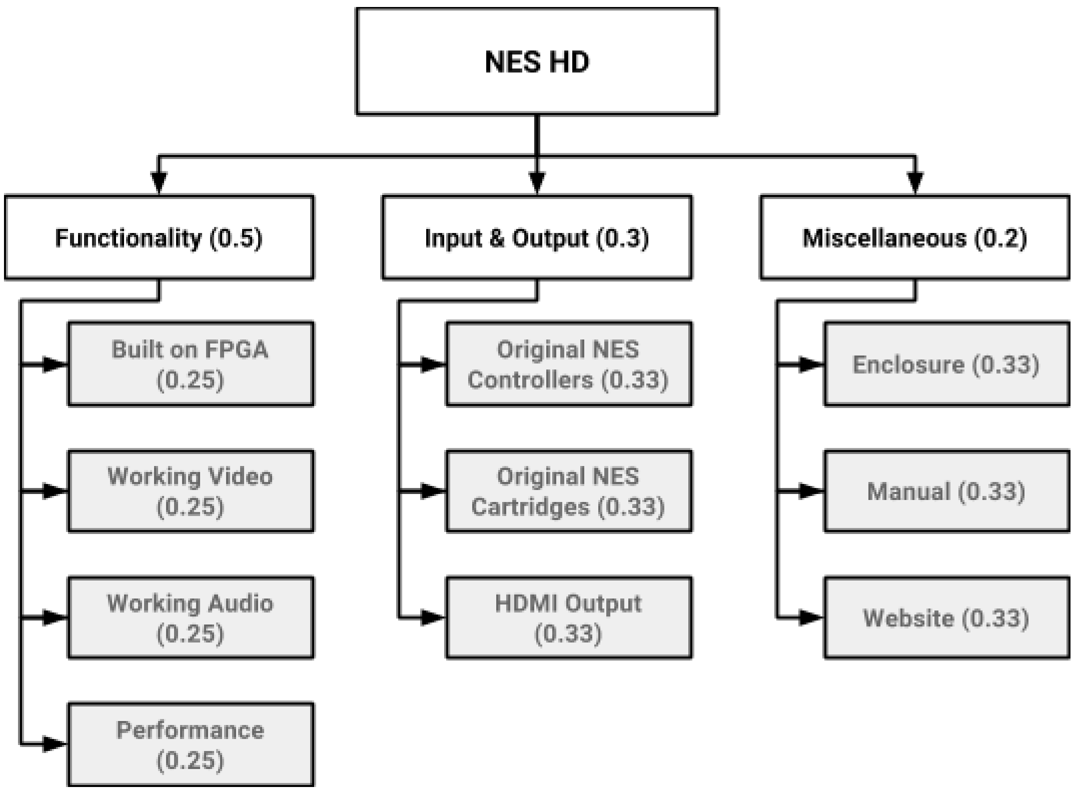

Figure 3. Objective tree representing the goals of the project and their weights.

Background

The issue that currently exists with playing games on a NES is that modern television do not support the video the NES outputs. Also, they are becoming more rare since the console is no longer in production. There still exists a large audience which enjoys the experience of playing their games from original NES cartridges and controllers, just like how many enjoy playing music on a vinyl record [5].

Unfortunately, there are not many options for those of interest. One option is to use video signal conversion hardware to convert the signal to an available input. Another option is to use emulation hardware such as the RetroN® 5. This hardware allows users to place cartridges in it which is read by an Android operating system and run on a software-based emulator.

With both options comes a small amount of lag. This is not something that is tolerable for those interested in a pleasant gaming experience. There are games which require a quick input to perform specific tasks and the lag would be a frustrating experience for the user. As for the emulator, the emulation itself means there is another layer of abstraction between the input from the user and the effect to the game.

Upon inspection of the emulation console, we noticed that it too is utilizing an FPGA on the board; however, we believe the sole purpose of the FPGA is used for reading the cartridges and writing to memory. We would like the FPGA to be a complete hardware substitute for the original system. Developing the system on the FPGA rather than an ASIC would allow the option of updating the system after production [6].

Another option nostalgic gamers have is using the Analogue Nt [1]. The Analogue Nt is a newly designed console out this year. The company is using the original chips from old NES consoles and using them on a newly designed PCB inside of a luxurious enclosure milled from a solid block of 6061 aluminum. This console provides the option of HDMI out while utilizing the original cartridges and controllers. This is exactly what we would like have as a final product. However, the fact that it is using the original chips means that there is a limited supply for the company to continue manufacturing. Secondly, the cost of one of an Analogue Nt starts at $500 and we would not like to have such an expensive product.

The patent Nintendo® had on the NES expired back in 2003, so we will not need to license our product with the company [4].

Marketing Requirements

The team has outlined a variety of different requirements that will need to be met — they are reproduced below. The satisfaction of these requirements will ensure that the final product appeals to as many potential customers as possible.

- The system should be able to use the original Nintendo cartridges.
- The system should be able to use the original Nintendo controllers.
- The system should connect to a display with an HDMI cable.
- The original game audio and video should be working without distortion.
- The system should be reasonably portable.
- The system should not require any additional hardware to work.
- The system should be enclosed in a user-friendly shell.
- The system requires user-friendly documentation, available in print or online.

Constraints

A number of constraints, across varying categories, must be acknowledged before beginning the development of this system. Similar to the marketing requirements, satisfying these constraints will ensure that the resulting system is a success.

Regarding Performance

- The system should be able to perform better than similar products that rely on emulator software (e.g., less lag).
- The system should be usable on modern display technologies through the use of the HDMI interface.

Regarding Functionality

- The system should be able to read and interpret data from the original NES game cartridges.
- The system should be able to read and interpret data from the original NES game controllers.
- The output of the system — an HDMI signal — should include both the audio and video for the Nintendo game, with minimal distortion to the original data.

Regarding Economic Viability

- The system should be as affordable as the original NES.
- The system should be more affordable than other, emulator-based solutions, depending on how it performs in relation to those other solutions.

Regarding Energy Consumption

- The system should be able to operate fully when connected to home outlets, both in the U.S. and abroad.

Regarding Health & Safety

- The system should not leave the electronic components exposed, so as to alleviate the risk of electric shock.

- The system should not have any parts on its exterior that could potentially be removed and consumed by small children.
- The system should never be at risk of overheating or causing any sort of heat-related damage to its environment.

Regarding Legality

- First and foremost, the system should not violate any intellectual property holdings; particularly, those of Nintendo.
- The system should be able to be mass produced and sold within the United States, as well as abroad.
- Any parts of the project that utilize publicly available code (i.e. open source projects) should be appropriately documented.

Regarding Maintainability

- The system should be enclosed in a user-friendly case that allows for efficient transportation and storage.
- The system should be able to be reset in the event that one or more components causes the system as a whole to fail.

Regarding Operation

- The system should be compatible with any hardware — game cartridges, controllers, and so on — that is compatible with the original NES.
- The system should function in a logically similar fashion to the NES.
- Ports and buttons should be properly identified.

Regarding Reliability

- The system should be able to function properly over a long period of time.
- Documentation should be made available (in print and on the web) that helps users ensure the long-term reliability of the system.
- The developers of the system should make their contact information available, in the event that the system is not behaving as expected.

Regarding Availability

- The system should be able to be mass produced and distributed within the United States as well as abroad.
- The documentation for the system and its development process should be available for those who are interested in learning more about digital electronics.
- The system should be available for users (and potential customers) to test in a hands-on fashion.

Regarding Social & Cultural Aspects

- The system should strive to recreate the original NES experience as accurately as possible.
- The system should be able to take the original experience and bring it to modern display technologies, in an effort to catch the attention of the next generation of gamers.
- Hypothetically, if made available internationally, the system should be able to provided tailored documentation and resources for different languages.

Functional Block Diagram

The functionality of the proposed system is abstracted to two different levels; the simplistic user interaction model, and the component behavior model, as shown below.

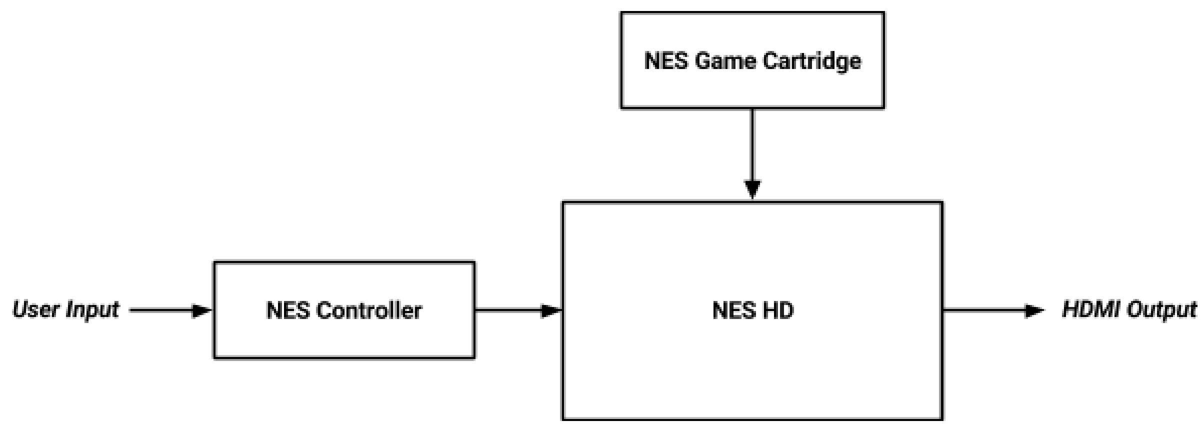

Figure 4. Functional block diagram representing the user interaction with the system.

Tables describing the functionality of the specific components are shown below.

Table 1. Functionality of the NES HD Component

Module	NES HD
Inputs	- User input, received from NES controller - Game data (ROM), read from NES cartridge
Outputs	- HDMI signal
Functionality	- Recreate the NES gaming experience by reading in game cartridge and controller input. Synchronizes audio and video components of the HDMI output signal.

Table 2. Functionality of the NES Game Cartridge Component

Module	NES Game Cartridge
Inputs	- No inputs.

Outputs	- Read-only-memory (ROM) of the associated NES game.
Functionality	- The data on this cartridge is read by the NES HD and used to create the audio and videos for the game.

Table 3. Functionality of the NES Controller Component

Module	**NES Controller**
Inputs	- User input, received from various different buttons
Outputs	- Signal corresponding to player actions in a given game.
Functionality	- The controller is the primary means of interfacing with a NES game. The user presses buttons on this controller, which in turn modified the signal sent to the NES HD.

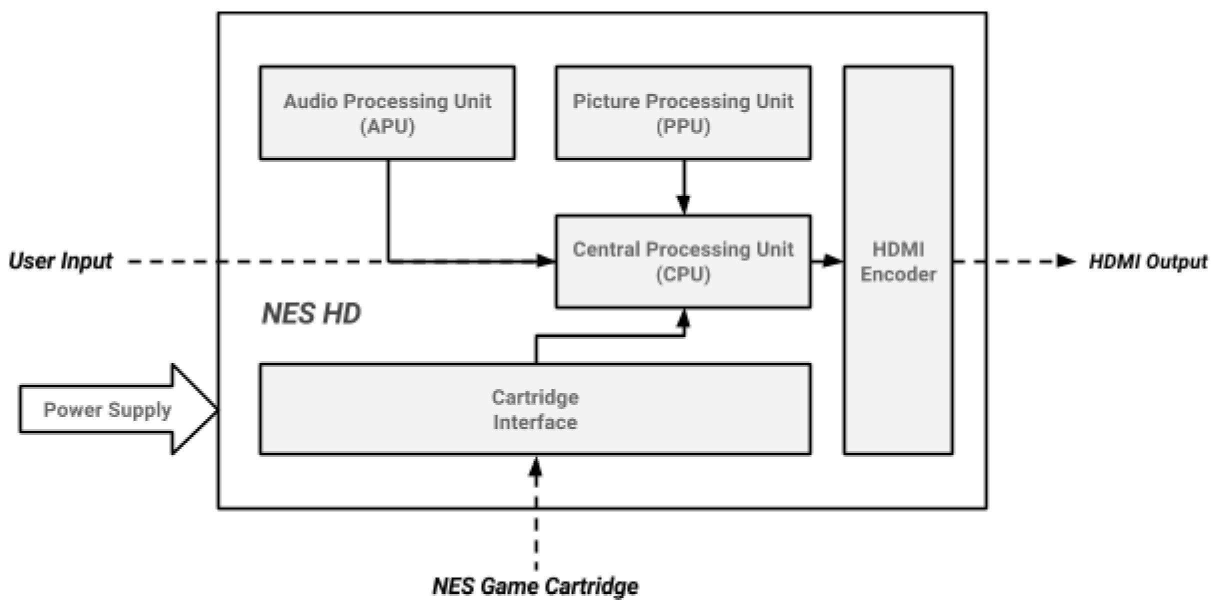

Figure 5. Functional block diagram representing the various components inside the system.

Table 4. Functionality of the Cartridge Interface Component

Module	**Cartridge Interface**
Inputs	- The read-only memory (ROM) from the inserted NES cartridge.
Outputs	- Writable game data; including audio and video information.

Functionality	- This component facilitates the processing of the game cartridge.

Table 5. Functionality of the Audio Processing Unit (APU)

Module	APU
Inputs	- Game data, originally read from the NES cartridge.
Outputs	- Audio signals that correspond to events and sequences in the game.
Functionality	- This component handles the creation of the audio signals.

Table 6. Functionality of the Picture Processing Unit (PPU)

Module	PPU
Inputs	- Game data, originally read from the NES cartridge.
Outputs	- Image signals that correspond to events and sequences in the game.
Functionality	- This component handles the creation of the images that are displayed on the screen.

Table 7. Functionality of the Central Processing Unit (CPU)

Module	CPU
Inputs	- Inputs from the cartridge interface, audio processing unit, and video processing unit.
Outputs	- Control signals that inform other components of the game's status. - A combined audio/video signal that needs to be converted to HDMI.
Functionality	- This component is tasked with synchronizing audio and picture events from the game cartridge with the user input that manipulates it.

Table 8. Functionality of the HDMI Encoder

Module	HDMI Encoder
Inputs	- Combined audio/video signal from the central processing unit.
Outputs	- HDMI signal that corresponds to the audio and video of the game, as generated as a result of user input.
Functionality	- This component generates everything we see on the display.

Alternative Solutions

There are a number of existing methods to play original NES games on modern displays. The team believes that original NES hardware implementation on a FPGA will yield the most success. This section will continue by elaborating on a few of the most popular alternatives, and why they do not stack up to the FPGA implementation.

Original NES with Video Conversion

One convenient way to use the NES on modern displays is by attaching an adapter to the output, converting the signal appropriately. While this can be a relatively cheap solution, the performance will suffer significantly. This alternative is only reasonable if a decent amount of money is put into a high-quality converter. Additionally, this method relies on the original NES hardware, which will be old and sluggish, affecting performance in its own right.

Modified NES

Another popular method involves the modification of the NES hardware in some way. As described earlier, the Analogue NT utilizes the original NES chips (obtained from previously-manufactured systems), placing them on a custom printed circuit board [1]. The absurd price aside, the Analogue NT suffers from the same issue that plagues the video-converted NES systems — it relies on old chips. Not only do these chips come burdened with age; they are also available in a harshly limited quantity. This is likely the cause of the $500+ price of this alternative, which is unacceptable, in our opinion.

Emulated NES

There are a number of different solutions that involve emulation in one way or another. The emulation can either be based in software or hardware. Software emulation involves users running a program on their PC which simulates the NES. This tends to inhibit the traditional console gaming experience, and is also legally questionable (as the ROM's used have typically been downloaded illegally from the Internet). Hardware emulation is favored because of its similarities to the traditional NES experience. At that point, the team must decide whether to use an FPGA or an ASIC. An ASIC would likely be more efficient, but would prevent the team from continually developing new features, bug fixes, and other improvements [2]. An FPGA would make the opposite trade-off [3].

Decision Matrix

One helpful way to visualize the different possible solutions is to present them using a decision matrix. Using the alternatives above, along with the objective tree described in Section 3, the team prepared a decision matrix to determine which solution was most viable and likely to succeed. This decision matrix is reproduced below.

Table 9. Decision Matrix for NES Implementation

Criteria	Weight Factor	Modified NES HD Output		Software Emulator		Hardware Emulator FPGA		Hardware Emulator ASIC	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score
Cost	25	0.2	5	1.0	25	0.7	17.5	1.0	25
Power	5	1.0	5	0.5	2.5	1.0	5	1.0	5
Performance	40	1.0	40	0.5	20	0.8	32	0.9	36
Testability	30	0.8	24	1.0	30	1.0	30	0.3	9
Total	100		74		77.5		**84.5**		75

Test Plan

Testing this system will be a critical aspect of the design process. The primary requirements for the test plan can be extracted from the objective tree. While this will be a heavily-iterative process, some initial considerations have been listed below.

Functionality

- Does the system accurately reproduce the video from the game ROM?
    - Is the image displayed correctly on displays of differing resolutions?
    - Video issues can be tested by simplifying the images that are displayed. We will test with simple black/white patterns, colors, letters, and so on.
- Does the system accurately reproduce the audio from the game ROM?
    - Are there any audio issues that arise when using different types of displays (televisions versus desktop monitors and so on).
    - Audio issues can be tested in a manner similar to video — testing with individual sounds, then small sets, and ultimately entire audio files.
- Does the system perform well, compared to other alternatives?
    - This could be tested by running our system alongside another alternative. They could load the same game, and differences in timing and lag can be recorded.

Input & Output

- Is the system compatible with the original NES game cartridges?
    - Previous projects lead our team to believe that the performance will vary from game to game. However, this can be studied by testing the system with a large set of different NES cartridges.

- Is the system compatible with the original NES controllers?
  - This should be less of an issue than the cartridge compatibility, however, they will be tested in the same manner. A large set of controllers can be tested to ensure that inputs are appropriately read and acted on.
- Does the system produce a proper HDMI output?
  - This will be very simple to test, as none of the previous elements will be observable unless the system is sending an HDMI output to the displays we test with. This success of this test is critical, because without verifying that the HDMI signal is being created properly, issues with other components cannot be isolated (and consequently addressed).

Miscellaneous

- Is the system enclosure durable enough to protect its interior components?
  - This will be a simple aspect of the testing process. We plan to check a number of different materials for their weight and durability. The most effective solution will be used to design the case of our system.
- Is the documentation (print and web) understandable and helpful?
  - This can be tested by making the documentation available to testers. It is possible that we could test the effectiveness of this documentation by conducting focus groups. However, the functionality of the system itself is our top priority.

Cost Analysis

For development purposes, the team will require a wide variety of supplies. Most of these items are already available through Ohio Northern University, so our actual budgetary requirements are not accurately reflected in this analysis. Also note that this analysis reflects the development of a single unit, which will serve as a prototype. Costs for production are expected to be significantly smaller.

Table 10. NES Implementation Cost Analysis

Component	Quantity	Cost (per item)	Cost (all items)
FPGA	1	$300 (approx.)	$300
NES Controllers*	2	$10	$20
NES Game Cartridges*	5	$5	$25
Displays*	2	$100	$100
Enclosure Materials	N/A (Will vary)	$100	$100
Miscellaneous Components	N/A (Will vary)	$50	$50
Total			**$595**

** Indicates a component that should be readily available (not requiring additional purchase).*

Project Schedule

Due to the time limitations associated with the university's academic schedule, proper planning for each component of the project is crucial to the team's success. A Gantt chart has been created to help visualize the project timeline, and is included as ***Appendix A***.

Conclusion

The Nintendo Entertainment System completely revolutionized the way that people look at technology. In a world where computers and other electronics were imposingly complex and impersonal, this gaming system showed that these systems could provide entertainment to families everywhere. It inspired an entire generation of tinkerers, engineers, and electronics hobbyists, and has certainly earned its place in history.

The NES already stands prominently in a number of museums. However, its influence over our culture cannot be seen behind a panel of glass — it has to be explored hands-on by playing its games. Our team believes that it is critical to continue making the NES available to the public, so that the next generation can learn from and enjoy it.

There are a number of different ways to play the original NES games today, due to the various efforts of our generation. However, the most popular options available today fail to capture the true NES experience — sitting around a television with family and/or friends. Enjoying games *together*. Northern Digital believes that it has a plan to bring a unique product to the table; one which will most accurately recreate that experience. Not only that, but we intend to make it *affordable* as well. With that in mind, it will most certainly be a success if brought to market.

References

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3. Ludde's FPGA NES. Retrieved September 30, 2015, from http://fpganes.blogspot.com/2013/01/luddes-fpga-nes.html

4. Nintendo Entertainment System Expired Patents Do Not Mean Expired Protection. Retrieved September 30, 2015, from http://www.gamasutra.com/view/feature/130867/nintendo_ entertainment_system__.php

5. The Psychology of Video Game Nostalgia. (2013, June). Retrieved September 30, 2015, from http://www.psychologyofgames.com/2013/11/the-psychology-of-video-game- nostalgia

6. Sieber, Jonathan. Implementing The Nintendo Entertainment System On A FPGA. 1st ed. 2013. Web. 28 Sept. 2015.

Appendices

Appendix A — Project Gantt Chart

Task Name	Duration	Start	Finish	Predecessors	Resource Names
Problem Identification	5 days	Mon 8/24/15	Fri 8/28/15		
Research Phase	5 days	Mon 8/31/15	Fri 9/4/15	1	
Set up weekly meeting schedule	0 days	Wed 9/2/15	Wed 9/2/15		
Requirements Specification	5 days	Mon 9/7/15	Fri 9/11/15	2	
Contribution Criteria	0 days	Wed 9/9/15	Wed 9/9/15		
Concept Generation	5 days	Mon 9/14/15	Fri 9/18/15	4	
Problem Identification	0 days	Wed 9/16/15	Wed 9/16/15		
Design Phase	35 days	Mon 9/21/15	Fri 11/6/15	6	
Peer-Peer Evaluation	0 days	Wed 9/23/15	Wed 9/23/15		
Formal Written Proposal	0 days	Wed 9/30/15	Wed 9/30/15		
Proposal Oral Presentation	0 days	Wed 10/7/15	Wed 10/7/15		
Peer-Peer Evaluation	0 days	Wed 10/21/15	Wed 10/21/15		
Prototyping and Construction Phase	75 days	Mon 11/9/15	Fri 2/19/16	8	
Start Ordering Parts	0 days	Wed 11/11/15	Wed 11/11/15		
Progress Written Report	0 days	Wed 11/11/15	Wed 11/11/15		
Oral Presentation 2	0 days	Wed 11/18/15	Wed 11/18/15		
Ethics Assignment	0 days	Wed 12/2/15	Wed 12/2/15		
Prepared Abstract for conference	0 days	Wed 12/9/15	Wed 12/9/15		
Peer-Peer Evaluation	0 days	Wed 12/9/15	Wed 12/9/15		
System Integration	30 days	Mon 2/22/16	Fri 4/1/16	13	
Test Phase	20 days	Mon 4/4/16	Fri 4/29/16	20	
Delivery and Acceptance	5 days	Mon 5/2/16	Fri 5/6/16	21	