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A Letter from the Provost of the University of Alabama in Huntsville

One of the greatest opportunities The University of Alabama in Huntsville offers is the chance for students from any major to participate in collaborative research and creative projects with faculty and research staff during their undergraduate academic careers. In 2015, undergraduate students and supporting faculty and staff established *Perpetua,* a student-run journal focused on undergraduate research. The purpose of *Perpetua* is to provide a peer-reviewed forum for UAH undergraduate students to publish their research findings. *Perpetua,* which is published online, gives our undergraduate research exposure to a wide audience and recognizes the scholarly and creative contributions of our students. *Perpetua* has the potential to become the standard bearer of undergraduate research at UAH.

Undergraduate research and creative activities provide students and their faculty mentors with mutually beneficial opportunities. Students learn how to engage in the discovery process by performing research and/or developing a creative project. Students learn how to ask the right questions, collect and interpret data, develop creative ideas, discover novel solutions, experiment with different art forms, use the language appropriate to their future professions, report findings, and produce creative works while faculty and research scientists mentor the students through the process. Through *Perpetua*, students learn how to disseminate the knowledge gained through the discovery and creative process and learn the rigors of the peer-review process that pushes the research and creative work to excellence.

Perpetua connects the entire university through undergraduate research, showing the breadth, depth and diversity of research and creative projects in which our undergraduate students, faculty and research staff are engaged. UAH is widely recognized as a major research university attended by some of the best and brightest students in our nation. This inaugural issue of *Perpetua* presents articles written by these undergraduates who are passionate about research and creative achievement in their respective fields.

Christine Curtis
Office of the Provost
University of Alabama in Huntsville

Special Thanks

This journal would not have been published without the involvement of the University of Alabama in Huntsville and several advocates and benefactors. Their contributions supported the journals founding, along with the production and publication processes.

Perpetua would like to thank our university's provost, Dr. Christine Curtis, for providing the journal with a foundation to be published upon. We would also like to thank UAH Student Government Association for their gracious letter, and recognition of our journal. We certainly thank our reviewers, both peer and faculty, for their hard work of ensuring that our manuscripts are built of quality research. We thank our faculty advisors for their careful instruction on the building of an academic journal. A special thanks to Michael Mercier for photographing our faculty and staff. We are grateful for the involvement of the Department of Chemical and Material Engineering, especially for providing our faculty and staff with a conference room. And lastly, we thank the university's undergraduate research department for their sponsoring of our journal.

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Abnormal social behavior in mice with tyrosinemia type I is associated with hypermyelination of the cerebral cortex

Marissa E. Moore
Department of Biological Sciences

Abstract **-** Tyrosinemia type I (TT1) is a rare metabolic disorder that results in mutations of the enzyme FAH, which is responsible for tyrosine breakdown. Without the current treatment of 2-(2-nitro-4-trifluoromethylbenzoyl) cyclohexane-1-3-dione (NTBC), toxic metabolites build up causing severe kidney and liver dysfunction that can lead to mortality. Cognitive and social defects have recently been observed in affected individuals on NTBC, and to investigate these effects mice with tyrosinemia type I were tested utilizing the Crawley three-chambered sociability test. Social behavior is analyzed in the three chambered apparatus by observing mice interaction with either a real or dummy mouse, or between a familiar or novel mouse. The results show that mice with tyrosinemia type I spend twice as much time investigating a dummy mouse compared to a real mouse, indicating sociability deficits. Due to the importance of olfaction in mouse behavior, the olfactory abilities of the mice were also analyzed by means of the buried food test. In order to assess a biological basis for these social and cognitive impairments, mice brains were stained using Luxol fast blue to visualize myelin in the cerebral cortex. Microscopic analysis of the stained cerebral cortex showed hypermyelination in mice with tyrosinemia type I in comparison to controls. The cognitive and sociability issues observed in tyrosinemia type I mice could be attributed to malformed neuronal pathways and synapses caused by hypermyelination of the cerebral cortex.

I. Introduction

The autosomal recessive disorder tyrosinemia type I results in a deficiency of fumarlyacetoacetate hydrolase (FAH, EC 3.7.1.2), the last enzyme in the pathway of tyrosine metabolism (Fig. 1). This lack of functional FAH leads to accumulation of deleterious metabolites that can cause liver failure and fatality. Treatment with NTBC (Nitisinone) blocks the enzyme 4-hydroxyphenylpyruvate dioxygenase (HPPD, EC 1.13.11.27) upstream in the tyrosine degradation pathway, which prevents the buildup of harmful metabolites such as malylacetoacetate and fumarylacetoacetate. These metabolites can accrue to be converted to succinlyacetone, which is a diagnostic marker for tyrosinemia type I due to its production exclusively in the absence of FAH (De Jesus et. al 2014). This metabolite is identified in newborns by using tandem mass spectrometry and has detrimental effects on heme synthesis as well as neurological function. The high mortality rates in children with tyrosinemia type I before the introduction of NTBC can be attributed to these metabolites causing hepatocellular carcinoma and liver damage. The treatment with NTBC results in an alteration of the enzymatic mutation, leading to increased tyrosine concentrations and hypertyrosinemia (Bendadi et. al 2014). Although this treatment has drastically increased the survival rate in affected individuals, the exact role NTBC plays in cognitive function has yet to be elucidated.

There have been recent reports of social behavior and cognitive issues in individuals with tyrosinemia type I on long-term NTBC treatment. Lowered IQ as well as social cognition and working memory deficits have been observed in patients with TT1 compared to healthy controls (van Ginkel et. al 2016). The high mortality rate in children with tyrosinemia type I before introduction of the drug NTBC explains why any long-term cognitive effects from the disorder were not able to be examined. The treatment options for children with the disorder before NTBC included liver transplant and dietary modification of tyrosine and phenylalanine. Whether the cause of these neurological and social issues in patients with tyrosinemia type I is due to the treatment or is an effect of the disease remained undetermined. Sociability and cognition of tyrosinemia type I (FAH^{mut}) mice was investigated and compared to wildtype mice treated with NTBC (WT-NTBC) and wildtype mice drinking water (WT-water) in order to discern the cause of these issues. It has been shown that mice

with tyrosinemia type I are unable to respond effectively to change, take longer to learn and make more errors compared to WT-NTBC and WT-water mice in the Barnes maze (Hillgartner et. al 2016). This suggests that the social and cognitive problems can be attributed to the disease process and not to the treatment with NTBC. In order to further study these effects social interaction was evaluated in mice with TT1 in Crawley's three-chambered sociability test.

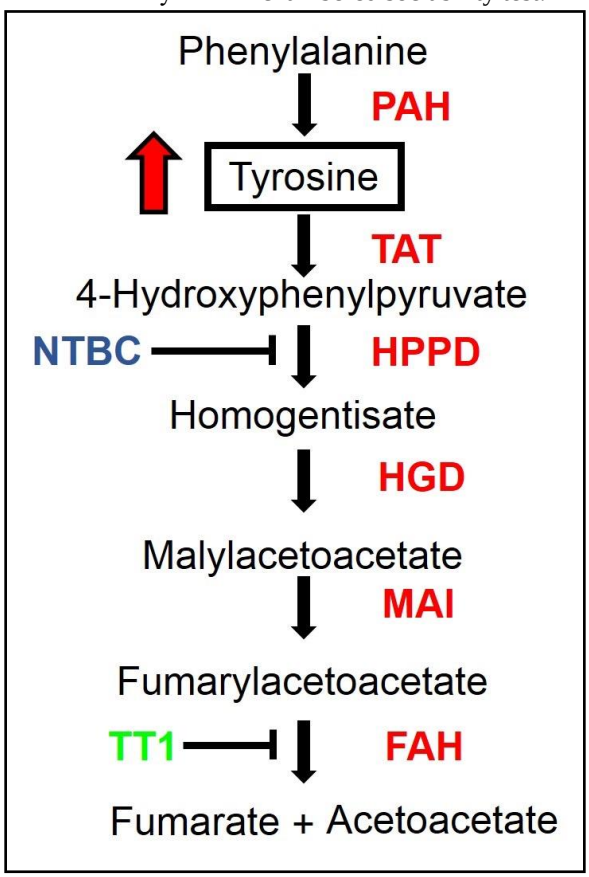

Figure 1. The tyrosine catabolism pathway. Tyrosine can be ingested from food, or synthesized by the hydroxylation of phenylalanine by phenylalanine hydroxylase (PAH). The first step in the breakdown of tyrosine is conversion to 4-hydroxyphenylpyruvate by tyrosine aminotransferase (TAT). The second step is conversion into homogentisate, by 4-hydroxyphenylpyruvate dioxygenase (HPPD) and this is the step that is inhibited by the pharmaceutical 2-[2-nitro-4-trifluoromethylbenzoyl) cyclohexane-1,3-dione (NTBC). Homogentisate is oxidized to malylacetoacetate by homogentisate dioxygenase (HGD) and isomerized by maleylacetoacetate isomerase (MAI) to form fumarylacetoacetate. The final step of tyrosine metabolism involves the breakdown of fumarylacetoacetate into fumarate and acetoacetate, and is catalyzed by fumarylacetoacetate (FAH). This is the enzyme mutated in tyrosinemia type I. In the case of tyrosinemia type I (TTI) where the enzyme FAH is compromised, toxic metabolites will accumulate and be converted to the metabolite succinylacetone which has deleterious effects on the liver, kidneys and the central and peripheral nervous system.

Sociability is examined by comparing the amount of time the mouse spends between a real mouse and a dummy (stuffed toy) mouse as well as between a familiar and novel mouse. This three-chambered apparatus is so widely used to study mouse social behavior because it provides an accurate method to analyze sociability and novel-seeking differences between various mouse strains (Pearson et. al 2010). *Mus musculus* is known for investigation of novel conspecifics as well as elevated engagement in social behaviors (Yang et. al 2011). It is therefore expected that mice with normal sociability will favor spending time with an actual mouse instead of a dummy, or no mouse, and that they will also tend to investigate a novel mouse more than a familiar mouse. Mice engage in numerous reciprocal social interactions; wherein olfactory abilities are critical for successful behavior (Moy et. al 2004). In order to ensure that the olfactory abilities of the mice were not affecting sociability, the mice were assessed with the buried food test. Mice olfaction is analyzed by how much time is taken to find a piece of palatable food buried in cage bedding. Increased latency to find the piece of food indicates gross impairments in olfaction and consequentially in social behavior. Owing to the importance of olfaction for normal mouse behavior, olfactory abilities of mice with tyrosinemia type I were analyzed to rule it out and focus on the disease process or NTBC as the cause of these neurological issues.

To examine the neurological source for these intellectual and social problems, myelin from the cerebral cortex of mice was stained using Luxol fast blue for microscopic visualization. The cerebral cortex is responsible for many aspects of brain function such as learning, attention and memory. Oligodendrocytes are responsible for myelination within the central nervous system, while Schwann cells produce myelin for the peripheral nervous system. Myelin is a fatty substance made of lipids and proteins that works to insulate neurons to help propagate action potentials and increase neuronal activity. It stems as an outgrowth of glial cells and acts to increase electrical resistance and decrease capacitance across

the membrane (Jahn et. al 2009). Signals are propagated in the central nervous system through salutatory conduction from one node of Ranvier to another, resulting in rapid depolarization of the membrane. This efficiency is due to multiple layers of myelin surrounding the nerve cells, acting as an insulator to maintain quick and accurate electrical impulses. Any defect in myelination can result in altered synapses as well as impaired neuronal pathways that subsequently alter cognition and behavior. Myelin was therefore assessed in mice with tyrosinemia type I to investigate any morphological differences that could explain this impaired cognition seen in TT1 mice.

II. Materials and Methods

Tyrosinemia type I mice

All mice were housed with 2-5 mice in each cage with corn cob bedding (Harlan), given water ad libitum and fed with mouse chow (Teklad Global 18 % Protein Rodent Diet with 0.1 % phenylalanine and 0.6 % tyrosine). All cages were supplied with cotton for nesting as well as wheels for lifestyle enrichment. All mice care and experimental protocols were approved by the UAH IACUC committee.

Social Behavior

The Crawley three-chambered sociability test utilizes the natural tendency of mice to investigate novel conspecifics as well as engage in high levels of sociability in order to compare different mouse strains. The testing apparatus is separated into three chambers, with a central chamber in which the mouse is habituated to before testing sociability. The mouse is placed into the apparatus after a dummy (stuffed toy) mouse and a stranger mouse familiarized with the cage are placed into small wire cages in either the left or right chamber. The doors blocking the entry into the side chambers were taken off, and the number of entries as well as time spent within each chamber was recorded for 10 minutes. Screen dividers were placed around the apparatus to ensure that the mice were not affected by the experimenters and the chambers were cleaned in between each trial. The side of the real and toy mouse as well as the side of the familiar and novel mouse was alternated for each trial. The mice were also tested for novel preference by habituating the mouse to the central chamber for 5 minutes followed by placing an unfamiliar mouse into one of the wire cages in either of the side chambers. The mouse is allowed to explore for 10 minutes and a novel (unfamiliar) mouse is then placed into the other wire cage. Time spent in and entries into each chamber for 10 minutes is measured in order to compare the novelty-seeking behavior of the mice (Moy et al. 2004).

Olfactory test

To analyze olfactory abilities in the mice the buried food test was conducted using Teddy Graham's as the palatable food to be buried in the cage bedding. A couple of days before the experiment, a teddy graham was placed into the mice cages and consumption was monitored to ensure its palatability to the mice. All food was taken away from the mice the night before testing. The test evaluates impairments in olfaction by observing how long it takes in a 15-minute trial for overnight-fasted mice to find the buried food. Mice who have been fasted overnight with normal olfactory abilities should therefore be able to find the buried food relatively quickly (Yang et. al 2009). The cage was filled with 3cm of corn cob (Harlan) bedding and the mice were allowed to explore the cage for 5 minutes. A separate cage was used for each trial and medical dividers were placed around the cage to eliminate any outside effects. After acclimating to the cage, the mouse was taken out while a teddy graham was buried and was then returned to the cage for 15 minutes to search for it. The latency to find the teddy graham was measured as well as if the cookie was consumed.

Mouse brain histochemistry

In order to examine the myelin in the cerebral cortex of the mice, brains were extracted and fixed with 10 percent formalin. The brain was placed into a brain block in order to section it for analyzation of the cerebral cortex. The tissue was then sequentially dehydrated, cleared, paraffin embedded and sectioned onto microscopic slides for staining to visualize the myelin. A microtome was used to slice the tissue into 20-micrometer sections for staining. The cerebral cortex was stained with Luxol fast blue and counterstained with cresyl violet, with the myelin staining blue and the cell nucleus staining purple. The cresyl violet acts to clearly distinguish the myelin sheath that is stained blue from the purple Nissl-stained cells (Kluver and Barrera, 1953).

III. Results

Mice were tested for social behavior in a three-chambered Crawley sociability test and the time the three populations of mice spent interacting in the zones with the real mouse and dummy mouse were measured (Fig. 2). WT-water mice spent equal amounts of time in the zone containing the mouse 222 ± 16.67 s (n = 8), as in the zone with the dummy mouse, 201.1 ± 20.07 s (n = 8, ns, $P = 0.4356$). The mice drinking NTBC behaved similarly also not discriminating between the real mouse and the dummy mouse, spending 250.7 ± 35.51 s, (n = 9) with the real mouse and 186.7 ± 22.46 s (n = 9) with the dummy mouse (ns, $P = 0.1468$). However, the mouse with tyrosinemia type 1 (FAH^{mut}) spend about twice as much time with the dummy mouse than the real mouse, spending 283.1 ± 24.75 s (n = 10) in the zone with the dummy mouse and only 148.1 ± 23.25 s (n = 10, $P = 0.0009$), in the zone with the real mouse (Fig. 2A). An example of the exact path an FAH^{mut} mouse took in the 10 minutes long experiment is shown in Figure 2C. The dummy mouse was then replaced with a novel mouse, and a test of social novelty performed. The WT-water mouse showed a preference for the novel mouse and spent 223.4 ± 16.58 s, (n = 7) in the zone with the novel mouse but only 157 ± 16.34 s (n = 7) with the familiar mouse ($P = 0.0147$). The WT-NTBC mouse showed similar behavior, spending about a minute and a half more time interacting with the novel mouse than the familiar mouse (259 ± 20.58 s, n = 9 vs 153.7 ± 19.34 s, n = 9, $P = 0.0018$). However, the mice with tyrosinemia type I (FAH^{mut}), did not discriminate between the two mice and spent similar time in the chambers housing the novel mouse (204 ± 12.51 s (n = 10) and the familiar mouse (195.3 ± 19.55 s, n = 10, $P = 0.7126$). An example of a WT-NTBC mouse in the social novelty test is shown in Figure 2D.

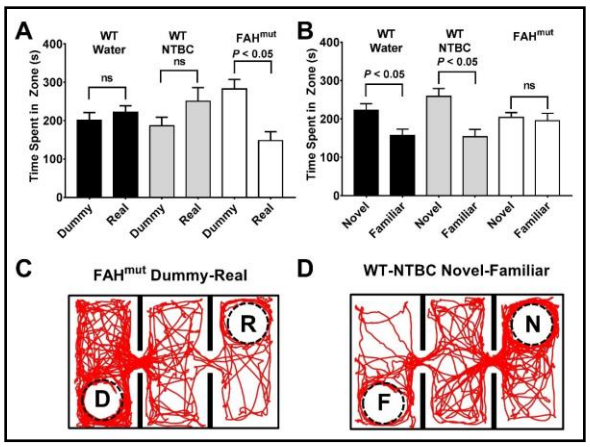

Figure 2. Mice with tyrosinemia type I show abnormal social behavior. A. Time spent in zone containing the dummy mouse or the real mouse. B. Time spent in zone containing the novel mouse or the familiar mouse. C. Example of mouse trail in the social experiment. The letter D represents the dummy mouse and R represents the real mouse. D. Example of mouse trail in the social novelty experiment. The letter F represents the familiar mouse and N represents the Novel mouse.

Mice were tested in a simple experimental test of their olfactory skills by timing how long it took them to find a buried Teddy Graham biscuit (Fig. 3). There was no difference in the abilities of the three groups of mice to find the Teddy Graham, $F(2, 16) = 0.3127$, $P = 0.7359$, with WT-water taking 24.4 ± 11.74 s (n = 5), WT-NTBC taking 36.77 ± 10.79 s (n = 6) and FAH^{mut} taking a total of 33.19 ± 9.367 s (n = 8).

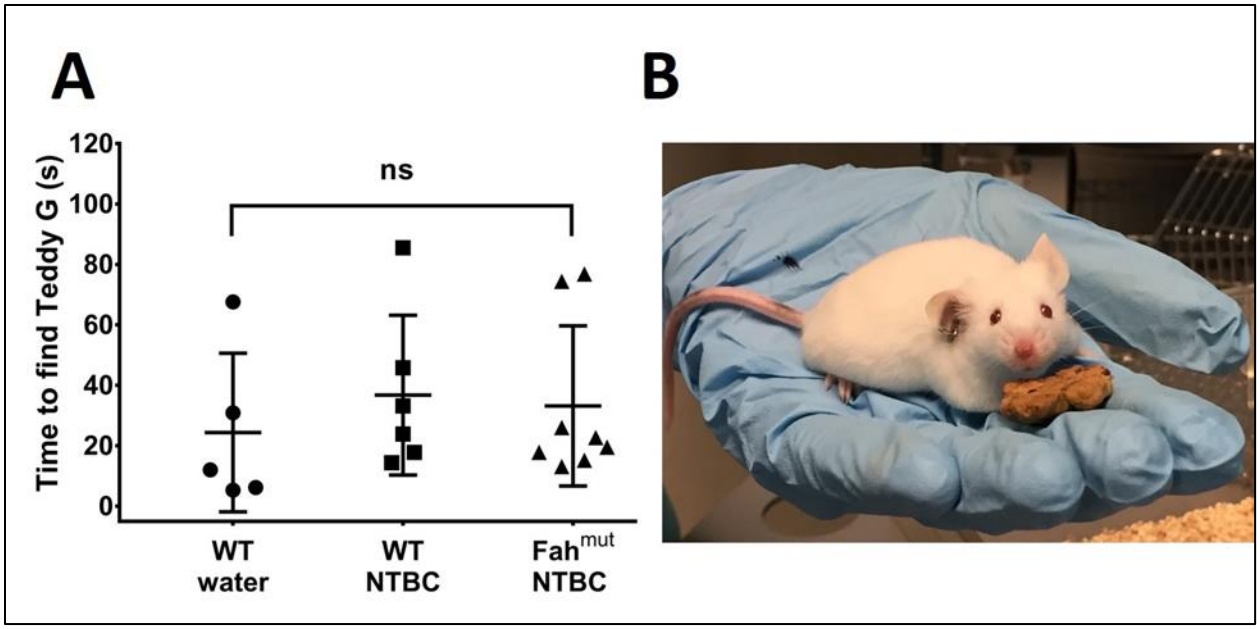

Figure 3. Mice with tyrosinemia type I are efficient in finding a Teddy Graham. A. There was no difference between the three groups of mice in finding a Teddy Graham buried in their cage. B. A picture of a mouse and a Teddy Graham.

To investigate any alterations in brain myelin, we isolated fixed and stained mouse brains from WT-water, WT-NTBC and FAH^{mut} mice. Brains were stained with the specific myelin dye Luxol fast blue and counterstained with cresyl violet. Brain slices from FAH^{mut} mice showed increased myelination (Fig. 4, Left Panel) as indicated by deep blue staining. Brains from the treatment control group of NTBC-WT mice showed less intense staining (Fig 4, Right Panel). Upon magnification of the cerebral cortex up to 10x, a diffuse hypermyelination was seen in the FAH^{mut} mice (Fig. 4, Bottom Panels).

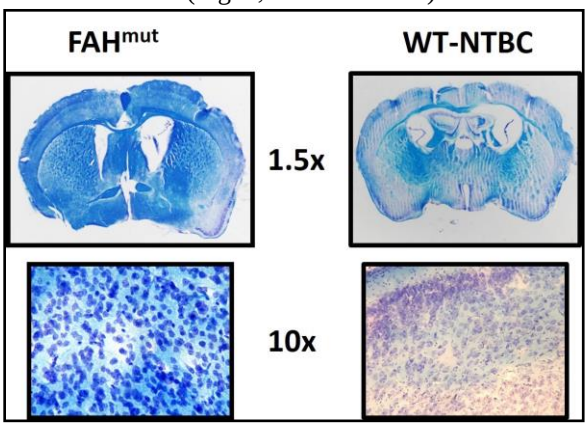

Figure 4. Mice with tyrosinemia type 1 show hypermyelination of the cerebral cortex. Left Panel. Here we show a brain slice from a FAH^{mut} mouse where myelin is stained blue. Right Panel. A brain slice from a WT-NTBC mouse shows much lighter staining for myelin. The cell nuclei are stained purple in both panels but are more visible in the WT-NTBC mouse.

IV. Discussion

The exact cause of the intellectual and social impairments recently reported in individuals with tyrosinemia type I has yet to be illuminated. The findings of altered sociability and hypermyelination in mice with tyrosinemia type I indicate possible neuronal pathways for impaired cognitive function and sociability (Fig 5.). Whether the cause of these social and cognitive problems was from the disease process or from treatment with NTBC remained unknown. Although it has been shown that NTBC increases the amount of blood tyrosine levels and transport to the brain, wildtype mice on NTBC show no altered learning or behavior. Tyrosinemia type I mice display hypermyelination of the cerebral cortex as well as behavioral and cognitive impairments in testing compared to WT-NTBC and WT-water mice. This indicates that these neurological problems can be accredited to the pathophysiology of the disease, and not to the treatment with NTBC.

The result that tyrosinemia type I mice spend twice as much time with a dummy mouse than with a real mouse compared to WT-water and WT-

NTBC mice suggests impaired sociability caused by the disorder. TT1 mice also show no preference for social novelty in comparison to WT-water and WT-NTBC mice who spent more time with a novel mouse. This lack of social preference for a real mouse and a novel mouse in TT1 mice is indicative of diminished sociability and altered exploratory mouse behavior. These results help to demonstrate the significantly different behavioral traits and sociability impairments in mice with tyrosinemia type I compared to the WT-NTBC and WT-water mice and further demonstrates the effects produced by the disorder.

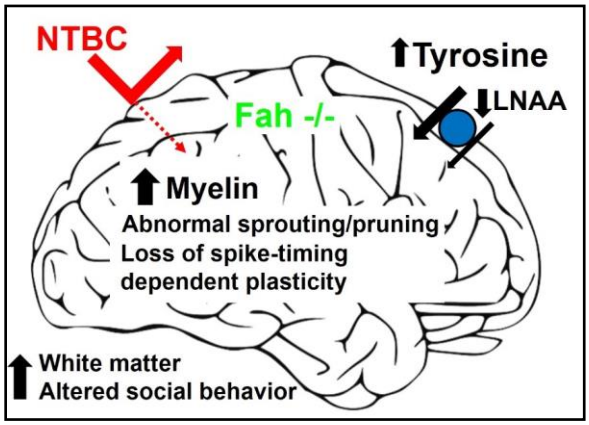

Figure 5. A schematic hypothesis to explain the social behavior changes observed in tyrosinemia type I mice. We propose that NTBC has limited permeability across the blood-brain barrier, providing insufficient inhibition of HPPD. Hence, NTBC is less efficient at the treatment of tyrosinemia type I of the CNS. The enzyme fumarylacetoacetate (FAH) is not expressed in the tyrosinemia type I mice, and results in the increased accumulation of myelin. Myelin can alter neuron sprouting and pruning and can cause the loss of spike-timing dependent plasticity. This altered neuronal architecture or the increased myelination itself is contributing to the altered social behavior in mice.

The lack of difference in time to find the teddy graham in the buried food test between all three genotypes indicates normal and equivocal olfactory abilities. This further demonstrates the suggestion that the disease process of tyrosinemia type I is responsible for the cognitive and sociability problems presenting in TT1 mice. Microscopic analysis of the mice brains revealed dramatic differences in the myelination of TT1 mice in comparison to WT-water and WT-NTBC mice. TT1 mice brains all expressed hypermyelination of the cerebral cortex after staining with Luxol fast blue, indicating different neuronal circuits that could aid in explaining the altered behavior. Myelin undergoes continuous maintenance from glial cells as well as developmental pruning of connections in order to form efficient and accurate neural connections (Lui et. al 2013). In order for proper cognitive and social abilities, neuronal circuits must have normal myelination or else the electrical impulses will be impaired. It is therefore suggested that these neurological deficits are associated with the observed hypermyelination of the cerebral cortex of mice with tyrosinemia type I.

V. Conclusion

The hypermyelination in mice with tyrosinemia type I may be associated with the impaired social behavior we observed. Behavioral testing of mice with tyrosinemia type I have shown altered memory and cognitive function as well as impairments in social behavior. Hypermyelination could lead to malformed neuronal connections as well as altered synapse formation and cause neurological problems. Any defect in white matter myelination of the central nervous system can lead to impaired action potential propagation and further cause deficits in cognition and social behavior. The altered memory, learning, and sociability observed in mice with tyrosinemia type I in comparison to WT-NTBC and WT-water mice indicates that these issues are a product of the disease and not with treatment of NTBC. This indicates that the social and cognitive impairments observed in individuals with tyrosinemia type I could be accounted for by deficits in neuropsychological development.

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Author contributions

MM and GM planned, designed and carried out experiments. MM and GM analyzed the data and wrote the manuscript.MM and GM have no conflicts of interest. MM and GM agree to the conditions of publication including the availability of data and materials.

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Web-Based Existential Graph Editor Tool

Spencer Bowen, Matthew Daigle, Irene Kasian, Telly Polychroniades, & Jason Thomas
Department of Computer Science

Abstract **-** Formal logic is a fundamental topic of computer science. This paper introduces readers to the basic logic operators of predicate logic and how they can be applied to a diagram-based notation for logic called existential graphs. Inference rules for sound and complete existential graph transformation are presented with brief examples of their application. The authors introduce a new web-based Existential Graph Editor Tool built to implement existential graphs. A brief tour of the tool's graphical user interface and key features is provided. The efficacy of the formal logic tool is demonstrated by proving an example theorem.

I. Introduction

The work presented here details a new web-based tool for exploring Charles Sanders Peirce's existential graphs. The authors believe that there are currently no other web-based tools that implement existential graphs and that this tool is a novel addition to tools available for formal logic practitioners. Existential graphs provide a diagram-based form of logic developed in 1897 by Peirce [13].

Before delving into the details of existential graphs, it may be helpful to give a brief explanation of what formal logic is and provide context as to why computer scientists might be interested in it. Students who have taken a computer science, math, or philosophy course have probably encountered formal logic. Formal logic is a system that seeks to determine the veracity of statements based on their relation to other statements. The tradition of formal logic and reasoning can be traced back to Aristotle [6]. The classic example is a syllogism in which known information is combined to deduce new valid information. Since that time the system has been expanded and refined.

In the mid-1800s formal logic was adapted as a basis of proving mathematical correctness. Since it guaranteed sound and correct deductions, formal logic was used as a method of convincing other mathematicians of the validity of a mathematical idea by producing a proof. George Boole, among others, helped establish this tradition of using proofs in mathematics [3,6]. In the early 1900s, shoring up the foundations of mathematics through logical proof was a major undertaking [5,14]. In the 1930s and 1940s, the theories of computation and digital logic were built and described in the mathematical tradition of formal logic. Unsurprisingly, the foundations of computer science are all built upon formal logic and Boolean representation [7].

II. Formal Logic

It may be useful to review a few basics of formal logic before exploring existential graphs. Propositional logic is built from propositions, which are assertions that are either true or false. Propositions can be combined with logical operators to produce new values similar to the way operands and operators in math are combined to create new values. In the case of propositional logic, both the input values and the resulting output value will always be either true or false. Table 1 shows a truth table for common logical operators for the propositions A and B. The first two columns indicate if the propositions are true (T) or false (F) for the row. The remaining columns show what value each operator produces for the given inputs of A and B.

Table 1: Logical Operator Truth Table

A	B	$A \wedge B$	$A \vee B$	$\neg(A \vee B)$
T	T	T	T	F
T	F	F	T	F
F	T	F	T	F
F	F	F	F	T

Table 2: Additional Logical Operators

A	B	$A \rightarrow B$	$A \Leftrightarrow B$
T	T	T	T
T	F	F	F
F	T	T	F
F	F	T	T

The third column in Table 1 shows the *and* operator, represented by the symbol ∧. In logic, this operator is also called the *conjunction* operator. Each row shows what value the conjunction operator produces from the given input values of A and B. In the third column notice that the expression $A \wedge B$ is only true if both of the values of A and B are true. If one or more of the inputs is false, the conjunction operator will also be false [4].

The fourth column in Table 1 shows the *or* operator (also known as the *disjunction* operator), represented by the symbol ∨. In the fourth column, notice that the expression $A \vee B$ is true as long as one or more of the inputs are true. The disjunction operator only returns false if both of the A and B inputs are false [4].

The fifth and final column in Table 1 shows the *negation* operator, represented by the symbol ¬. The fourth and fifth column are the same with the exception that the fifth column contains the negated value of the fourth. By negating the fourth column, the fifth column contains the opposite values of the fourth [4].

Table 2 shows the truth table for two more logical operators. The third column of Table 2 illustrates the *implication* operator, represented by the symbol →. Implication functions like an "if-then" statement: if the left-hand side of the arrow holds, then the right-hand side of the arrow is implied. In the case of the third column of Table 2, if A then B [4].

The fourth column of Table 2 shows the *equivalence* operator represented by the symbol ⇔. The equivalence operator in the fourth column asserts that A if-and-only-if B is true, that is if A and B have the same input then the output is true. Notice that the fourth column of Table 2 is only true when the values in the first two columns of the table match [4].

Predicate logic, sometimes called first order logic, builds on propositional logic by adding quantifiers. For this brief discussion on quantifiers, consider the proposition $A \rightarrow B$, where A is the proposition that "the day is sunny" and B is the proposition "it is hot outside." Taken together with the implication operator, the statement reads "if the day is sunny, then it is hot outside." There are two commonly used quantifiers, the universal quantifier and the existential quantifier. If the universal quantifier is applied to the proposition A the statement becomes "for all sunny days, if the day is sunny, then it is hot outside." If the existential quantifier is applied to the proposition A then the statement becomes "there exists a sunny day such that, if the day is sunny, then it is hot outside." The universal quantified statement makes a stronger claim since it makes a claim about all days and the temperature outside. It also precludes the existence of cold sunny winter days. The existential quantified statement makes a weaker claim since there only needs to exist at least one hot sunny day to satisfy the statement. For the purposes of this paper it is only important to know that existential graphs assume that the existential quantifier applies to all propositions used to build graphs [4,7].

III. Existential Graphs

Existential graphs were developed by the polymath Charles Sanders Peirce in 1897. In addition to contributing to logic, Peirce also contributed to fields including mathematics, physics, history, and economics as well as founding the philosophical school of American pragmatism [2]. Peirce graduated from Harvard in 1859 with a degree in chemistry. He later drew inspiration from the diagrams used in organic chemistry when he attempted to build a graphical notation that would help simplify symbolic logic [11].

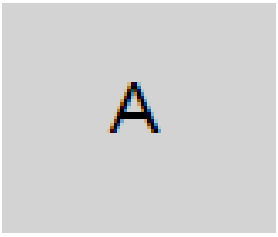


Figure 1: Asserts A is True

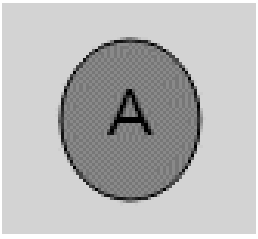


Figure 2: Asserts A is False

Existential graphs do not use the full set of logical operators introduced in Section 2. The system

only uses the conjunction and negation operators. Existential graphs also assume that all predicates are quantified by the existential quantifier, thus the name existential graphs. Figure 1 shows an existential graph that simply asserts that there exists an A that is true. In existential graphs, the negation operator is indicated by surrounding an assertion with a circle. Figure 2 shows a negated A which asserts the opposite value of the A in Figure 1.

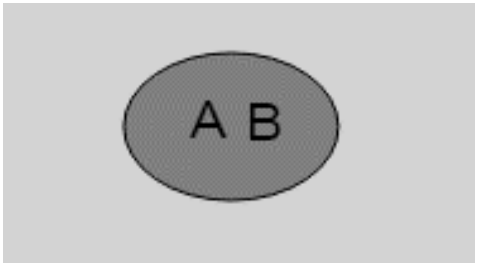


Figure 3: Asserts $\neg(A \wedge B)$

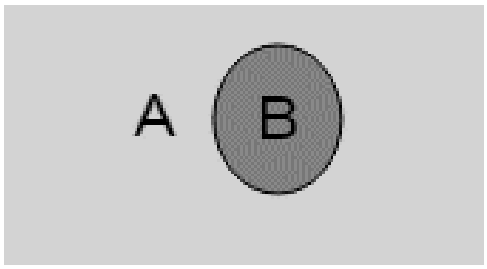


Figure 4: Asserts $A \wedge \neg B$

In existential graphs, the conjunction operator is indicated when two objects are in a shared space. Figure 3 shows the graph for "*not (A and B).*" Since the A and B are placed together, the conjunction operator is understood. Because the two assertions are also surrounded by a circle, the entire statement is negated. Figure 4 shows another example of conjunction. In this case there are two assertions depicted "*A and not B*." Since they are placed together, the conjunction of A and $\neg B$ is assumed and the entire figure asserts $A \wedge \neg B$.

Table 3: Logical Disjunction Truth Table

A	B	$A \vee B$
T	T	T
T	F	T
F	T	T
F	F	F

Table 4: Negation Equivalence to Disjunction

$\neg A$	$\neg B$	$\neg A \wedge \neg B$	$\neg(\neg A \wedge \neg B)$
F	F	F	T
F	T	F	T
T	F	F	T
T	T	T	F

Even though existential graphs only implement two of the logical operators introduced in Section 2, all of the logical operators can be represented in existential graphs through the use of some clever tautologies. A tautology is a statement that is always true regardless of the inputs of its predicates [4]. Consider the operators presented in Table 3 and Table 4. Table 3 shows the truth table for the disjunction operator which was also introduced in Table 1. Table 4 shows how the sample values of the disjunction operator can be produced using only the negation and conjunction operators. Notice that the third column of Table 3 is exactly the same as the fourth column of Table 4. Thus we can say that $A \vee B$ is equivalent to $\neg(\neg A \wedge \neg B)$ which can also be expressed by the tautology $A \vee B \Leftrightarrow \neg(\neg A \wedge \neg B)$ [11]**.**

Table 5: Logical Implication Truth Table

A	B	$A \rightarrow B$
T	T	T
T	F	F
F	T	T
F	F	T

Table 6: Negation Equivalence to Implication

A	$\neg B$	$A \wedge \neg B$	$\neg(A \wedge \neg B)$
T	F	F	T
T	T	T	F
F	F	F	T
F	T	F	T

Existential graphs can also express the implication operator through the use of another tautology: $A \rightarrow B \Leftrightarrow \neg(A \wedge \neg B)$ [11]. Table 5 shows the implication logical operator as introduced in Section 2. Table 6 shows how the same truth values can be produced using only conjunction and negation operators. Notice that the last columns of both tables have the same truth values.

The equivalence operator ⇔, introduced in Section 2, is trivial to implement in existential graphs. If two graphs contain the same assertions, they are equivalent. Thus, all of the logical operators introduced in Section 2 can be implemented in the diagrammatic notation of existential graphs.

IV. Existential Graph Inference Rules

One of the reasons for working in a formal logic is the availability of sound and complete inference rules. Peirce defined a set of such rules for existential graphs that ensures any graph that is produced via the rules will be a correct and true set of inferences [12]. There are six rules that describe the legal transformation of existential graphs. These rules can be grouped into three pairs. For each pair, there is one rule that allows the graph to be generalized by removing graph components and another that allows the graph to be specialized by adding new graph components. The rules, as described in [12], are briefly presented here. Note that each rule has a suffix of either (i) or (e). A rule with the (i) suffix is responsible for *inserting* a new object or set of objects into the graph. A rule with the (e) suffix is responsible for *erasing* an object or set of objects from the graph. For the purposes of discussing existential graphs, a *context* is an area of the graph usually defined by a circle drawn around a subgraph.

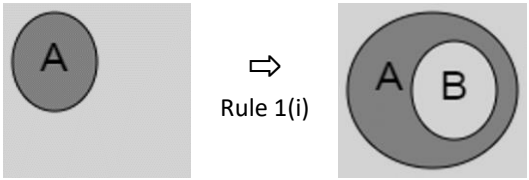


Figure 5: Example of Insertion Rule 1(i)

The first pair of manipulation rules deals with graph *specialization* and *generalization*. Specialization inserts a subgraph into a negative context in order to restrict a given graph or subgraph. Any subgraph may be added as long as it is added into a negative context [12]. The left-hand side of Figure 5 shows the graph for $\neg A$. The dark shaded area represents a negative context because it is inside a circle. Remember from Section 2 that a circle indicates negation. The right-hand side of Figure 5 shows that the subgraph for $\neg B$ is inserted into the negative context following rule 1(i), specialization.

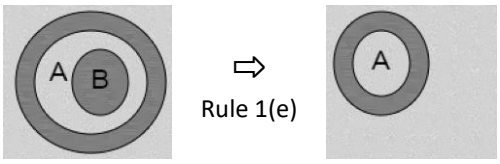


Figure 6: Example of Erasure Rule 1(e)

Rule 1(e) deals with graph generalization and is the inverse of the insert rule. Rule 1(e) broadens a subgraph by allowing the removal of another subgraph from any positive context. The left-hand side of Figure 6 shows the graph for $\neg(\neg(A \wedge \neg B))$. Note that the $A \wedge \neg B$ portion of the graph is in a positive context because it is nested in two circles. Each circle represents a negation operator, and anything nested in an even number of circles will be in a positive context due to double-negation. As in math, two negations result in a positive; for example: $-(-2) = -1 \cdot (-2) = 2$. In Figure 6, the $\neg B$ subgraph can be erased from the graph, as shown in the right-hand side of Figure 6, since it is in a positive context. The assertion A may also be removed following the same rule.

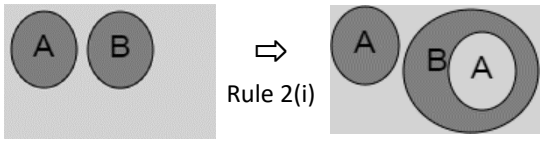


Figure 7: Example of Iteration Rule 2(i)

The second set of Pierce's manipulation rules are known as the rules of *iteration* and *deiteration*. Iteration allows a subgraph to be copied within a graph. A subgraph may be copied into the same context as the source subgraph or into a deeper nested context, but not into itself [12]. In
Figure 7 the left-hand side shows the graph for $\neg A \wedge \neg B$. The right-hand side of
Figure 7 shows that the subgraph $\neg A$ has been copied into $\neg B$ resulting in the new graph $\neg A \wedge \neg(B \wedge \neg A)$. Since the negative context holding B is a portion of the graph that is nested more deeply than the original subgraph, $\neg A$ may be copied into the negative context holding B.

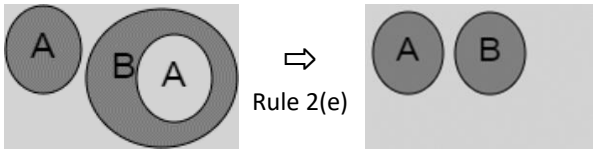


Figure 8: Example of Deiteration Rule 2(e)

The deiterate rule 2(e) is the inverse of the iterate rule. It states that any subgraph that could

have resulted by a rule 2(i) copy can be removed. It does not matter if the subgraph was actually the result of an iterate rule or not [12]. The left-hand side of Figure 8 shows the graph for $\neg A \wedge \neg(B \wedge \neg A)$. Since the most deeply nested $\neg A$ could have been copied by rule 2(i), as shown in Figure 7, then by rule 2(e) it can be removed. The resulting graph is shown in the right-hand side of Figure 8.

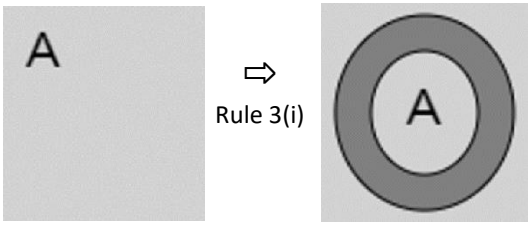


Figure 9: Example of Double Negation Rule 3(i)

Rule 3(i) states that a double negation can be added to any subgraph as long as there is nothing between the two surrounding circles [12]. This is allowable since adding a double negative does not change whether the context of any subgraph is positive or negative. A double negation added in this manner will always cancel itself out. The left-hand side of Figure 9 shows the graph for A. Note that since the A is not in a dark shaded context, it is in a positive context. The right-hand side of Figure 9 is the result of adding a double negation by rule 3(i). Since the double negation cancels itself out, the A is still in a positive context.

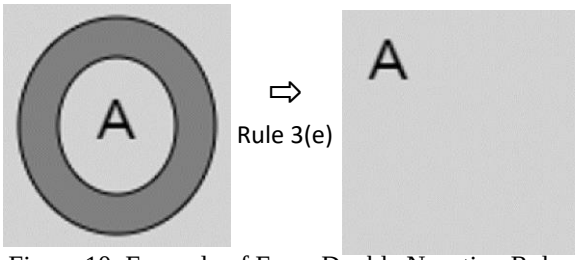


Figure 10: Example of Erase Double Negation Rule 3(e)

Rule 3(e) is the inverse of rule 3(i) and states that any double negation may be erased from the graph as long as there is nothing between the outer and inner circles [12]. The left-hand side of Figure 10 shows the graph for $\neg(\neg A)$. Since there is nothing between them, the two surrounding circles can be erased by rule 3(e), resulting in the right-hand side of Figure 10. Notice that in both sides of the figure, A remains in a positive (non-shaded) context.

V. Existential Graph Editor Tool

The Existential Graph Editor Tool is a web-based tool that implements the diagrammatic logic presented in Section 3 and enforces the inference rules presented in Section 4. The tool is built in HTML and JavaScript and uses the JavaScript Bootstrap [1] and JointJS [8] libraries. The Bootstrap library provides user interface features for the tool. The JointJS diagramming toolkit provides the components for building and manipulating graphs.

The Existential Graph Editor Tool is compatible with the Chrome and Firefox browsers. A demonstration version of the tool is available for examination [9] and the source code can be examined on GitHub [10].

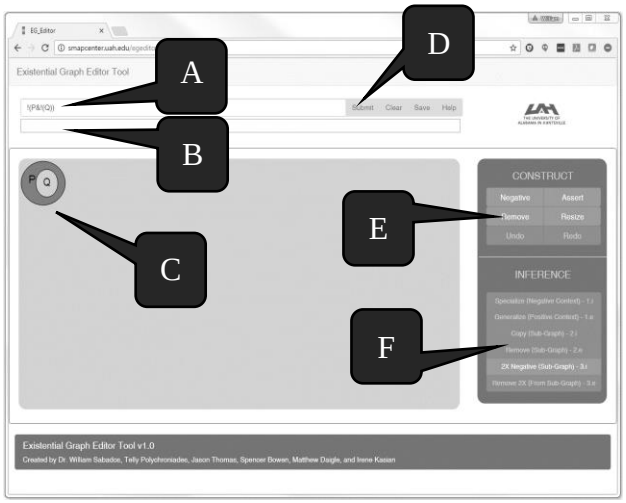


Figure 11: The Existential Graph Editor Tool

Figure 11 shows a screenshot of the Existential Graph Editor Tool with annotations calling out features of the tool. Callout A is an expression input field where users can enter linear logic strings into the tool. The tool accepts a modified set of logical operators as shown in Table 7.

Table 7: Logical Operators the Tool Accepts

Logical Operator	Tool Operator	Example Tool String
Negation ¬	!()	!(P)
Conjunction ∧	&	P&Q
Disjunction ∨	|	P|Q
Implication →	>	P>Q

Once an expression is entered in the input field, the tool will automatically convert any disjunction or implication operators into the equivalent negation and conjunction operators by applying the tautologies presented in Section 3. If necessary, the tool will add additional parenthesis to help disambiguate an expression. The resulting existential graph will then be rendered in the graph area identified by Callout C. If there are any syntactic problems with the expression an error message will be displayed in the feedback box identified by Callout B.

The suite of buttons identified by Callout D helps the user with entering and exporting logic from the tool. The *Submit* button will automatically apply tautologies, if necessary, and render the resulting existential graph. The *Clear* button will clear both the expression input box and the graph area. The *Save* button will create a raster image of the current existential graph and download the PNG file to the browser. The *Help* button displays a pop-up box with instructions on how to use the tool.

The Construction button suite, as identified by Callout E, provides tools to help create an existential graph from scratch if the user prefers that method instead of using the expression input box to enter a linear logic expression. Users can add assertions or negated assertions one-by-one to the graph and the linear expression box will update automatically. *Undo* and *Redo* buttons are included as well to roll back previous alterations in case of mistakes.

The Inference button suite identified by Callout F allows users to derive new logically sound graphs by applying the inference rules presented in Section 4. The tool is context sensitive and will automatically enable and disable buttons depending on what is currently selected in the graph. For instance, the specialized graph inference rule, rule 1(i), is only applicable in negative context areas. If a negative context is currently selected, the button for the rule 1(i) will be enabled. The tool also checks to see if a selected context is a valid target for removing a double negation, or if the currently selected subgraph could have been copied using rule 2(i). If so, it will enable the remove button that implements inference rule 2(e).

VI. Example Proof Using the Tool

This section demonstrates how the web-based Existential Graph Editor Tool can be used to derive logical proofs. The example proof, and its formulation as an existential graph proof, was devised by John Sowa in [12]. The proof is of some historical interest having been proved by Gottfried W. Leibniz of calculus fame. In the Principia Mathematica the authors note that the theorem pleased Leibniz so much that he called it *praeclarium theorema*, which translates to the *splendid theorem* [12,14]. The Principia Mathematica's version of the proof takes 43 steps whereas Sowa's existential graph version takes seven.

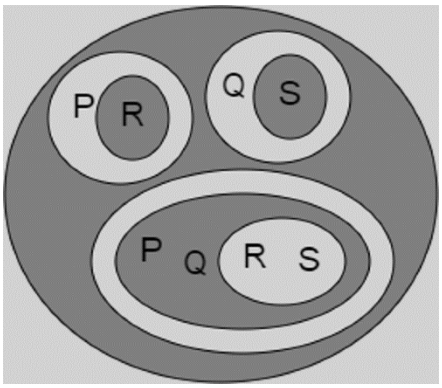


Figure 12: The Splendid Theorem as an Existential Graph

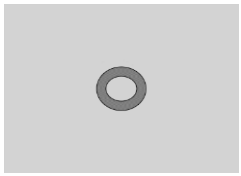
The original version of the splendid theorem states $((P \rightarrow R) \wedge (Q \rightarrow S)) \rightarrow ((P \wedge Q) \rightarrow (R \wedge S))$. By applying the tautology for implication introduced in Section 3, the theorem can be converted into a statement that uses only conjunction and negation as follows:
$\neg(\neg(P \wedge \neg R) \wedge \neg(Q \wedge \neg S) \wedge \neg(\neg(P \wedge Q \wedge \neg(R \wedge S))))$[1]. The linear form of this theorem results in the existential graph shown in Figure 12. For the purposes of the proof Figure 12 acts as the target. The challenge is to see if a proof can be constructed starting with a blank

[1] The equivalent expression for the input box of the web tool is !(!(P&!(R))&!(Q&!(S))&!(!(P&Q&!(R&S))))

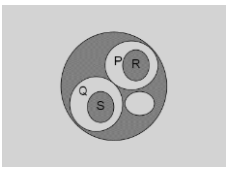
page following the rules of inference as described in Section 4 that results in the graph shown in Figure 12.

Start with an empty graph.

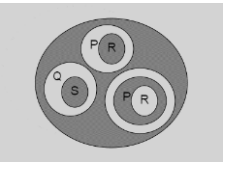
1) Rule 3(i): Insert a double negation.



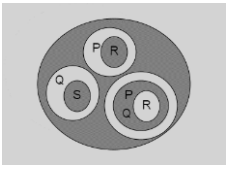
2) Rule 1(i): Insert $\neg(P \wedge \neg R) \wedge \neg(Q \wedge \neg S)$ into the negative context.



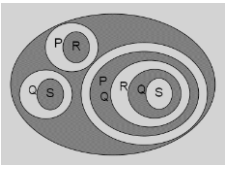
3) Rule 2(i): Copy $\neg(P \wedge \neg R)$ into the nested positive context.



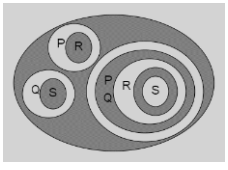
4) Rule 1(i): Insert Q into the most nested negative context.



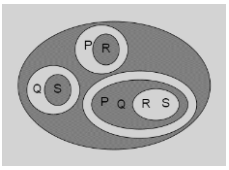
5) Rule 2(i): Copy $\neg(Q \wedge \neg S)$ into the most nested context.



6) Rule 2(e): Erase the most nested instance of Q.



7) Rule 3(e): Erase the double negations around the most nested instance of S.



The proof is complete and the target theorem shown in Figure 12 was produced following the rules of inference presented in Section 4. Using the Inference buttons (Callout F in Figure 11) of the Web-based Existential Graph Editor Tool it is possible to construct the proof and produce all of the images shown here. The tool was also used to produce all of the existential graph images presented in this paper.

VII. Future Work

The web-based Existential Graph Editor Tool recently reached version 1.0. As with most tools, there are additional improvements that can be made in future versions. The user experience can be streamlined and improved. This might include improvements to better differentiate when users are building existential graphs in a freeform fashion using the construction tools from when they are deriving new graphs using the inference rule tools. It would be nice if the tool could automatically produce a proof summary similar to the one presented in Section 6. Ideally, this would produce a document that would step through the inference rules and the resulting graph images produced.

One challenge in any graph tool is automatic layout. The tool currently lays out and renders existential graphs, but further improvements can be made to make the resulting graphs easier to read and adjust. Additionally, there are possible improvements to the data model used to manipulate the graph and enforce inference rules that could result in faster manipulations or opportunities to implement new features.

While it is possible to enter graphs into the tool using the expression input box and output graphs as PNG files, better import/export tools are desirable. Perhaps something that allows users to import/export a graph as XML so that layout adjustments can be persisted between sessions. Another possibility is adding network storage to the tool so that users can log-in and continue working on graphs previously started. This would also open the possibility of allowing users to share graphs as html links that would return embeddable images.

VIII. Contributions

The web-based Existential Graph Editor Tool was built by a team of undergraduate computer science students working at the University of Alabama in Huntsville's (UAH) Systems Management and Production Center under the mentorship of Dr. William T. Sabados. The initial HTML interface prototyping was completed by Jason Thomas. User interface, view manager, automatic layout, and graph manipulation features were implemented by Spencer Bowen and Irene Kasian. The data model, logic parser, and control features were implemented by Matthew Daigle and Telly Polychroniades. This paper was written and revised jointly by the team.

IX. Conclusion

The web-based Existential Graph Editor Tool allows for users to explore existential graphs. The tool presented here provides the capability to convert linear logic expressions into existential graphs as well as build new graphs and proofs via sound and complete inference rules. Formal logic is foundational to computer science, philosophy, and math. Existential graphs provides a diagrammatic means for users to engage with formal logic and explore this important topic. The web-based Existential Graph Editor Tool will hopefully make this form of logic exploration more accessible.

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Antonio's Lament

"Mightily Abused" in *Twelfth Night*

Quintin Walton
Department of Women's and Gender Studies

Abstract **-** The play Twelfth Night depicts the fluid nature of sexuality, although it ends with the standard trope undergirding romantic comedy: inevitable heterosexual unions. Additionally, Twelfth Night upsets stereotypical constructions of masculinity and sexual desire by provocatively introducing
Antonio (a heroic sea captain) who saves Sebastian (a beautiful young man) from watery destruction; moreover, they form a homoerotic domestic partnership that lasts three blissful months—a substantial timeline in Shakespearean comedy. The ongoing critical conversations on this topic are limited to a discussion of bisexuality (Pequigney), a consideration of the implications of homoerotic partnership (Thomas), and an observation of the inherent cruelty in the comic situation (Adelman). My critical intervention highlights the fact that Shakespeare scholars tend to focus on the homosocial pairs of Viola/Olivia and Cesario/Orsino rather than scrutinizing the function of Antonio and Sebastian's passionate partnership within the context of romantic comedy. Therefore, this essay shall offer three strains of analysis to help alleviate this aforementioned critical deficit. First, it posits that Antonio's downward spiral (due to his refusal to pursue traditionally-sanctioned matrimony) is in line with tragedy rather than comedy. Next, this essay theorizes that Sebastian's Roderigo alter-ego, which he adopts to engage intimately with Antonio, profoundly fractures his sexual psyche. Finally, it offers an elastic rendering of the play's end in which Sebastian reconciles with his Roderigo persona and invites Antonio to join his marriage, all with Olivia's approval, merging homoerotic passion and heteronormative inevitability into a flexible middle sphere.

I. Antonio's Lament: "Mightily Abused" in *Twelfth Night*

William Shakespeare's romantic comedies, including *Twelfth Night* (subtitled *What You Will*), follow a conventional formula: boy meets girl, boy and girl fall in love, they undergo some trial or period of separation in which some kind of antagonistic force (nature, society, family, etc.) tests the limits of their love; however, comic conventions also dictate that, by the end of the play, the boy and girl reunite, reconcile, and either are betrothed or married. Regarding *Twelfth Night*, Camille Slights posits that the move from personal frustration and social disorder to individual fulfillment and social harmony (drawing on what Leo Salingar identifies as the traditional comic combination of beneficent fortune and human intrigue) likens *Twelfth Night* to other Shakespearean romantic comedies (537). Moreover, Lisa Marciano argues that the dark aspects of *Twelfth Night*, which permeate so many of William Shakespeare's comedies, precludes the play from appearing light (3). Marciano offers, "Shakespeare's comic characters repeatedly come face to face with mortality, learn that one must, therefore, live well, and teach others wisdom accordingly" (3). She suggests that not only are a brush with death and exhorting others to live well staples of Shakespeare's comedies, but *Twelfth Night* abounds with scenarios in which characters who are aware of mortality attempt to bring others to reform through means of this knowledge (3). Through the comic lens of *Twelfth Night*, Marciano alleges that a dark didacticism, an urgent sense that life must be lived well because it is ephemeral, undergirds Shakespeare's plays. Yet even within this context of tragic circumstances happening alongside love and marriage, *Twelfth Night* presents a situation that is unusual in comedies—the dissolution of a relationship that seems otherwise loving in order to attain the standard happy ending.

The story dictated sabotage of the union between Antonio and Sebastian, while expected, nevertheless creates an unsatisfying resolution. Within comedy as a genre, the audience expects homosocial pairs to transition into heterosexual couples, yet I contend that the contrived breakup of Antonio and Sebastian approaches unwarranted cruelty; Sebastian inexplicably jettisons his loving partnership with Antonio, grounded in fidelity and loyalty, to enter a conventional paradigm with Olivia, which conversely derives from convenience and bribery. By evincing that Antonio and Sebastian begin *Twelfth Night* as domestic partners, I do not superimpose a modern-day or

anachronistic connotation on the play. The text explicitly relates that once Antonio rescues Sebastian from the fateful shipwreck, they adhere for three uninterrupted months at each other's side. Furthermore, the glaring lack of a promise from Sebastian to recompense Antonio with gold for his valor equivalent to the bargain Viola strikes with her heroic captain connotes that the love Antonio harbors toward Sebastian exceeds a commercial enterprise. In truth, Sebastian spends as much time with Antonio as Viola shares with Orsino (the object of her affection), with the exception that Antonio and Sebastian's future together is unceremoniously interrupted and does not extend beyond the play's finale. While Antonio's commitment to Sebastian exudes an unwavering loyalty, Sebastian fails to reciprocate likewise at the end of the play when Antonio needs Sebastian's immediate intervention to abate Count Orsino's wrath and thwart Antonio's impending incarceration. Thus, the melancholy denouement of Antonio's abandoned domestic partnership with Sebastian warrants deeper analysis because no other pair (male/male, male/female, or female/female) in the play embody a singularly devoted bond. I posit that denying Antonio a happy resolution and thereby simultaneously withdrawing a counter presentation of a traditional love story, the play explicitly recommends that if a man fails to advance from homosocial pair into heterosexual marriage, such a man is not reconcilable and should be subject to punishment and imprisonment.

I propose that the romantic relationship between Antonio and Sebastian if examined from their inception right up to the moment of Sebastian's decision to renounce his Roderigo guise and search out his presumed dead sister diverges from the conventional comedic construction of a heteronormative couple navigating toward an inevitable happy ending. For the broader purposes of Shakespearean and gender/queer studies by extension, I assert that an autopsy of Antonio and Sebastian's abandoned romance reveals that a rarely achieved happy ending involving two sexually viable males is initially presented and then almost immediately becomes undone and deconstructed throughout the play albeit with pervasive references to the strength and ostensible constancy of their original love pairing. Consequently, although *Twelfth Night* is a romantic comedy, it nevertheless borrows the darker overtones of tragedy. I assert that Antonio is the only truly heroic character, the dashing Romantic Savior as it were, who ends the play worse off than his circumstances when the play commences. This arbitrary character assassination reorients the standard trajectory of romantic comedy as a literary genre, but also lends itself to ripe analysis of a heroic male character who resists a romantic existence beyond a homoerotic pairing. Additionally, this essay unpacks the heretofore largely unexplored Roderigo dual-identity Sebastian adopts, which I allege grants him freedom to conduct a sexual liaison with another man. However, when dissected independent of his Roderigo persona, Sebastian's relationship with Antonio resembles exploitation rather than reciprocation and suggests that Sebastian is merely a spurious romantic hero. Operating like a subtle opportunist, he deftly uses his tempting face and figure to manipulate spellbound Antonio. For descriptive purposes to connote character designations, I dub Sebastian the Sexual Chameleon who ultimately exudes stunning passivity throughout his intimate liaisons, but traverses a bisexual gray scale with arguable ease and occasional ambivalence. Lastly, expanding on the scholarship of previous critics, I interject an alternative conclusion for *Twelfth Night* utilizing queer elements inherent in the play, which subverts fossilized romantic comedy tropes by enabling Antonio to enjoy a romantic threesome sanctioned by Olivia and initiated by Sebastian. The overall import of such an ending melds the concepts of passionate homoerotic attachment introduced earlier in the play and heterosexual inevitability demanded by normative constructs into a middle sphere where both can exist successfully in future broader conceived productions. Ideally, the intervention I initiate in this paper prompts other Shakespearean critics to invoke a queer inquiry of *Twelfth Night* that encompasses the diversity of Antonio's relationship with Sebastian compared to other Romantic Saviors that advances from rescue to domestic bliss to being pulled asunder by various contrived plot devices. Also, I invite further scholarship that attempts to address the provocative reason besides survival that Sebastian chooses an alternate persona as Sexual Chameleon to engage with Antonio as his domestic partner when concealment of his true identity considering Antonio's unconditional allegiance to him seems unwarranted during his three month residency.

II. Antonio's Loss: "That most ungrateful boy"

The moment Antonio and Sebastian appear in *Twelfth Night*, their dialogue evokes the private intimacy of lovers. The palpable homoerotism emanating from Sebastian's exchange with Antonio (in act 2, scene 1) contrasts sharply with the life and death

circumstances in which the audience meets Sebastian's twin sister, Viola. She does not mention love (in act 1 scene 2), but vacillates between imagining her brother at peace in "Elysium" (3) and the faint hope that "Perchance he is not drowned" (4). In stark relief, given the intimate nature of their discourse, it is appropriate to envision Antonio and Sebastian limbs intertwined, conversing softly on an exquisite bed, luxuriating unclad in the afterglow of sensuality. Such a possibility matters in the presentation of Antonio's and Sebastian's relationship because their intercourse telegraphs that

Antonio feels more than platonic camaraderie for Sebastian. Antonio implores: "Will you stay no longer, nor will you that I go with you?" (2.1.1.)

The tone and timbre of Antonio's tentative inquiry telegraphs approaching interruption to their domestic bliss. The implication of impending separation threatens to disturb that which Antonio cherishes with Sebastian. This unanticipated contingency takes Antonio aback, as if it never occurred to him that Sebastian would return from whence he came or that he would seek an existence beyond Antonio's companionship. After all, at this point in the play, they live as domestic partners. The question ominously foreshadows that Antonio fears his life without Sebastian will be unbearable. At this juncture, the loyalty Antonio exhibits to his lover surpasses the allegiance Viola elicits from the courageous captain who plucks her from a watery oblivion. Alas, Sebastian's reply obliterates Antonio's hope. He responds: "By your patience, no. My stars shine darkly over me, the malignancy of my fate perhaps distemper yours. Therefore, I shall crave of you your leave that I may bear my evils alone. It were a bad recompense for your love to lay any of them on you" (2.1.3-8). In contrast to his lover, Sebastian contemplates the disaster that befell him and realizes that staying with Antonio subjects his benefactor to whatever perilous fate stalks him. On the surface, Sebastian's decision surpasses noble because he fears that his proximity to Antonio increases the chance of his misfortune infecting Antonio. Thus, proceeding without Antonio becomes the best way for Sebastian to repay Antonio's love. Remarkably, Sebastian fails to justify how his absence benefits Antonio. Since Antonio materialized fatefully as his Romantic Savior to rescue him from the shipwreck Sebastian's current circumstances contradict his flimsy assertion that he carries catastrophe that may eventually afflict Antonio. Quite the contrary, Antonio exemplifies his good fortune and his vehement objection to Sebastian's departure indicates that separation from his beloved dooms him far more than the Sexual Chameleon's imaginary prognostications.

Cosmetically, Sebastian's desire to spare Antonio from the destructive force that pursues him resembles altruism, but upon closer inspection, Sebastian's decision to abandon Antonio also exposes selfish motivations. Subsequent to his rescue, Sebastian claims inescapable "dark stars" shadow his future. Yet, when Antonio presses him for details about his destination, Sebastian reveals only his intention to wander aimlessly; glaringly, such an explanation belies the truth. Sebastian eventually confesses that he plans to journey to Count Orsino's court (where, unbeknownst to Sebastian, his sister has already arrived disguised as the eunuch Cesario and fallen in love with Orsino). During the three months Sebastian abides with Antonio, he must notice Antonio's blatant ardor and devotion. Indeed, later in the play, Antonio proclaims as much to Orsino after confusing Viola/Cesario for Sebastian:

> That most ungrateful boy there by your side
> From the rude sea's enraged and foamy mouth
> Did I redeem. A wreck past hope he was
> His life I gave him and did thereto add
> My love, without retention or restraint
> All his in dedication. For his sake
> Did I expose myself – pure for his love
> Into the danger of this adverse town. (5.1.73-80)

Antonio's lamentation broadcasts his depthless constancy; speaking in terms of redemption and purity of love, Antonio represents a messianic figure to Sebastian. Although *Twelfth Night* is a romantic comedy, nothing about Antonio intervening as Sebastian's savior elicits humor; moreover, Antonio feels punished for the deeds he performed for Sebastian's benefit. In fact, George T. Wright observes that Shakespeare includes "two main strands of language: a verse language whose form marks it as significant or as carrying significant content; and a 'prose' language that, for the most part, is the common currency of colloquial exchange" (163). However, as Wright qualifies, "Shakespeare found it inconvenient or deforming to make too many changes as the characters move into or out of The Significant. A kind of aura of significance surrounds the verse passages and in a sense, mythologizes even the parts that are mere ordinary colloquial give-and-take" (163). In other words, when Antonio delivers Sebastian from certain death, the destructive power of the baptizing sea, he resurrects Sebastian spiritually and physically. Employing

verse, the language of lovers and heroes, Antonio solemnly refutes Orsino's incendiary accusation that he is a rapacious swashbuckler. Rather, Antonio illuminates himself as a sympathetic hero who jeopardizes his own life to accompany this cursed young man safely to Illyria, where Orsino now relishes the opportunity to castigate him as a criminal for speculative transgressions.

The dashing Romantic Savior commits no crime against love that earns his unsatisfying resolution: to the contrary, notorious abuse and great loneliness befall him because of his attachment to the bewitching Sexual Chameleon. When he confronts Antonio, who bested him in a contest of wills on the tumultuous sea, Orsino excoriates him: "Notable pirate, thou salt-water thief / What foolish boldness brought thee to their mercies...?" (5.1.65-66). Even before Antonio eloquently acquits himself: "Be pleased that I shake off these names you gave me. Antonio never yet was thief or pirate" (5.1.69-70) with his regal rejection of the count's spurious allegations, Antonio's actions heretofore show him to be more noble, honorable, and a far gentler soul than Orsino's bitter portrayal permits. Despite all that dashing Antonio risks for love, love (or, more aptly, Sebastian's gross ingratitude) leaves Antonio spurned, bereft, and vulnerable to Orsino's unreliable witness testimony and his seething retribution.

Sebastian betrays Antonio once he succumbs to Olivia, a wealthy heiress in Illyria, who purchases him (more or less) for marriage with promises of lifelong care and luxury. Olivia paints her pursuit of Cesario and Sebastian (who she mistakes for Cesario) in terms of economic exchange, asking Maria, "How shall I feast him? What bestow on him? / For youth is bought more oft than begg'd or borrow'd" (3.4.2-3). As Joseph Pequigney productively notes, "This observation clearly has retrospective reference to the purse, indicating that it is given with the ulterior motive of pleasing if not purchasing the desired youth" (204). When Pequigney compares Olivia's scheme to seduce Cesario through a gift "to the purse," he refers to the purse Antonio has earlier given Sebastian: "A kind and generous gesture, to be sure, but the intent behind it is less simple than the reply suggests" (204). Sebastian spurns Antonio's abundant affection although he embraces his financial largesse with barely token reluctance. Perceptively, Olivia surmises that dazzling jewels attract the companionship of ambitious young men. Sebastian's awed reception of the object Olivia bestows upon him betrays his avarice more than aroused sexual attraction for her as his potential lover: "This pearl she gave me, I do feel't and see't / And though 'tis wonder that enwraps me thus / Yet 'tis not madness. Where's Antonio, then?" (4.3.2-4). The effect of Olivia's pearl on Sebastian supersedes any lukewarm fondness he might otherwise manifest for Antonio. If Sebastian feels genuine love for Antonio, he conceals it adroitly; although Sebastian invokes Antonio as he tries to discern the appropriate course of action: "His counsel now might do me golden service" (4.3.8). Ironically, Sebastian never sought Antonio's golden counsel before he decides to travel to Illyria and he does not utter Antonio's name in Olivia's presence, where such an invocation might indicate affection for his benefactor, and Sebastian does not confer with Antonio before accepting Olivia's proposal. As Pequigney alleges, Antonio's purse attaches Sebastian to Antonio, which elucidates Sebastian's zeal to marry Olivia with no previous courtship or familiarity. Possessing no prior alluded to professional money-making acumen or mastered skills, the Sexual Chameleon cannot survive without benefit of a smitten patron. Their gender matters little to him contrasted against their ability to provide his comfort.

Sebastian's rash betrothal to Olivia mocks his previous concerns about alleged "dark stars" hovering over him and unveils the young man as an opportunist who exhibits scant love for his Romantic Savior beyond tepid gratitude. Earlier, Sebastian highlights his propensity for deception by only revealing his true name after he fails to dissuade Antonio from accompanying him to Illyria. Conversely, his sister, Viola, adopts her Cesario persona as a safety precaution to conceal her gender status, an unchaperoned young woman, in a potentially aggressive environment. Moreover, Sebastian dons his own alter-ego (Roderigo) because his new surroundings might spark physical intimacy with Antonio, which he hides under cover of his surreptitious identity. As Pequigney notes: "When initially about to depart, Sebastian makes the curious admission that as a companion to Antonio that he had always gone by another name, calling himself Roderigo. Why he should do so goes unexplained...The alias may be...a means to hide his identity, his true name and family connections, during a drawn-out sexual liaison with a stranger in strange lands" (205). Pequigney concludes that Sebastian's charade facilitates his sexual adventure in his new location—and lends credence to the

premise that Antonio and Roderigo are closer than mere friends. I concur with Pequigney's summation and I further allege that Sebastian's Roderigo facade emphasizes his pathological compulsion to deceive Antonio. I rigorously maintain that no plausible motive exists for the Sexual Chameleon to deceive his Romantic Savior for three months after observing that Antonio put Sebastian's welfare before even his own safety. If Antonio did not prove his intrinsic worthiness of Sebastian's confidence by saving him from calamity and granting him sanctuary, no deeper form of emotional connection seems conceivable. Perhaps Sebastian's bizarre behavior and mysterious motivations rest firmly upon the fact that he is mentally incapable of enjoying physical intimacy with Antonio as his namesake's scion. Immediately, Sebastian may have sensed his Romantic Savior's unbridled desire for him and decides in gratitude that he cannot remit Antonio's sexual love without the buffer of a psychological mask. Maybe the Sexual Chameleon journeys to find his dead sister because the mask began to crack or he realizes his sexual identity demands fluidity.

III. Sebastian's Fractured Psyche: "Both Maid and Man"

Once removed from certain death, Sebastian and Viola each cope with the loss of the other by conjuring an alternate persona, one which subsequently becomes a love object for a potential romantic partner in each's new life. In this, they are not mere twins, but become quadruplets. Her brother's absence allows female Viola to reinvent herself as male Cesario, a boy who loves Orsino, functioning as his right hand but also with the soul of a woman. Cesario camouflages Viola's gender and maintains an illusion of her deceased brother as she lives two existences. She partially obscures her femininity as Cesario, but processes the new environment and experiences love as Viola. Sebastian's resurrection from a saltwater grave by his Romantic Savior creates a marginal circumstance for him to invent his Roderigo identity, the Sexual Chameleon. Paradoxically, Sebastian's motivation for constructing the Roderigo alias remains nebulous if I remove the catalyst of sexual attraction. He performs for three months as Antonio's domestic partner. Sebastian perpetrates his own male twin; the brother he never had. According to Antonio's narrative while in Orsino's custody, nary a sliver of sunlight or moonlight came between them as Roderigo clung to his side: "Today, my lord, and for three months before/ No interim, not a minute's vacancy / Both day and night did we keep company" (5.1.90-92). I extrapolate that proximity arouses Roderigo's passions and he indulges in Antonio's freely offered tenderness as Sebastian's newborn twin brother. Resurrection from near death awakens erotic possibilities in his new surroundings. Anonymity guarantees secrecy for his sexual exploits.

Unlike Viola in her Cesario guise, however, I contend that clothes do not play a primary role in Sebastian's transformation to Sexual Chameleon. Viola, in a sense, becomes her own brother, as she recalls during her street brawl with Sir Toby and Sir Andrew: "In favour was my brother, and he went / Still in this fashion, colour, ornament / For him I imitate (3.4.378-380). Viola refashions herself into the image of her brother, and she recalls him each time she witnesses her own reflection. Relatedly, although Malvolio cannot identify him, Feste brags of his own deception: "Nay, I am for all waters" (4.2.62). Thus, both Viola and Feste use garb to perpetrate their masquerade. Maria even scolds Feste that his fraud warrants no accoutrement since his victim cannot see him: "Thou mightest have done this without thy beard / and gown he sees thee not" (4.2.63-64). Just as Feste has no necessity to conceal himself from the clueless Malvolio, Sebastian's ruse also serves no purpose, except to slip furtively inside a new sexual skin. When Antonio snatches him from the raging sea following the shipwreck, Sebastian's garments (and the form underneath) confirm him as male. Certainly Antonio's heroism was not predicated upon a belief that Sebastian is female (in the same way that motivated the Sea Captain to fish Viola from the sea).

Since his adoption of the Roderigo persona does not obscure his gender or elevate his social status, as Viola's and Feste's respective disguises do, Sebastian's alternate identity supplies a way to reciprocate the intense love Antonio professes for him. Late in the play, Sebastian's Roderigo-persona reappears after Antonio witnesses Sebastian side by side with Cesario and cannot resolve which half of Sebastian loves him: "How have you made division of yourself? / An apple cleft in two is not more twin / Than these two creatures. Which is Sebastian?" (5.1.218-220). Perhaps the answer, albeit unsatisfying, is that Sebastian struggles with ambivalence as to whether he loves Antonio. Indeed, maybe his unorthodox, passionate love only expresses itself when

the Roderigo side of Sebastian's identity controls his heart. Thus, Sebastian's Roderigo persona allows a space for him either to meet Antonio's romantic expectations or to suspend his own inhibitions. Apparently, the time Antonio spends with Roderigo happens undercover from anyone who knew him as Sebastian; what precipitates the Sexual Chameleon's prolonged separation from his birthplace? Most of Antonio's relationship with Roderigo transpires offstage and beyond the audience's purview. However, when Sebastian reveals his "true" identity, we witness a recommitment of his Romantic Savior's undiminished devotion. Unlike with the confused Cesario/Orsino/Viola and Viola/Olivia/Cesario permutations, gender discontinuity does not rip Antonio and Sebastian/Roderigo asunder; conversely, Antonio affords Sebastian undeserved credit for unimpeachable honor and integrity. That generous praise turns out to be woefully misplaced. Although sincere Viola reveals her true self except for her maiden's weeds at the play's end, Olivia never learns because her "honest" husband, the Sexual Chameleon, keeps hidden the details of the three months he spent sequestered as his Romantic Savior's youthful companion and domestic partner, Roderigo.

Thus, sexual elasticity between Antonio and Sebastian undergirds a homoerotic frisson that threatens extension beyond the play's final curtain. Antonio, Sebastian, and Olivia, potentially flourish in an elegant ménage à trois union that supersedes the conventional homosocial pair or inevitable heteronormative matrimony—the courageous privateer, the beautiful young male damsel, and the rich countess. This new configuration becomes more probable when considering Sebastian's attachment to his Roderigo persona. Sebastian cryptically directs his final words of the play to Olivia: "You would have been contracted to a maid / Nor are you therein, by my life, deceived / You are betrothed both to a maid and man" (5.1.257-259). This may be the closest Sebastian comes to confessing the exact nature of his relationship with Antonio. If he is a maid to Olivia (because he lacks sexual experience with a woman), perhaps he conversely became a man by virtue of his physical relationship with Antonio.

The revelation that a man can love another man romantically as other men love women would not be a foreign disclosure to Olivia. Before Viola divulges her true identity, Olivia asks: "Where goes Cesario?" (5.1.129). Viola, who follows obediently behind Orsino, answers Olivia's query: "After him I love / More than I do love these eyes, more than my life / More by all mores than e'er I shall love wife" (5.1.130-132). In man's attire, Cesario speaks passionately to Olivia about loving another man more than any woman. While Olivia may be hurt or confused by Cesario's proclamation of love for Orsino, she does not question the validity of the declaration, even though both Cesario and Orsino are ostensibly men. Rather than rebut the veracity of Cesario's love, Olivia accepts that he has discarded her for a man: "Ay me, detested, how am I beguiled!" (5.1.135). Of course, Olivia is not beguiled, as neither Cesario nor Sebastian deliberately deceives her; still, this misunderstanding introduces Olivia to the concept of all-consuming homoerotic attachment, an idea which she acknowledges as unexceptional if not favorably. Moreover, the proposed scenario that Olivia welcomes Roderigo's desire for Antonio offers a clever and witty inverse of the prior scene between Olivia and Cesario. Critics affirm this transgressive possibility. Here, Pequigney alludes to Sebastian's sexual ambiguity in his assessment of Antonio and Sebastian:

> Sebastian turns out to be the most extreme exemplar of this recurring theme of bisexuality, for he is not only attracted to, but also able and willing sexually to enjoy, both a man and a woman...who are, and with obvious passion, enamored of him. While he remains heterosexually virginal, he is unlike the virgins Viola and Olivia or Orsino in that he entertains homosexual impulses that are fully conscious. (209-210)

Reading Sebastian expansively, Pequigney suggests that Sebastian enters sexuality via a same-sex relationship and that Sebastian is comfortable with both Antonio and Olivia as intimate partners. However, even with Pequigney's expansive reading of the end of the play as a romantic threesome, Sebastian's sexual fluidity seems motivated largely by financial feasibility; Sebastian behaves like an erotic chameleon, gauging which purse can best secure his desires. Sexuality does not breed character just as sexual compatibility may supersede erotic identity. In Shakespeare's tragic comedy or love's fickle realm, neither of these factors guarantees humane regard. Sebastian's accrual of sexual experience with a man, while remaining a heterosexual virgin, tantalizes the imagination with erotic intrigue, even if, at the play's resolution, his actions do not communicate that Sebastian will maintain his partnership with Antonio (or any

other man). Surely, no financial imperative exists for Sebastian to include Antonio in his economic windfall with Olivia.

Sebastian's behavior with both Antonio and Olivia is steeped in an archetypical feminine passivity while his sister employs her gorgeous intellect to devise a brilliant stratagem stereotypically correlated to masculine ingenuity and cunning. The aftermath of her collision with death inspires Viola's bravery and boldness which eschews the performance of damsel in distress as she undertakes the hero's journey through the strength of her spirit. She designs a position for herself in Orsino's court touting exceptional musical talents that she never actually displays. However, Viola/Cesario possesses an oral ability that makes her/him indispensable to Count Orsino. Sebastian, on the other hand, relies naively upon serendipity. He just happens to be miraculously lifted from the sea by a love-struck guardian who intervenes between Sebastian and death and then devotes his emotional and financial resources to him. Then Sebastian blithely stumbles upon heiress Olivia, who instantly craves the pretty youth for her husband and wins him with her dowry. Sebastian never calculates how to survive challenges; the world simply acquiesces to his ostensible childlike innocence coupled with his irresistible magnetism. Sebastian's ethereal pulchritude navigates him through life and he complacently relies upon providence.

IV. Comic Conventions, Tragic Possibilities: "For His Love Dares Yet Do More"

Up until this point in the essay, I stressed the improbability of Antonio, the Romantic Savior, sharing a happy ending with Roderigo, the Sexual Chameleon, in which he receives love as unselfishly extravagant as he relinquishes it by the conclusion of *Twelfth Night*—after all, the play is a romantic comedy, and comic convention dictates that heterosexual couples replace homosocial pairs by the time the final curtain falls. However, beyond the pairs of happy lovers, an inconsolable pall pervades the end of *Twelfth Night*: Malvolio swears he will have revenge, Sir Toby has no choice but to marry Maria, and Antonio stands excluded while Sebastian kisses Olivia—all of which suggest the potential for tragic elements. In his study of Shakespeare as a tragic playwright, Robert Ornstein argues that the number and variety of pattern developments in Shakespeare's tragedies present an enormous obstacle to broad generalization (259). He insists that a cogent definition of Shakespearean tragedy is not all-inclusive although "all tragic plots are threaded by ironies" (262). Ornstein doubts "whether a template abstracted from Shakespeare's tragedies can encompass the different ways the tragedies speak to us of the mysteriousness of human destiny" (263). Moreover, the study of Shakespeare's tragedies hinge upon appreciating the idiosyncrasy of Shakespeare's creativity and becoming familiar with the various tragedies so that readers are able to use the knowledge of one play to refine an understanding of another (264). Ornstein concludes: "The longer we live with the plays, the more we appreciate the wholeness of Shakespeare's artistic achievement. We recognize that he returns again and again to the moral themes and dramatic situations that interest him…[and] sometimes recognize significant parallels in plays that are very different from one another" (265). That said, Antonio's problematic ending resembles tragedy more than comedy, which further challenges the standard expectations of comedy (and of tragedy.)

Twelfth Night imports tragedy into its comedy and offers Antonio's unsatisfying resolution immediately in the wake of Sebastian's impetuous decision to yoke his future to Olivia. Independent of his callous rejection by Sebastian, Antonio's predicament is extremely troubling. Preceding his reunion with Sebastian, Antonio defends Cesario, who he mistakes for Sebastian, when Sir Toby and Sir Andrew attack the youth: "Put up your sword. If this young gentleman / Have done offence, I take the fault on me / If you offend him, I for him defy you (3.4.307-310). Although Antonio confuses Cesario for Sebastian, his undeniable love not only punctuates the scene, but repels the violence threatening Sebastian's disguised sister. When Sir Toby enquires about Antonio's identity and why he interferes, Antonio answers: "One, sir, that for his love dares yet do more / Than you have heard him brag to you he will" (3.4.311-312). Whether he battles a violent sea or razor-sharp steel, Antonio proves himself irrefutably heroic on multiple occasions. He is a Romantic Savior worthy of a lover who does not throw his depthless attachment back on his face like cheap ale—and deserving of a pardon for any past infractions he committed. Viola testifies to Orsino of Antonio's intercession, announcing: "Here comes the man, sir, that did rescue me" (5.1.46). Certainly, protecting Orsino's beloved Cesario should register favorably

upon the count, but he does not acknowledge Antonio's gallantry even when Viola repeats it. She explains: "He did me kindness, sir, drew on my side..." (5.1.62). Still, Orsino remains unable to fathom Antonio's valorous behavior, and, even at the end of the play, Orsino does not connect the succession of events to deduce that without Antonio shielding Cesario, Viola could not share a future with Orsino.

Antonio's lugubrious quandary originates from loving Sebastian and doing everything possible to secure Sebastian's happiness—even though ultimately, Antonio is ostracized from his former lover's happiness. Towards the very end of the play, Feste, in a mockery of Malvolio's previous hubris, pantomimes: "Some are born great, some achieve greatness / and some have greatness thrust upon them" (5.1.364-365). To paraphrase Feste, Antonio is neither born lonely, nor achieves loneliness from his actions, but has it thrust upon him. The end of the play provides "an image of loss that it can do little to assuage, since at the end Antonio finds Sebastian only to stand silently by, watching him commit himself to Olivia" (89). Antonio's future without a partner who reciprocates wholeheartedly his attachment darkens the play in a manner, I struggle to nonchalantly shrug away. His predicament especially resonates because humanist education avows specific sentiments regarding fairness, equality, and justice. Antonio's love prospect, his champion does not exist. His faithfulness wrought punishment instead of fidelity.

Olivia exclaims "Most Wonderful!" as she appraises the titillating spectacle of her two favorite men (Cesario and Sebastian) side by side, which reinforces the notion that physical/sexual attraction possesses duality (5.1.221). If Olivia can love both Cesario and Sebastian without conflict, it stands to reason that no qualms would circumvent her from loving both Roderigo and Sebastian. By the same token, Sebastian could emulate Olivia and refuse the finality of Antonio being banished from his life. Maybe Roderigo reemerges powerfully when Sebastian exclaims: "Antonio! O my dear Antonio / How have the hours racked and tortured me / Since I have lost thee!" (5.1.214-216). The text does not explicitly authenticate this supposition, but it's easy to envision Sebastian leaping effusively into Antonio's arms. Arguably the visceral outburst Sebastian unleashes upon seeing Antonio again after only a brief separation rivals the discovery of Viola, alive and well, who was absent from him for three months: "Were you a woman, as the rest goes even / I should my tears let fall upon her cheek / And say, 'thrice welcome, drowned Viola" (5.1.235-237). The twins' reunion superficially elicits relief from Sebastian, but his unbridled enthusiasm upon seeing Antonio bristles with naked intensity; and at last, an unmistakable impression manifests that Antonio is irreplaceable in Sebastian's life, his loss threatens to haunt Roderigo forever. Of course, this is the conundrum of Roderigo's/Sebastian's fraught relationship with Antonio; it teeters emotionally each moment and totters between breathtaking commitment and unabashed indifference.

Sebastian's reunion with Viola emboldens Antonio to reconsider the role he served for the hapless young beauty. Startled by Viola's visage identical to his own, Sebastian declares: "I never had a brother" (5.1.222). He expresses this sentiment unequivocally in Antonio's presence (who acted as father, uncle, and brother to him). For his part, Antonio presents his case best:

> Let me speak a little. This youth that you see
> here I snatched one half out of the jaws of death
> Relieved him with such sanctity of love
> And to his image, which methought did promise
> Most venerable worth, did I devotion.
> (3.4.356-360)

After Antonio enumerates all the actions he performed to his benefit, what more could Sebastian desire from a brother? Literally and metaphorically, he found a fraternal sibling in Antonio. Casey Charles points out that the dimension of Antonio's role in Sebastian's life defies conventional labels: "What is unusual in this relationship is that Antonio, although of lower social status than Sebastian, is the more powerful and principled figure, a circumstance that places their connection outside the scope of the usual master/servant, teacher/student matrices" (137). Indeed, because Sebastian initially conceals his true identity, Antonio possesses no other recourse than to intuit what Roderigo desires from him and to perform that part. Additionally, Sebastian adopts an alter-ego that attracts Antonio's unrestrained adoration. If Sebastian cajoled Antonio into believing that he is orphaned without family, Antonio gladly substituted himself for the nuclear relations Sebastian lacks.

Because no other viable romantic candidate exists in *Twelfth Night* to provide Antonio the happiness he temporarily enjoyed with Roderigo in Elysium, I adamantly assert that Sebastian represents

Antonio's sole incarnation for homoerotic companionship. This means Roderigo must return to the forefront of Sebastian's sexual psyche and demand a place in his marriage for Antonio. Laurie Osborne concurs with my theory and invokes Pequigney: "He claims 'that in taking a wife Sebastian will not need suffer the 'rack and torture' of losing his male lover [Antonio]' and in a footnote, imagines an appropriate staging for the final scene: If I were to direct the play, I would want Olivia, Sebastian (in the middle), and Antonio to leave the stage together, arm in arm" (108). Pequigney's hypothetical stage direction possesses seductive appeal, but detractors may interject that Shakespeare's intent does not permit romantic threesomes, and that Shakespeare's Elizabethan- era audiences would reject the possibility. Respectfully, such a rejection fails to account for the durability of Shakespeare through four hundred years of shifting cultural mores and social norms.

If Olivia sanctions the prospect of a romantic threesome, she then becomes the catalyst that upends the stark tableau of Antonio as a frustrated eunuch condemned to loneliness and desolation. The incontrovertible truth is that Antonio cannot continue in Sebastian's life unless Olivia embraces Rodrigo's homoeroticism, which thrives matter of factly alongside Sebastian's desire for feminine companionship. This contingency might also hinge upon Osborne's description of an 1810 revision of Antonio's invented pardon by John Philip Kemble: "'[Sebastian runs to Antonio, embraces, brings, & presents him to Olivia.]' By including this stage direction, Kemble presents the reunion of Antonio and Sebastian in vivid physical stage action. This dramatic gesture seems fully to support Pequigney's reading of the scene's resolution as involving a complete reunion of the two men" (111). Although Kemble's stage direction unleashes an opportunity for Antonio and Roderigo to recapture their time together in Elysium, it does not ameliorate the preceding scene in which Sebastian greets Viola costumed as Cesario and behaves toward Antonio as if their domestic partnership for three months meant nothing. However, the promise of a passionate display of affection from Sebastian to Antonio resurrects the private intimacies in which they engaged prior to his seduction by Olivia's handsomeness (and luxury).

The precise nature of Sebastian's and Antonio's relationship encourages vigorous speculation because their prolonged physical intimacy transpires beyond the audience's scrutiny. Roderigo may love Antonio, but feckless Sebastian loves himself more and displays little of his sister's wisdom beyond her years. Charles offers: "Similarly, though critics assume Antonio to be older and more experienced than Sebastian...the play does not make the age difference between the two so discernible that this relationship falls squarely within the man/boy paradigm" (137-138). Charles' observation dovetails with the circumspect reality of the play that divulges meager clues revealing Antonio's maturity or youth. What contributes to the illusion of Antonio being more sophisticated than Sebastian rests on the dichotomy between how Viola and Sebastian react to life after confronting death's cold kiss. Almost immediately, Viola strategizes how to proceed forward and infiltrate a new environment. Her stratagem comes to fruition within three days. Conversely, Sebastian seems sanguine at Antonio's side for several months until Illyrian wanderlust bites him. Remember Viola's cryptic confession to Orsino: "I am all the daughters of my father's home / And all the brothers" (2.4.1120-121)? Paraphrasing Sebastian, Antonio represents many males of the Sexual Chameleon's family—father, brother, uncle, and cousin--during their seclusion together.

IV. Endings (Happy and Otherwise): "Do Not Tempt My Misery"

This essay sows a conversation that may continue fruitfully along fresh paths of inquiry. Further analysis of sexuality in *Twelfth Night* could delve into how Sebastian reverses gender performance as a survival strategy eschewing traditional masculine identifications. A more avant-garde critical reading could juxtapose the twins' roles of objectified males in the play, reconfiguring the comedic terrain of sexuality and gender. The text implies that Viola and Sebastian are practically orphans. It's telling that Sebastian and Viola lack parental supervision because the ill-fated shipwreck allows them to reconnect with paternal symbols and a maternal substitute. Are Antonio and Olivia lovers who stimulate Sebastian's libido or is Antonio the stalwart father who will never leave Sebastian's side and is Olivia the sexy mother who can nurse him at her breast even as she provides him safe haven in her bed? Is Orsino truly the man of Viola's girlish fancy or does he personify a father with whom she can permissibly make love?

Their parents' absence leaves indelible psychic impressions on the twins' sexual proclivities that beg commentary and notation.

Presently, Antonio's unsatisfying resolution at the end of *Twelfth Night* fails to engender mirth as comedy often does. Besides the vague transgression that Orsino and Antonio murkily reference, which collaterally injures Orsino's nephew, Antonio's behavior during the play prohibits that solitude should define his destiny. His aspirational selflessness prevents Sebastian's demise and also abbreviates Viola's mourning of her presumed dead brother. Yet, Antonio's heartbreaking peril derives from his exponential love for Sebastian which receives no gold recompense. To the contrary, he begs Sebastian: "If you will not murder me for my love, let me be your servant" (2.1.32-33). To his remarkable credit, Antonio utters this earnest plea after learning Sebastian deliberately deceived him for months while shamelessly luxuriating in Antonio's extravagant love without even submitting a cursory explanation or half-hearted apology for his fraud. Viola, on the one hand, remunerates the captain handsomely who saves her: "I pray thee—and I'll pay thee bounteously/ Conceal me that what I am, and be my aid" (1.2.49-50). She not only finesses her captain's help (physical and fiscal), but Viola also brags that she (disguised as a boy) will entertain and delight Orsino. On the other hand, since Sebastian neither rewards Antonio for wresting him from the clutches of death nor describes how he entertained and delighted his benefactor, their situation registers as decidedly more poignant. More disturbing, Sebastian seems to exploit Antonio as a placeholder until a better prospect materializes in the form of Olivia. Indulging self-gratification while callously ignoring a person who bathes one in affection, indicates the absence of either a soul or conscience. Sebastian's wanton narcissism mars his sexual appeal and undercuts the powerful charisma that obviously beguiled Antonio.

Ultimately, Antonio's unsatisfying resolution squanders the strength of a potent character uniquely atypical in *Twelfth Night*. He is no less worthy of love than Olivia; and, ironically, Antonio and Olivia swap dispositions. At the beginning of the play, Olivia mourns her brother and by the end of the play Antonio faces imprisonment because he accompanies his beloved Sebastian to a hostile country. Antonio does not obfuscate or pretend to be anyone except who he is—honorable, chivalrous, and loving. He executes no physical or emotional subterfuge and he deserves better than ashes and soot. And yet, as Chad Allen Thomas argues, "A happy ending for Antonio might not, however, have seemed out of place on the early modern stage. Whereas our modern conception of sexuality often coincides with ideas about sexual identity, which are relatively recent formulations, Shakespeare's audiences viewed eroticism and sexual attraction as fluid and multivalent" (227). As Thomas observes, the modern temptation to categorize may seduce one to conclusively identify Antonio's sexual orientation, yet the validation of Antonio's love for Sebastian is not contingent upon ascribing a queer orientation to him. Furthermore, Alan Sinfield theorizes that marriage does not preclude Antonio and Sebastian from participating in fully realized sexual love: "I see no reason why Antonio should appear at the end as the defeated and melancholy outsider that critics have assumed... [Sebastian] is the man Antonio thought he was. There is no significant confusion in their relationship, and no reason why marriage to a stranger heiress should change it" (*Faultlines* 73). While Sinfield is persuasive in his assertion that Sebastian's marriage to Olivia is perplexing, this essay argues strenuously that Antonio does not apprehend what he's purchasing in Sebastian. A happy ending may exist for Antonio and Roderigo, but if Sebastian ever really loved Antonio, he taints that love irrevocably after he becomes Olivia's passive conquest.

Antonio's happy ending shall remain improbable until a savvy stage director highlights the schism between the Sebastian and the Roderigo personalities in order to project that Antonio is sincerely loved by Roderigo beyond his role as Sebastian's expendable source of protection. After all, if Orsino cherishes both Cesario and Viola, it will not strain credulity or the elasticity of romantic comedy for Sebastian to satiate both sides of his sexual psyche by loving Antonio and Olivia. Real life teems with posers who soil love and exploit it for inexplicably base motivations. A sensitive, virile character with boundless integrity and unmatched depth, such as Antonio, finding contentment with the object of his affection, almost balances the scales for every cheated loser who earned love and regrettably did not reap the fruits of their labor. Sinfield imagines a love-affirming production of *Twelfth Night* that caresses Antonio: "If I were directing the play, I would show Antonio delighted with the way it all turns out. Sinfield

also has suggested the possibility of Sebastian leaving the stage 'flanked by both Olivia and Antonio'" (*Faultlines* 73). Sinfield also calls attention to "why such an arrangement is more likely to suit Olivia (who loves the still-impossible Cesario and has only a forced and formal marriage with Sebastian" (*Shakespeare, Authority, Sexuality* 15). Lastly, Sinfield surmises that the continuation of Antonio's relationship with Roderigo in Illyria is inextricably linked to the largesse of Olivia. To extend Sinfield's suggestion, an additional gesture might show Roderigo leading Antonio away from Orsino's guards towards Olivia, with Sebastian's arm encircled around Antonio's waist to instantiate that, in spite of Sebastian's sudden marriage to the lovely heiress, Antonio is no inconsequential dalliance but a treasured paramour. Furthermore, if Roderigo bestows a simple kiss upon Antonio, matched by an analogous kiss from Olivia upon Antonio, this would telegraph that Olivia not only accepts but fully embraces the reality of Antonio--an invited connubial gift for Sebastian. Thus, the addition of a single moment corrects the standard ending found in romantic comedy without inserting a single word of additional dialogue: the protagonists do not have to choose between admiring an erotic dessert and consuming it. They really can have "what they will." Such a reading of *Twelfth Night*, which alludes to a polyamorous connection between Antonio, Roderigo/Sebastian, and Olivia, exceeds the expectations of what most lovers will: love never leaving any lover humiliated, deserted, exploited, abandoned—unloved.

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Reading Historical Photographs

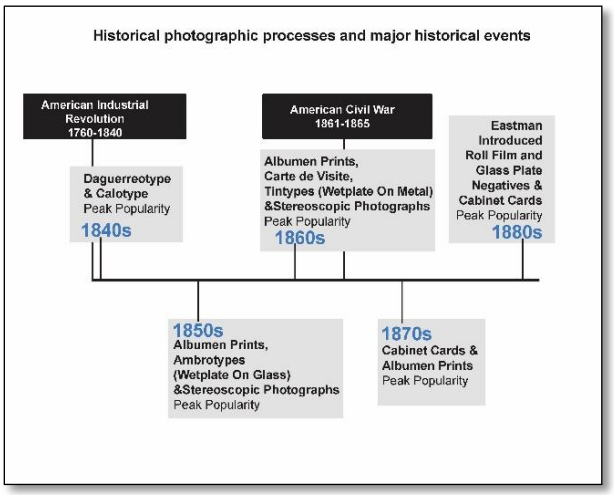
Emily Pate
Department of Art, Art History, and Design

Abstract **-** For the past two years Emily Pate researched early historical photographic processes and how they are interpreted to gain historical knowledge of the past. The challenges of this project included understanding historic photographic processes that are not commonly used in today's society, and how those photographs can provide historical insight. In the spring of 2013, Pate began an ongoing research project to explore photographic materials and their history through found negatives and undeveloped film. She then began to plan the process of documentation, research, and archiving the photographs, as well as the photographic techniques used. The images she works with are possibly missing from any other archive and could show something not previously recorded.

I. Introduction

The photograph was invented in 1839 almost simultaneously by Louis Daguerre in France and by William Henry Fox Talbot in England. The Enlightenment and the Industrial Revolution periods both contributed to the invention of photography. Scientific experimentation with natural materials and innovations in technology during these periods led to changes in how society perceived reality and art, which ultimately led to the invention of photography.

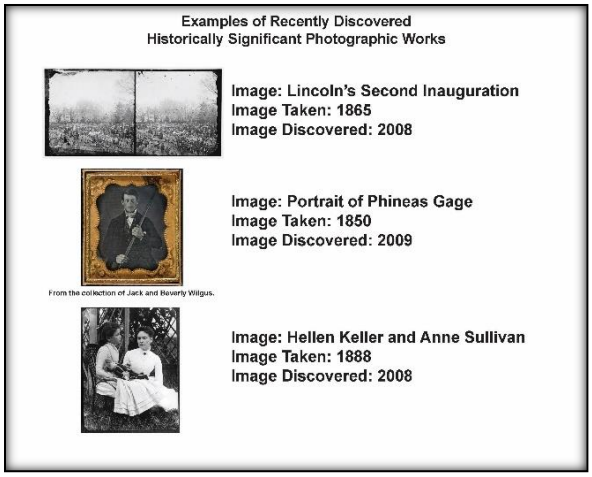
Photography coincided with other major cultural and political events in American history. When photography was popularized in the United States, the Industrial Revolution was just ending and photography continued to grow as a medium through the period of the United States Civil War (see Fig. 1). Since its inception, the photograph took on many different forms. The information provided by the techniques and materials used to make a photograph explain how photography has been used as a means to record a person or event, and how it developed as an art form.



(Fig. 1) Source: Lavedrine, Bertrand. *Photographs of the Past Process and Preservation*. Getty Publications. 2009.

Photographic processes include daguerreotypes and calotypes in the 1840s, albumen prints, ambrotypes, and stereographic images in the 1850s, carte-de-visites and tintypes in the 1860s, cabinet cards in the 1870s, and roll film in the 1880s (Fig. 1). Each process built off of the process that preceded it both in method and in quality. Every time a new process emerged, more knowledge was gained from the physical details recorded by these processes. Eventually, with the invention of roll film, photography became accessible to the professional and the amateur alike, meaning that not only would the wealthy be able to document their lives, but so would the common man and woman.

Photography opened the door for the physical recording of history that had been unavailable to previous generations. It is through this medium we are able to learn so much about the generations that proceed our own. In modern times, there have been many discoveries of photographic articles that contribute to the understanding of historical events. Images such as *Lincoln's Second Inauguration* weren't discovered until 2008 and the only known photo of historical figure Phineas Gage was discovered in 2009 (Fig. 2).



(Fig. 2) Source: "10 Fascinating Recently Discovered Photographs." *Listverse*, 27 Oct. 2009, http://listverse.com/2009/10/27/10-fascinating-recently-discovered-photographs.

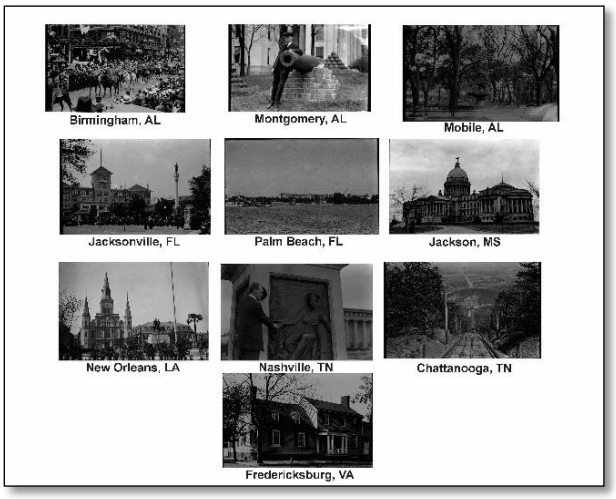
Images are often misinterpreted or misplaced, which can lead to data being mislabeled or discarded. For example, the image of *Lincoln's Second Inauguration* was mislabeled in the Library of Congress collection as an image of Grant's Inauguration (Eisele).

These are just a few of the many examples of historically important information from previous centuries that have been discovered in modern times. Whether it is simple labeling mistakes or an unknowing viewer, information is easily discarded and misplaced. While it takes the work of historians to verify the identity of these images, it is crucial that the images be conserved so that they can also be verified through their medium—photography.

II. Body

Over the past two years, Emily Pate used her knowledge of historical photographic processes by pursuing a personal photographic preservation project. In 2015, Pate purchased a Kodak Negative album with about 100 negatives.

With no knowledge of what would actually be in the album, Pate began her research as soon as the album arrived in the mail. She carefully studied the content of the images and determined that they were from the early 1900s, and taken throughout the southern United States. She contacted experts on the places that had been identified in the photographs, and they were asked to verify or correct the interpretations of the photographs. The images Pate discovered and authenticated were from Birmingham, AL; Mobile, AL; Montgomery, AL; Jacksonville, FL; Palm Beach, FL; Jackson, MS; New Orleans, LA; Chattanooga, TN; Nashville, TN; Fredericksburg, VA (Fig. 3). While Pate has not yet been able to identify the photographer behind these unique photos, they have provided a unique opportunity to learn about the past and the process of archiving historical photographs.



(Fig. 3)

Pate's process involves cleaning each negative, making a physical print in the dark room of each negative, and making notes about her research on each photograph. Next, Pate uses online resources, as well as expertise from archivists and historians to verify her research. Cleaning the negatives involved gentle wiping the non-emulsion side of the negative with a cotton ball with distilled water. It is important not to try to clean the emulsion side because it is easily damaged and scratched. Once the negatives were clean, Pate made prints in the darkroom from each negative. Pate chose to make 8x10 inch prints so that the images were large enough to research details with a loupe (magnifying tool).

It is important to note that there is always the possibility that these images had not been previously printed in physical form. Photographers often only printed what would be used for their business purposes and the rest of the images would be stored or discarded completely. It is Pate's belief that these images had been stored for quite some time before she purchased them. The amount of dust on the negatives and the lack of

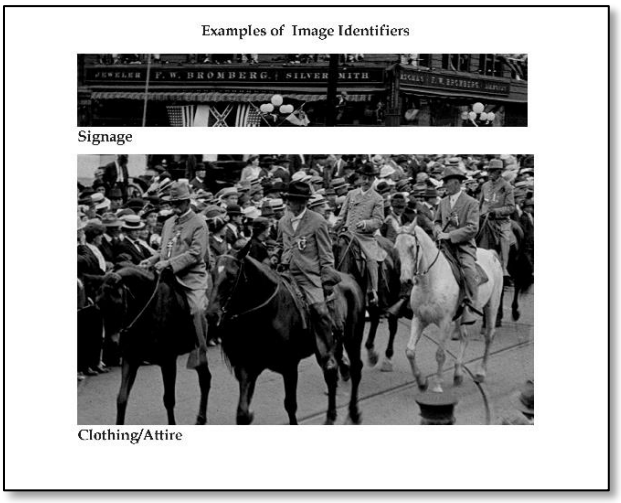
scratches or deterioration of the negatives lead her to this conclusion.

The research of the images involved many aspects. First, Pate considered the medium. These photographs were printed from an unusual negative. Most negatives in their original state have borders. These particular negatives had their borders cut off, so the negatives had only the images without borders. This type of exception in the medium can often make it difficult when trying to identify the type of film being used. Photographers often use the information on a negative to help identify a date range for when the image was taken. Typically, starting around the 1930s, film would often have a manufacturer's name and a film type indicated on the edge of the negative, as with 35mm film. Later, larger sheet film, could be identified by the types of notches (or cut outs) used to correctly place the film in the camera.

Despite the unusual negatives, measuring the dimensions of the image itself gives insight to the type of film and possibly when it was manufactured. Based on the film's dimensions of 2 ¼ in. by 3 ¼ in., Pate was able to identify the film as medium format 120 mm film ("Standard Film Sizes and Plates."). Medium format, 120 mm, was produced beginning in the early 1900s and is still produced today ("Standard Film Sizes and Plates."). This information helped Pate to set the frame of when these pictures could have possibly been taken.

The next step in Pate's identification process was to look more closely at the details of the images. Street signs, buildings, posters, transportation, and clothing are all factors that are taken in to consideration when trying to date an image. For this particular project, Pate used key identifiers, such as the ones previously mentioned, to continue narrowing down possible time periods.

One specific example of her research methods can be seen in Fig. 4. This is an image of Birmingham, Alabama. Pate was able to identify Birmingham from several distinct indicators in the image. The first indicator she used was the business sign seen clearly in the upper left hand corner of the image "F.W. Bromberg Jewelers." Upon investigation of this business, Pate determined that the image could possibly be from Birmingham, since there was an F.W. Bromberg Jeweler in that area. At this point in the process she is not certain about the image's location, but it is a starting point for Pate to continue a deeper investigation into the image.



(Fig. 4)

Another indicator is the dress and decorum of the men riding the horses. The people on the horses appear to be taking part in some sort of parade or procession. Pate assumes that the image was taken in Birmingham, as well as acknowledging that the medium format film was likely from the early 1900s. With these assumptions, she began researching the clothing of the men in the parade procession. It seemed that they are in uniforms, possibly related to the military. This conjecture led Pate to research military parades and processions in Birmingham Alabama in the early 1900s. Pate did most of her research by comparing her images to ones she found online, for example at the Birmingham Public Library Archives website ("View of Great Confederate Reunion Parade in Birmingham."). She then emailed her image to an archivist at the Birmingham Public Library and asked for help in confirming the location. The archivist was able to verify Pate's findings and the image was determined to be the Reunion of the United Confederate Veterans on May 16-18, 1916 ("View of Great Confederate Reunion Parade in Birmingham.").

This process was repeated for each of the nearly 100 negatives that Pate purchased. Each negative proved to have its own challenges and mysteries, but the process of attempting to identify the images remained the same.

III. Conclusion

The purpose of this project was to attempt to use the knowledge of historical photographic processes and media to understand history. It was also a study of preservation and how important it is to understand a medium in order to preserve history itself. While some of the images Pate found have yet to be identified, more than three-fourths of the images have been identified. She plans to take the necessary steps in preserving the physical negatives as well as to make digital copies of each negative to create a digital archive of the images.

As more people begin to use digital technology as a way of documentation, many analog techniques of photography are discarded and lost forever. Even images such as the "snapshot" are important for gathering information for historical insight and preservation. Consider the many negatives and prints that exist but have yet to be discovered and authentically interpreted. This information is crucial to providing insight about past generations.

Preservation of documents is essential for preserving the history of a generation, a place, and time period. With the emergence of digital technology, understanding older technologies such as film and the early processes of photography, has become a more specialized field.

With historical photographic works being discovered every day, it is imperative that we have people who understand the significance and value of these images. Interpreting and protecting such work is crucial to preserving our history.

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Inflationary Gravitational Waves and B-Mode Polarization of the Cosmic Microwave Background

Kylie Todd Heflin
Department of Physics

Abstract **-** This paper is an attempt to introduce the concept of gravitational waves, interpret the results of BICEP2 and *Planck*, analyze the methods employed by both missions, and evaluate the implications of the existence of inflationary gravitational waves (IGWs). BICEP2/*Keck Array* are experiments aimed at measuring the polarization of the cosmic microwave background (CMB), as well as providing speculation regarding the origin of B-Mode polarization of the CMB. In June 2014, BICEP2 reported the detection of such polarization but acknowledged uncertainty regarding its origin due to the possibility of gravitational lensing caused by cosmic dust. BICEP2's detection used a CMB polarimeter specifically designed to observe the B-mode power spectrum around a multipole moment l ~ 80. In May 2015, the European Space Agency's *Planck* mission published a mapping of the intensity and polarization of the sky at microwave frequencies in an attempt to address the problem of cosmic dust. In a joint analysis of their data in 2015, BICEP2/*Keck Array* and *Planck*, by evaluating the tensor-to-scalar ratio *r*, concluded that confirmation of inflationary gravitational waves would require additional data. The detection of inflationary gravitational waves would have a profound impact on cosmology, and could provide insight into the earliest moments (~10^{-32}s) after the Big Bang. The presence of IGWs, or lack thereof, may disconfirm or confirm, respectively, the validity of the standard ΛCDM-model of cosmology, which does not include a period of inflation.

I. Introduction

Gravitational Waves

Mass in nonspherical, nonuniform motion produces ripples in the curvature of spacetime referred to as gravitational waves. It is believed that gravitational waves are produced by a variety of astrophysical phenomena, including binary star systems, supernova explosions, collapse of black holes, and, as we shall explore, the big bang. For the sake of simplicity, this introduction will concern itself primarily with *linearized* gravitational waves. That is, a gravitational wave traveling through a flat spacetime (referred to here as Minkowski spacetime), denoted by the metric $g_{\alpha\beta}(x) = \eta_{\alpha\beta}$, where

$$\eta_{\alpha\beta} = \begin{array}{c} \\ \mathrm{t} \\ \mathrm{x} \\ \mathrm{y} \\ \mathrm{z} \end{array} \begin{array}{c} \begin{array}{cccc} \mathrm{t} & \mathrm{x} & \mathrm{y} & \mathrm{z} \end{array} \\ \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \end{array}.$$

Note that here we employ geometrized units (c = G = 1). Some properties of linearized gravitational waves are that they propagate at the speed of light, they are transverse, they have two independent polarizations, they can be detected by their effect on the relative motion of test masses, and they carry energy [15].

The propagation of a gravitational wave can be thought of in terms of a perturbing metric to the metric of Minkowski spacetime. Namely,

$$h_{\alpha\beta}(t, z) = \begin{array}{c} \\ \mathrm{t} \\ \mathrm{x} \\ \mathrm{y} \\ \mathrm{z} \end{array} \begin{array}{c} \begin{array}{cccc} \mathrm{t} & \mathrm{x} & \mathrm{y} & \mathrm{z} \end{array} \\ \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & f_+(t-z) & f_\times(t-z) & 0 \\ 0 & f_\times(t-z) & -f_+(t-z) & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \end{array}$$

where $f_\times(t - z)$ and $f_+(t - z)$ are representative of the two possible polarizations of our linearized gravitational wave traveling in the *z*-direction. Now, a complete description of our metric $g_{\alpha\beta}$ is available [15]:

$$g_{\alpha\beta}(t, z) = \eta_{\alpha\beta} + h_{\alpha\beta}(t, z).$$

For now, we need only consider the case of a gravitational wave of + (plus) polarization. In this case, our perturbing metric can be written

$$h_{\alpha\beta}(t, z) = \begin{array}{c} \\ t \\ x \\ y \\ z \end{array} \begin{array}{c} \begin{array}{cccc} t & x & y & z \end{array} \\ \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \end{array} f(t-z),$$

with $f(t - z)$ being any function of $t - z$ where $|f(t - z)| << 1$ (meaning that the perturbation is small) [15].

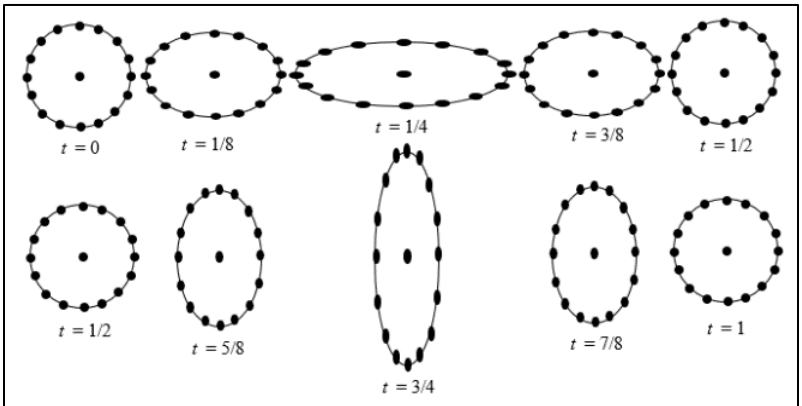

Figure 1: Compression and expansion of a ring of particles through time due to a gravitational wave propagating into the page, where the time *t* is measured in fractions of complete cycles (*t* = ½ indicates half a cycle).

If we set $f(t - z) = a \sin[\omega(t - z)]$, we obtain an equation representative of a gravitational wave with frequency ω and amplitude a. Arranging a group of particles in a circle through the x-y plane around a central test mass with coordinates $(t, 0, 0, 0)$, we can see that directions perpendicular to the direction of propagation oscillate between a compressed state and an expanded state throughout time. The line element of such a spacetime is

$$ds^2 = -dt^2 + \{1 + a \sin[\omega(t - z)]\}dx^2 + \{1 - a \sin[\omega(t - z)]\}dy^2 + dz^2$$

The line element illustrates the curvature of spacetime due to the gravitational wave, and corresponds to our metric, $g_{\alpha\beta}(t, z)$. We can see that as time increases, the actual distance between two points on the x-y plane oscillates. This becomes even more apparent if we define a new time-dependent coordinate system for the x-y plane:

$$X(t) = [1 + a \sin(\omega t)]x,$$
$$Y(t) = [1 + a \sin(\omega t)]y,$$

for which we receive the familiar Euclidean line element $dS^2 = dX^2 + dY^2$ [15]. This oscillation in the *curvature of spacetime is responsible for the detection of B-modes in the CMB [19, 20, 23, 29, 30].

Polarization of Electromagnetic Radiation by Gravitational Waves

The CMB is characterized entirely by its temperature and polarization in a given direction. Gravitational waves have the potential to impart a unique polarization, called B-mode polarization, on radiation. As we will discover later, the presence of B-mode polarization in the CMB is a source of intrigue in cosmology, and can be indicative of IGWs. Before discussing the mathematics of E- and B-mode polarization, we shall explore them conceptually [19, 20, 23, 29, 30].

Consider an electron at rest in the midst of a pressure wave (Figure 2). From the reference point of the electron, a fluctuation in density occurs. Because density is a scalar, we refer to this as a scalar fluctuation. Next, consider the possibility of photons approaching the electron from all directions. Because there are fewer surfaces for them to scatter from, photons will, on average, prefer to scatter into regions of lower density (or higher temperature). An observer looking at this scenario would find that light is polarized in a horizontal direction for the moments in which the electron was in a cold region of a pressure wave propagating in the horizontal direction (Figure 2A). Conversely, an electron in a hot region of the same pressure wave will polarize light vertically (Figure 2B). The resulting polarization pattern is referred to as E-mode polarization and can be seen in Figure 3A [5].

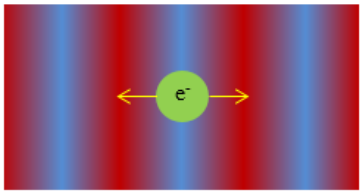

Figure 2A: Light polarizes horizontally when scattered off of an electron in a cold region of a pressure wave traveling in the *x*-direction.

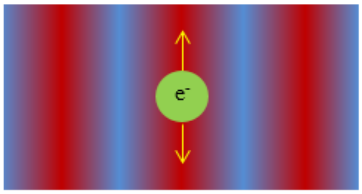

Figure 2B: Light polarizes vertically when scattered off of an electron in a hot region of a pressure wave traveling in the *x*-direction.

E-mode polarization can be produced by gravitational waves of plus (+) polarization as well as by pressure waves [5, 15]. Indeed, as is indicated by Figure 1, the effect of curved spacetime due to a + polarized gravitational wave propagating into the ring

of particles is strikingly similar to the effect of a pressure wave propagating from left to right across the ring. If the central test mass is an electron, then t = ¾ in Figure 1 roughly corresponds to Figure 2A, where the electron is in a cold region of a pressure wave. Conversely, t = ¼ roughly corresponds to Figure 2B, where the electron is in a hot region of a pressure wave. This behavior is characteristic of dipoles, which can polarize in two directions (horizontal and vertical for our pressure wave). [5, 12, 13, 15]

This, of course, is but one of two possible polarizations of the gravitational wave. Consider the perturbing metric describing a cross (×) polarized gravitational wave:

$$h_{\alpha\beta}(t, z) = \begin{array}{c} \\ t \\ x \\ y \\ z \end{array} \begin{array}{c} \begin{array}{cccc} t & x & y & z \end{array} \\ \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \end{array} f(t-z).$$

Again, we'll suppose that $f(t - z) = a \sin[\omega(t - z)]$. In this case, the direction of oscillation of the ring of particles is not vertical and horizontal but rather in the two diagonal directions. This, in turn, produces polarization in the diagonal directions, called B-mode polarization, as illustrated by Figure 3B. The fact that this type of polarization changes when reflected is reminiscent of curl, while the E-modes presented before, with their reflective invariance, are reminiscent of divergence. [5, 15, 16, 32]

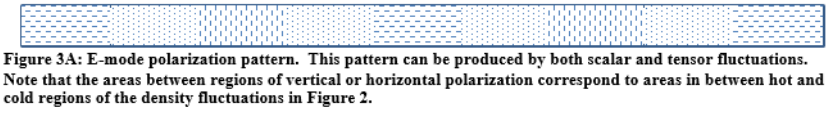

Figure 3A: E-mode polarization pattern. This pattern can be produced by both scalar and tensor fluctuations. Note that the areas between regions of vertical or horizontal polarization correspond to areas in between hot and cold regions of the density fluctuations in Figure 2.

Figure 3B: B-mode polarization pattern. This pattern can only be produced by tensor fluctuations (as in gravitational waves). Note that, contrary to E-mode patterns, B-modes are not invariant under reflection. That is to say, if I were to hold Figure 3A up to a mirror, I would see the same image. If I were to hold Figure 3B up to a mirror, however, I would see a reflected image. Forward diagonal polarizations (/) would become backward diagonal polarizations (\ ). This characteristic is vital to understanding B-modes.

In fact, this is where the terms "E-mode" and "B-mode" originate. In electrodynamics, Maxwell's Equations state [13]:

$$\nabla \cdot \mathbf{E} = \frac{1}{\epsilon_0}\rho \qquad \nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

In the case of electrostatics, however, the partial derivatives with respect to time yield zero, causing the curl of the electric field to vanish. The only terms of consequence, then, are the divergence of the electric field ($\nabla \cdot \mathbf{E}$) and the curl of the magnetic field ($\nabla \times \mathbf{B}$). For this reason, when considering polarizations, divergence is associated with the electric field (E-modes) and curl with the magnetic field (B-modes). The analogy of E-modes and B-modes in polarization to electrostatics goes no further than this [5, 16, 32].

The most important piece of information to take away from this is that scalar fluctuations like pressure waves tend to only produce E-mode polarization, while tensor fluctuations like gravitational waves produce both E-modes and B-modes [5, 16, 23]. Because of this, the tensor-to-scalar ratio r is of great interest in the study of the polarization of the CMB [2, 3, 4, 28]. In order to calculate this tensor-to-scalar ratio, we must first consider Stokes' parameters.

Polarization is characterized by the Stokes parameters Q, U, and V. For a monochromatic electromagnetic wave moving in the z-direction, the components of the wave's electric field vector are [19]:

$$E_x = a_x(t) \cos[\omega_0 t - \theta_x(t)],$$
$$E_y = a_y(t) \cos[\omega_0 t - \theta_y(t)]$$

where ω_0 represents frequency. The wave is considered polarized if these two components are correlated. The Stokes parameters are defined by the following relations [19, 20, 23, 27, 29, 30]:

$$I \equiv \langle a_x^2 \rangle + \langle a_y^2 \rangle,$$
$$Q \equiv \langle a_x^2 \rangle - \langle a_y^2 \rangle,$$
$$U \equiv \langle 2a_x a_y cos(\theta_x - \theta_y) \rangle,$$
$$V \equiv \langle 2a_x a_y sin(\theta_x - \theta_y) \rangle,$$

where the angled brackets denote time averages. Though the radiation intensity I does not directly characterize the polarization, it is sometimes necessary in the calculation of Q and U, which are used to determine E-mode and B-mode amplitudes. A complete description of polarization comes from the polarization tensor, given in spherical polar coordinates (θ, ϕ) as [19, 27]:

$$P_{ab}(\hat{\mathbf{n}}) = \frac{1}{2}\begin{pmatrix} Q(\hat{\mathbf{n}}) & -U(\hat{\mathbf{n}})sin\theta \\ -U(\hat{\mathbf{n}})sin\theta & -Q(\hat{\mathbf{n}})sin^2\theta \end{pmatrix}$$

The polarization tensor matrix is reminiscent of the x-y submatrix of the general form of the gravitational wave perturbation metric $h_{\alpha\beta}$ given earlier. Note that this similarity is not exact, since the polarization matrix is given in spherical polar coordinates, not Cartesian coordinates. As was suggested earlier,

the plus mode of gravitational wave polarization is responsible for E-mode polarization of electromagnetic waves. Conversely, the cross mode of gravitational wave polarization is responsible for B-modes.

We seek to estimate power spectra relaying the amplitude of E-mode and B-mode polarization in the CMB as a function of multipole moment l. Ref. [19] provides a complete derivation for such estimators. The result is:

$$\widehat{C_l^{\mathrm{G}}} = \sum_{m=-l}^{l} \frac{\left|a_{(lm)}^{\mathrm{G}}\right|^2}{2l+1}, \qquad \widehat{C_l^{\mathrm{C}}} = \sum_{m=-l}^{l} \frac{\left|a_{(lm)}^{\mathrm{C}}\right|^2}{2l+1},$$

where

$$a_{(lm)}^{\mathrm{G}} = \frac{1}{T_0}\int d\hat{\mathbf{n}} P_{ab}(\hat{\mathbf{n}}) Y_{(lm)}^{G\,ab*}(\hat{\mathbf{n}}),$$
$$a_{(lm)}^{\mathrm{C}} = \frac{1}{T_0}\int d\hat{\mathbf{n}} P_{ab}(\hat{\mathbf{n}}) Y_{(lm)}^{C\,ab*}(\hat{\mathbf{n}}),$$

T_0 is the mean CMB temperature, and $Y_{(lm)}^{G\,ab}(\hat{\mathbf{n}})$ and $Y_{(lm)}^{C\,ab}(\hat{\mathbf{n}})$ are spherical harmonic functions [19, 20, 23, 29, 30]. The C_l^{G} and C_l^{C} estimators listed above provide approximations of power spectra corresponding to E-modes and B-modes, respectively, and an experimental calculation of these spectra was a primary goal for the BICEP2 mission.

It is worth noting that the propagation of a gravitational wave does not directly affect the polarization tensor. Rather, the gravitational wave alters the very metric of the polarization tensor according to the perturbing metric $h_{\alpha\beta}$. The metric of Minkowski spacetime in spherical polar coordinates is given by [15]:

$$\eta_{\alpha\beta} = \begin{array}{c} \\ t \\ r \\ \theta \\ \phi \end{array} \begin{array}{c} \begin{array}{cccc} t & r & \theta & \phi \end{array} \\ \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & r^2 & 0 \\ 0 & 0 & 0 & r^2\sin^2\theta \end{pmatrix} \end{array}.$$

Alternatively, we can express this with the line element

$$ds^2 = -dt^2 + dr^2 + r^2 d\Omega^2,$$

where

$$d\Omega^2 = d\theta^2 + \sin^2\theta\, d\phi^2.$$

Our generalized metric is given, as before, by the formula

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}.$$

We therefore require an expression for the perturbing metric $h_{\alpha\beta}$ of a gravitational wave propagating in the *z*-direction in spherical coordinates. Rewriting the metric listed earlier, we obtain

$$h_{\alpha\beta} = \begin{array}{c} \\ t \\ r \\ \theta \\ \phi \end{array} \begin{array}{c} \begin{array}{cccc} t & r & \theta & \phi \end{array} \\ \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & f_+\sin\theta\cos\phi + f_\times\sin\theta\sin\phi & f_\times\sin\theta\cos\phi - f_+\sin\theta\sin\phi & 0 \\ 0 & f_+\cos\theta\cos\phi + f_\times\cos\theta\sin\phi & f_\times\cos\theta\cos\phi - f_+\cos\theta\sin\phi & 0 \\ 0 & -f_+\sin\phi + f_\times\cos\phi & -f_\times\sin\phi - f_+\cos\phi & 0 \end{pmatrix} \end{array}$$

via coordinate transformation. Our new metric $g_{\alpha\beta}$ differs from that of the Minkowski spacetime $\eta_{\alpha\beta}$ by this perturbation, and is given by:

$$g_{\alpha\beta} = \begin{array}{c} \\ t \\ r \\ \theta \\ \phi \end{array} \begin{array}{c} \begin{array}{cccc} t & r & \theta & \phi \end{array} \\ \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 + f_+\sin\theta\cos\phi + f_\times\sin\theta\sin\phi & f_\times\sin\theta\cos\phi - f_+\sin\theta\sin\phi & 0 \\ 0 & f_+\cos\theta\cos\phi + f_\times\cos\theta\sin\phi & r^2 + f_\times\cos\theta\cos\phi - f_+\cos\theta\sin\phi & 0 \\ 0 & -f_+\sin\phi + f_\times\cos\phi & -f_\times\sin\phi - f_+\cos\phi & r^2\sin^2\theta \end{pmatrix} \end{array}$$

That this alteration to the Minkowski spacetime will have an effect on the polarization tensor $P_{ab}(\hat{\mathbf{n}})$ is immediately apparent.

We have seen that gravitational waves can "bend" electromagnetic waves into a polarized state by warping the spacetime through which they propagate. However, gravitational waves are not the only source of spacetime curvature. In fact, according to general relativity, any massive body curves spacetime around it. For such delicate phenomena as the polarization of CMB radiation, it is necessary to consider even the minutest contributions. Indeed, the influence of even IGWs is rather small due to the attenuation that occurs across the distances involved in detecting CMB polarization [4, 19, 20, 23, 29, 30]. In seeking the amount of polarization of the CMB due to IGWs, then, it becomes necessary to determine and exclude perturbations to the spacetime metric due to cosmic dust. Though the effect of a single dust particle is negligible, the cumulative lensing effect that occurs over the distances traveled by CMB radiation can have a profound effect on polarization. This lensing effect can produce B-modes from E-modes which are distinct from inflationary gravitational waves [4]. It is therefore imperative that some method be employed to rule out contributions due to cosmic dust.

Following BICEP2's declaration in June 2014 of the potential discovery of IGWs [3], this imperative fell on the European Space Agency's *Planck* mission. In May 2015, the *Planck* team published a mapping of the intensity and polarization of the sky at microwave frequencies in an attempt to address the problem of cosmic dust [28]. The data collected by *Planck* provided a framework for the members of both teams to evaluate dust contribution and attempt

to either confirm or disconfirm, once and for all, the possibility of IGWs [4].

Inflationary Gravitational Waves in Cosmology

The verification of the existence or nonexistence of IGWs will shape the development of cosmology, and could potentially disprove the standard ΛCDM-model of cosmology, which does not include a period of inflation. Ref. [24] approximates the Friedmann equation, which governs the expansion of spacetime, as

$$|\Omega - 1| = \frac{|k|}{a^2 H^2}$$

with the density parameter Ω representing total energy density, the scale factor *a* representing the total size of the universe, *k* representing the spatial curvature of the universe, and Hubble parameter *H*. Typically, a^2H^2 is decreasing. This means that Ω strays from unity, given that Ω starts near one. In other words, $\Omega = 1$ is an unstable critical point. Based on current observations, Ω appears to be within an order of magnitude of one. The instability of this value under conventional big bang models coupled with the observational evidence for it necessitates a period during which the Hubble length

$$D = \frac{c}{H},$$

which is the distance from the observer at which objects appear to be moving away at the speed of light, was decreasing. That is to say,

$$\frac{d(c/H)}{dt} < 0.$$

This is the inflationary solution to the so-called flatness problem, and helps to explain isotropies in regions of the CMB that were not causally connected in the early universe. [6, 20, 21, 24]

This early period of inflation would involve significant perturbations to spacetime in the form of IGWs [15], detectable through B-mode polarization of the CMB [3, 4, 28]. Though these perturbations were initially very violent, their propagation since the inflationary period would significantly decrease their amplitude, making them more difficult to detect directly [4]. The successful detection of an IGW, however, would provide conclusive evidence for an inflationary period in the history of our universe, and would significantly alter the pool of valid cosmological theories [6, 20, 21, 24]. In the next section, we will discuss the methods used in the BICEP2 and *Planck* missions in determining the validity of a potential IGW detection via measurement of B-mode polarization of the CMB.

II. Methods and Instruments

The BICEP, or Background Imaging of Cosmic Extragalactic Polarization, and *Keck Array* experiment series began in January 2006 with BICEP1 [2, 17]. Due to the striking similarities between BICEP1 and BICEP2, we shall endeavor to explain the BICEP1 instrument before moving on to BICEP2. Known during its development as the Robinson Gravitational Wave Background Telescope, BICEP1 first began observing in the 100 – 220 GHz (1.2 – 3.0 mm) range from the Dark Sector Laboratory at the Amundsen-Scott South Pole station in order to exploit the exceptional ~1 mm wavelength transparency of the atmosphere above the cold Polar plateau. The BICEP1 receiver was comprised of a focal plane of 49 Polarization-Sensitive-Bolometer (PSB) pairs. A PSB is, essentially, a device which provides simultaneously a measurement of total intensity and the difference between orthogonal linear polarizations (Stokes *I* and *Q*, respectively). Though PSBs can operate at frequencies up to 600 GHz (0.5 mm), the BICEP1 device, for a majority of its operations, featured 25 PSB pairs at 100 GHz, 22 at 150 GHz, and two at 220 GHz. The PSBs were arranged in pairs such that each member of a pair would respond to orthogonal linear polarizations. A two-lens refracting telescope provided full width half-maximum (FWHM) angular resolution of 0.93° at 100 GHz and 0.60° at 150 GHz and an 18° field of view. [2, 3, 4, 17]

BICEP1 spent 85% of its total operating time focusing on a region known as the "Southern Hole" (located at a right ascension and declination range of $|\alpha| < 60°$ and $-70° < \delta < -45°$), which was selected due to its low dust emission (shown in Figures 4 and 5). The apparatus operated over a two-day cycle, with four nine-hour phases observing the Southern Hole. Each phase consisted of ten 50-minute long scansets, each comprised of 50 leftward and 50 rightward half-scans. Scanning at 0.25° steps in elevation between scansets, the telescope covered the full CMB field after just two phases [2, 3]. We are, however, only concerned with BICEP1 to the extent that it is similar to BICEP2 (for more information on BICEP1, consult Ref. [2]).

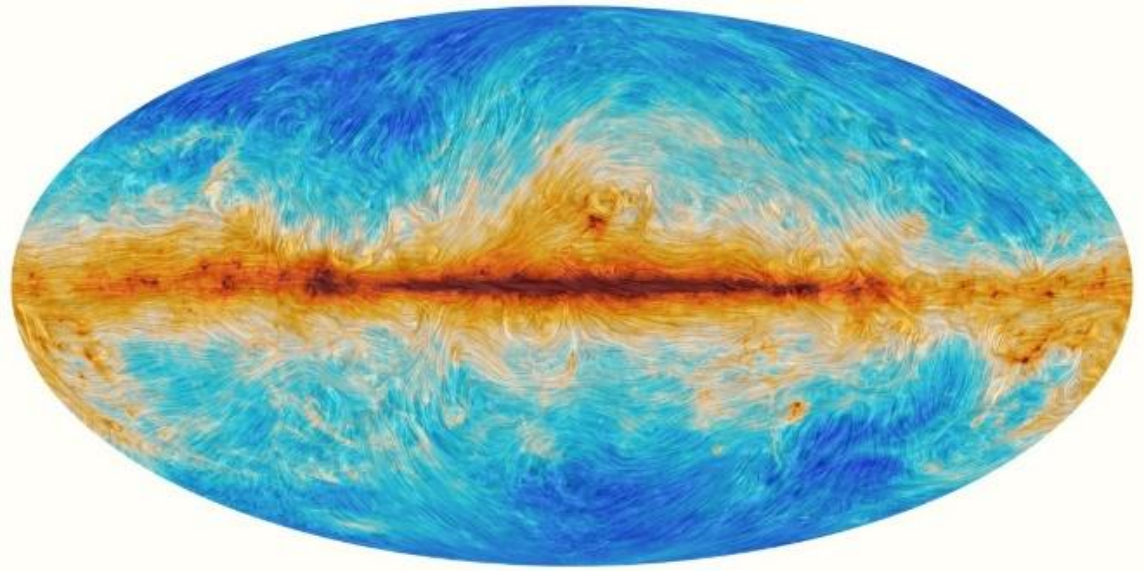

Figure 4: A map of polarized dust emissions released by the *Planck* collaboration. The circled region indicates the so called "Southern Hole", an area of minimal polarized dust emissions. This has been an area of primary focus in studying the polarization of the CMB. [11]

Like BICEP1, the optical system of BICEP2 featured a 26.4 cm aperture all-cold refractor in a housing cooled by liquid helium. According to Ref. [3], BICEP2 differed from BICEP1 mainly in the use of a focal plane array of planar antenna-coupled devices with voltage-biased transition-edge sensor (TES) detectors and a multiplexed superconducting quantum interference device (SQUID) readout. A TES is a superconducting detector designed to detect individual photons. When a photon strikes the tiny superconducting circuit, its energy is absorbed as heat. The rise in temperature causes a slight increase in electrical resistance and a slight decrease in current, which is registered in the electronics of the unit as the detection of a photon. SQUIDs are very sensitive detectors of magnetic flux typically fabricated from thin films of niobium or of $YBa_2Cu_3O_7$. SQUIDs are often used to measure a variety of physical quantities, including magnetic field, magnetic field gradient, voltage, and magnetic susceptibility. [2, 3, 22, 26, 31]

As in BICEP1, the BICEP2 mission operated in 50 minute scansets. During this time, the telescope covered a 60° angle of fixed elevation, scanning 53 leftward and 53 rightward half-scans at 2.8° per second. Contrary to BICEP1, BICEP2 observed at only 150 GHz (2mm). The scan speed and angular resolution of the BICEP2 instrument formed a mapping of multipole l = 100. Once again, BICEP2 primarily focused on imaging the Southern Hole due to the low contributions of cosmic dust to polarization measurements. Speculation surrounding the significance of cosmic dust contributions in this region ultimately led to *Planck*'s development of a comprehensive map of cosmic dust polarizations. [2, 3, 4, 28]

The *Planck* spacecraft, launched in 2009, contained two major components: the payload and service modules. The payload module was made up of a telescope, cryogenic focal plane units of the Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI), and the instrument cooling chains [8, 9]. The service module comprised a system for controlling power generation and management, devices for attitude and orbit monitoring and modification, ground-to-satellite data management systems, and radio frequency communications systems for data retrieval and command reception. The service module also stored elements of the instruments which did not require cooling as well as certain members of the cooling chains. Our primary focus will, obviously, be on the instruments aboard *Planck*. Of particular interest to us is the HFI, which addresses regions of the electromagnetic spectrum relevant to the studies of BICEP [9].

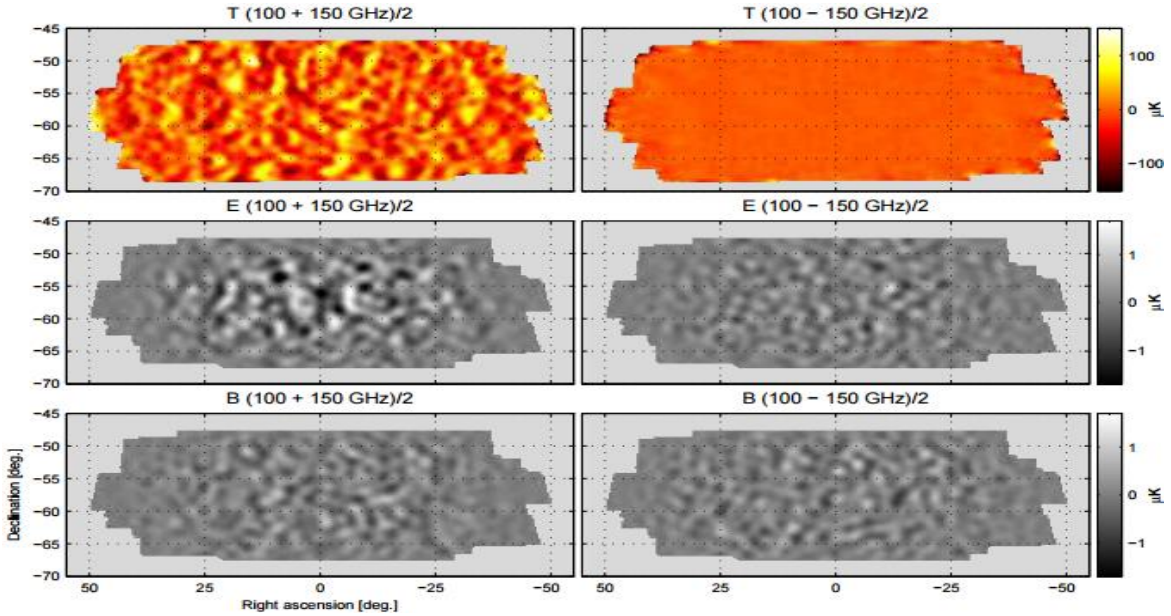

Figure 5: BICEP1's images of the Southern Hole. The images above were generated over three years of data collection. The top two images show temperature, the two images in the center display E-mode polarization, and the two images on the bottom display B-mode polarization. The left-side images show basic signal maps, and the right-side images show difference maps made from the first and second halves of the data set, produced by a method known as "jackknifing". As we shall see later, a similar approach to the one used to generate these images was repeated in the BICEP2 observations. [2]

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The LFI was designed to take measurements of the microwave sky in the 27 – 77 GHz (11.1 – 3.9 mm) range with high sensitivity [9]. The detector used by the LFI was a series of high electron mobility transistor (HEMT) radio receiver arrays. A HEMT is, essentially, a field-effect transistor (FET) featuring a junction between two materials with different band gaps. For this reason, HEMTs are also known as heterostructure FETs (HFETs) or modulation-doped FETs (MODFETs). A material is said to be doped when impurities are introduced, reshaping the electron holes in the band structure of the material, thus forming a semiconductor. In the case of MODFETs, this doping effect is modulated by the formation of a junction between two materials. [12, 26]

The HFI was designed to take measurements of the microwave sky in the 84 GHz – 1 THz (3.6 – 0.3 mm) range with high sensitivity. The HFI featured a spider array of 52 bolometric detectors constructed from neutron transmutation doped (NTD) germanium thermistors. The use of NTD Ge thermistors is relatively common in the construction of large arrays like *Planck*'s HFI. This is due to the fact that NTD Ge thermometers tend to be quite uniform and also quite predictable. Germanium has four naturally occurring stable isotopes, two of which can produce a gallium-doped material. The isotopes are presumed to be distributed randomly throughout the resulting lattice. This, in turn, means that the neutron flux through large portions of the resulting NTD Ge is uniform. The uniformity of NTD Ge thermistors is due to the fact that multiple thermometers can be cut

from relatively large blocks of NTD Ge. The thermistors constructed from NTD Ge are able to act as bolometric detectors due to the change in resistivity that occurs as heat is added to the system. This is registered in the electronics of the system in a manner reminiscent of the TES detectors mentioned before. [25]

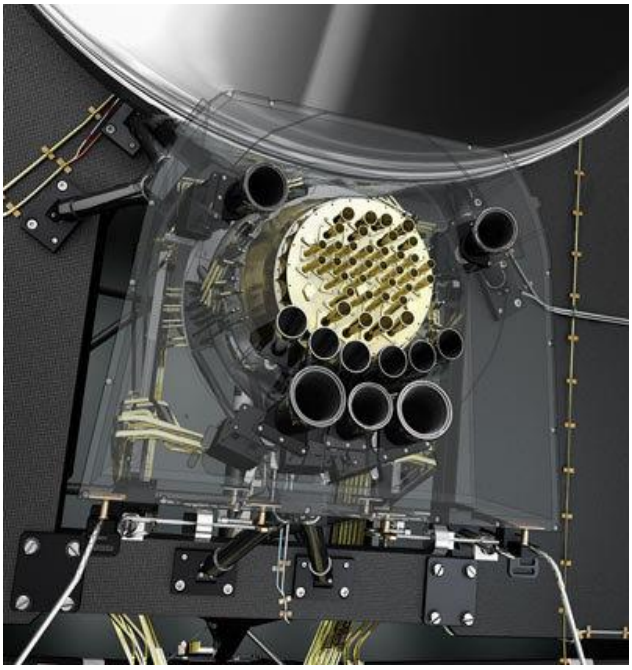

Figure 6: The combined focal plane of *Planck*'s two instruments. The HFI is the circle of horn-shaped wave guides at the center. The LFI is the outer ring of wave guides. These wave guides direct microwave radiation into the LFI and HFI. [7]

The elements of both the HFI and the LFI were arranged in the focal plane (Figure 6) of a single telescope [7]. The telescope design featured on *Planck* was an off-axis tilted Gregorian system. The four classes of Gregorian telescopes are the classical Gregorian, the aplanatic Gregorian, and designs that either cancel out astigmatism or cancel out astigmatism and coma. The Gregorian system featured on the *Planck* satellite belonged to the class which cancels out astigmatism. Such Gregorian telescopes are said to obey the Dragone-Mizuguchi condition, allowing them to operate without significant degradation over a large focal plane array. Submission to the Dragone-Mizuguchi condition also ensures that polarization of incoming electromagnetic radiation by the system itself is minimized [14]. This feature of the *Planck* satellite is obviously of critical importance to the study of polarized cosmic dust. The optical enclosure was formed from a large, self-supporting conical shield element covered with multi-layer insulation and was used to reduce the level of unwanted light produced by the spacecraft. In addition to this, the telescope featured a baffling element which shielded the HFI and LFI from thermal radiation originating from the optical enclosure [7].

Though the *Planck* mission ended in 2013, the wealth of data obtained from its observations continues to serve as an invaluable resource in the study of the CMB. The measurements made by the HFI and LFI were combined to produce an all-sky map (Figure 7) of CMB anisotropies, which is one of the richest sources of cosmological data to date. As we shall explore in the next section, data collected by the HFI was used to evaluate the extent to which B-mode polarization observed by BICEP2 was due to cosmic dust.

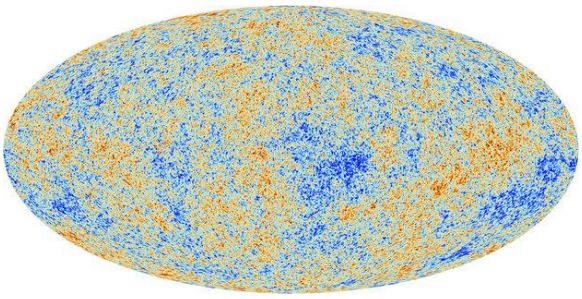

Figure 7: Map of cosmic microwave background anisotropies as observed by *Planck*. This image is based on the first 15 ½ months of observation by the *Planck* satellite. [10]

III. Results

In their calculation of E-mode and B-mode power spectra, BICEP2 faced the issue of converting raw data in the form of Stokes *I* and *Q*. This was accomplished by constructing the amplitude of E-modes and B-modes from the Fourier Transform of Stokes *Q* and *U* (Stokes *U* can be derived from the raw data of Stokes *I* and *Q*). The means of these amplitudes squared were, in turn, taken as estimates of the CMB band powers. Further steps were taken to reduce the amount of E and B mixing that resulted from the implementation of this procedure. [3]

In the publication of their results, BICEP2 reported nine band powers, each approximately 35 multipoles wide, spanning the range $20 < l < 340$. After obtaining the sets of E and B Fourier modes, it became possible to form apodized E and B maps (Figure 8), which are reminiscent of the polarization patterns seen

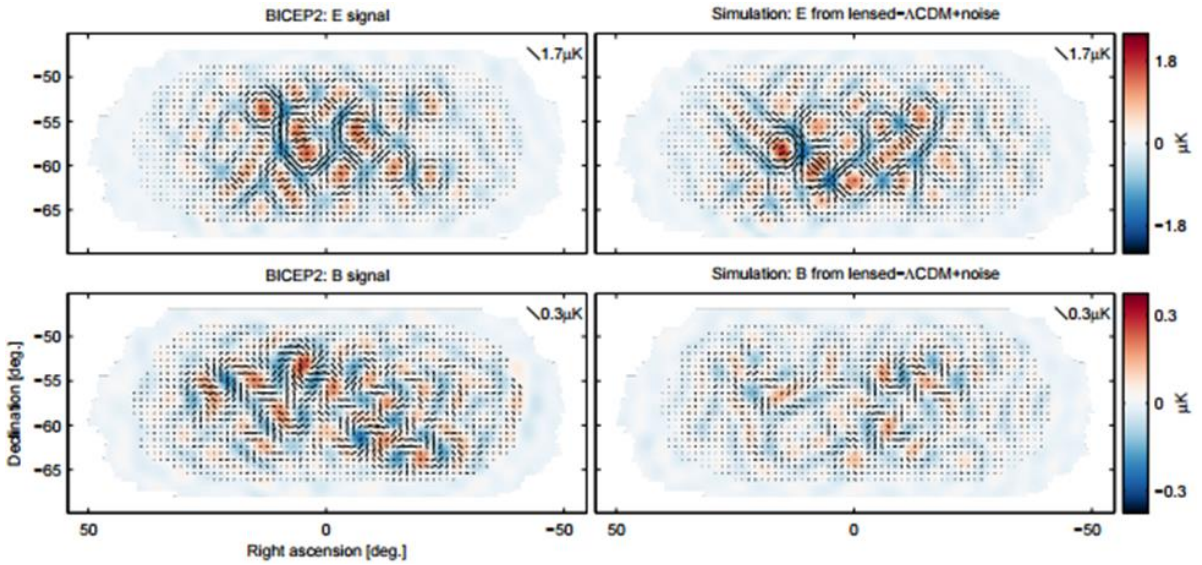

Figure 8: Maps of E and B modes obtained by BICEP2. The two images on the left represent actual data obtained by BICEP2. The two images on the right are obtained by simulations run by the BICEP2 team. [3]

in Figure 3. These maps serve as another useful illustration of the characteristics of E and B modes. In the E signal maps, one can see a curl-less pattern that is invariant under reflection. In the B signal maps, one can see a divergence-less pattern that changes fundamentally under reflection. [3, 4]

More important than the formation of these maps, however, was the development of the power spectra as a function of multipole moment. Observationally, multipole moment corresponds roughly to angular resolution. With this in mind, the BICEP2 team was able to fit a tensor-to-scalar ratio *r* to the observed B-mode power spectrum. Their result was a tensor-to-scalar ratio $r = 0.20^{+0.07}_{-0.05}$. Initially, BICEP2 interpreted this result as an IGW detection, disregarding the perceived insignificant contribution of B-mode polarization due to cosmic dust. Their interpretation was based on the fact that the $r = 0.20$ value best matched their results in the regions of lower multipoles, particularly in the l = 80 region. This multipole region corresponds to the predicted value of the so called "recombination bump", which is the expected location of a peak in the IGW B-mode. (Another peak is predicted to exist at the l < 10 region, but measurement of this region is beyond the capabilities of the instruments discussed here.) [3, 4]

The BICEP2 team interpreted the $r = 0.20$ result to be an IGW detection based on the compatibility of a curve produced by such a value with the B-mode power spectrum at the multipole moment of the recombination bump [3]. Upon further analysis by the BICEP2 and *Planck* teams, however, at least some portion of this tensor-to-scalar ratio was due to gravitational lensing by cosmic dust. The result obtained by this join analysis was a cosmic dust tensor-to-scalar ratio of $r = 0.075$, meaning that approximately 38% of the tensor perturbations included in BICEP2's alleged IGW was due to cosmic dust [4].

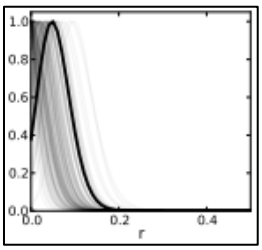

Figure 9: Likelihood of *r* as determined by the BICEP2/*Keck* and *Planck* joint analysis, using data from each team. Note the uncertainty in the result, with half of the curves peaking at *r* = 0. This is a useful illustration for the implicit uncertainty of the alleged IGW detection. [4]

IV. Conclusion

The detection of IGWs is of critical importance to the confirmation of an inflationary period in the history of the universe, which in turn will provide a more accurate model of the evolution of the universe. IGWs can be detected indirectly by measurements of B-mode polarization of the CMB, as was attempted by BICEP2. Although BICEP2 interpreted their results as an IGW detection, further analysis proved that some 38% of the polarization detected was due to cosmic dust. It is unclear whether the remaining signal observed by BICEP2 can be interpreted as an IGW detection or as pollution of the CMB signal due to cosmic dust. Further speculation on the nature of BICEP2's readings, evidently, requires greater observation of the multipole moment l ~ 80 range corresponding to the recombination bump in the B-mode power spectrum.

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Taking Alabama: Andrew Jackson, National Security, and Alabama, 1812-1836

Hayden Herfurth
Department of History

Abstract - This paper seeks to examine Andrew Jackson's actions during his time as a general in the Tennessee state militia and his tenure as president of the United States, focusing heavily on events that impacted Alabama and the national security of the United States. Because Alabama was once the frontier of the United States, securing it and ousting threats was a crucial factor in the development of the US as a nation, and the steps Jackson took to secure this southern frontier as general and statesman were integral in shaping the physical and demographic structure of the United States.
To effectively investigate and explain Jackson's efforts, this essay looks at two events: Jackson's participation in the Creek War and his involvement in the creation and execution of the Indian Removal Act. To study these events, this essay analyzes certain primary documents. The main source of information derives from treaties between the US government and Native American tribes, but personal correspondences and speeches also provide specific source material to support this paper's claim that Jackson worked to ensure the national security of the United States by solidifying America's claim to Alabama and ousting its many threats.

I. Introduction

Discussions about the American frontier often elicit ideas of one of the most romanticized and fantasized parts of American history, the Wild West. The West, however, had not been the frontier forever. In fact, while Americans still thought of the West as a vast and relatively unexplored region, they considered another part of the country to be the American frontier. The Mississippi Territory was once the furthest west and south that American rule of law and influence extended. It was a place of new beginnings and a place where extreme wealth and fortune could be had for very little. Within the Mississippi Territory, there were regions that were heavily populated by Native Americans, while there was even more land totally devoid of human habitation. Threats from foreign powers, namely, the British and Spanish, as well as constant harassment and assault from the Indians occupying the western portion of the Mississippi Territory, that is modern-day Alabama, eventually led one man, Andrew Jackson, to take Alabama from the hands of the enemies and firmly secure the United States' southern borders. This paper seeks to examine Alabama's importance in Andrew Jackson's campaigns through the South as general of the Tennessee state militia and president of the United States as he secured America's southern frontier.

This paper utilizes a number of primary and secondary sources to support this argument. Some of the main sources used are government treaties between the US and Indian tribes. These treaties serve to show official American policy towards native people groups across the South, specifically those in Alabama. Analysis of these documents allows for a better understanding of broad national sentiment. Personal correspondence and speeches also provide important aspects to this research. They allow for a more informal and non-typical view of events at the time. They can allow for more insight into national attitudes towards the Southern frontier before and during Andrew Jackson's involvement in the War of 1812, the Creek War, and the Indian Removal Act. A number of secondary sources are used as well to provide additional information and arguments that support this paper. These secondary sources also contain primary source information which would be difficult to obtain otherwise.
It is also important to note the usage of different terms. The Mississippi Territory refers the modern-day states of Mississippi and Alabama prior to their acceptance into the Union in 1817 and 1819 respectively. Because this paper looks specifically at Alabama, there are times when it will reference Alabama specifically, either during the Mississippi Territory period or before statehood. It is also possible that when referring to the Mississippi Territory, Alabama is the intended area of focus rather than Mississippi or the territory as a whole. I use these terms somewhat interchangeably, understanding that there is a definite difference, but lacking the knowledge of how to properly refer to the different Alabamas of each time period.

II. Threats to Peace

It is important to understand the history of the southern and western parts of the United States in order to comprehend how important Alabama's position was along the southern border of the nation. At the outbreak of the War of 1812, Louisiana and the newly christened Missouri Territory bordered the Mississippi Territory, or the present-day states of Mississippi and Alabama. Louisiana also contained the incredibly important port city of New Orleans. Situated at the mouth of the mighty Mississippi River, New Orleans controlled the only major access to the river. The British, French, Spanish, and Americans all wanted access to the river, not just to transport goods but also to use the river as a sort of security measure; the river allowed access to the heart of North America, giving whoever controlled it the ability to ferry troops deep into the continent. Spanish Florida bordered the Mississippi Territory to the south, and it would soon bring into fruition the fears many Americans had about a foreign neighbor to the south.

The United States had hesitated from becoming too heavily involved in the Mississippi Territory, in part, because of the numerous claims to the land. Abundant resources and lucrative trade available in the South meant that the Europeans, Americans, and Indians all had a strong determination to secure this territory for themselves. With the Spanish to the south in Florida, the British occupying the Old Northwest, and the French situated along the entire western border, the US had to contend with the threat of the three most powerful European countries of the previous century.[1] Because of the variety of claims and the constant awareness that war over the territory might become a reality, American settlers in the South venturing into the frontier faced potential death, either at the hands of an enraged Indian or as a volunteer in an international war. Land rights disagreements between Europeans, Americans, and Indians meant conflict was almost inevitable, putting the security of the United States' southern border at risk. The Alabama region of the Mississippi Territory was significantly less populated than Mississippi or Georgia, and it was the perfect region for conflict between the various factions.

Some of the most blatant threats to the US were Indian uprisings, especially those incited by the British along the populated American frontier. The English Crown had a long history of allying with native populations, often for trade rights or military assistance. During the French and Indian War, both the British and the French allied themselves with Indian tribes, hoping to supplement their own forces and provide European troops with New World trackers. In the nineteenth century, the most tangible threats to US sovereignty were Anglo-Indian alliances, including the Anglo-Tecumseh alliance. Tecumseh, a leader of the Shawnee tribe, was located around present-day Ohio. After a series of visions prophesying Indian self-determination, he became known as the Great Shawnee Prophet, and with the assistance of his brother Tenskwatawa, Tecumseh began to rally their tribe and others together against the ever-encroaching American frontier.[2] British officials in Canada had long sought an alliance with Tecumseh, hoping to exploit his ideals to incite the tribes to war against the US.[3] By the outbreak of the War of 1812, Tecumseh's tribal confederacy had allied with the British, and Tecumseh's Rebellion would become the physical embodiment of America's fear.

Like Tecumseh to the north, the British had a long history with the Creek Indians in Alabama. The Creeks, like their cousins following the Prophet, would soon be at war with the United States, due in part to British urgings. With Tecumseh rallying his followers in the Northwest and Indian tribes across the South making trade agreements and protective alliances with both Great Britain and Spain, many in the United States began to feel threatened. As tensions between the United States and Great Britain continued to rise over matters still unsettled since the American Revolution, war began to be seen as a definite possibility. It would be within this context of national fear and an increased desire for a more secure nation that Andrew Jackson would secure Alabama, and thus the nation's southern border, from potential threats.

Before Jackson began campaigning across Alabama and the South in the name of national security, though, a certain amount of treaty-making had already taken place in an attempt to establish a peaceful relationship with America's Indian neighbors. Official treaties between the US government and Indian tribes, signed in the late 1780s and 1790s, established boundaries between sovereign Indian territory and that land claimed by the US or white settlers. Some of the tribes involved in this series of treaties included the Creek, Cherokee, Choctaw, and Chickasaw tribes, all located inside of or along the borders of present-day Alabama. These treaties established a policy of punishment, including an article in which the United States gave full authority to the tribes to punish trespassing American citizens as they saw fit.[4] In addition to treaties

that granted greater authority to Indian tribes, certain members of the political elite also sought to treat with the native population. Thomas Jefferson, in a letter of good faith to the Creek nation, explicitly promised the Creek people that the United States would protect Indian land claims "not only against others but against our own people."[5]

While these policies of delegating punishment to Indian authorities or becoming directly involved in maintaining Indian sovereignty might be hard to understand today, they demonstrated the end goal of the US government, that is, national security. By establishing legal territorial boundaries and methods of punishment with the native Indians in populated regions of the South, namely the future states of Mississippi and Alabama, as well as the western portion of Georgia, the United States was attempting to not only secure more land, but to also ensure that there would be as little settler-Indian conflict as possible. This situation of appeasement would remain until the beginning of what would become known as the Creek War.

The Creek Indians were one of what Americans considered at the time to be the Five Civilized Tribes. Besides the Creeks, the Five Civilized Tribes included the Cherokee, Choctaw, Chickasaw, and Seminole nations. Of the five, only the Seminole tribe lacked a presence in Alabama. Civilizing the native peoples, as men like George Washington and Thomas Jefferson called it, involved a number of things, including teaching them sustainable agriculture and animal husbandry, educating them according to American values, and enlightening them on the basic principles of Christianity. According to the historian Robert Remini, Americans presumed that by adopting these practices, these accouterments of white American culture, "Native Americans would win acceptance from white Americans."[6] And for a while, this worked. White settlers lived and worked alongside native tribes in the Mississippi Territory, intermarrying and socializing with each other. This situation of relative peace and security along the American frontier that came with increased Indian assimilation would soon change, though, as both the British and Indians in Alabama entered into war with the US.

In 1813, a year into the War of 1812, Americans became aware of a truly horrific event that had occurred in Alabama. The Fort Mims Massacre, as it would come to be called, shook the nation already at war. The battle took place at Fort Mims, located near Alabama's southern port of Mobile. A force of Red Stick Creek Indians attacked the American outpost, and after several hours of fighting the the Creeks eventually took the fort. Of the 400 or so occupants within the fort, only around thirty were able to escape.[7] The Red Stick Creeks had attacked the fort using arms supplied by the British. The British felt that if they could arm the Red Sticks and encourage attacks against more northern targets in the South, they could distract American forces long enough to take strategic points across the South with the intent of invading into Alabama.[8] This became a clear threat to the security of the US. Karl Davis, in an article analyzing the massacre, argues that the attack on the fort was not necessarily a threat against the United States. Instead, he writes that a close examination of events makes it clear that the attack "was primarily a punitive expedition" against assimilated Tensaw Creeks.[9] The Fort Mims Massacre was not directly related to the War of 1812, according to Davis, but rather that it was serendipity, with the Red Sticks gaining access to better weapons because of the British presence in the South, but not necessarily executing the attack against the US itself. While this is not necessarily wrong, the Fort Mims Massacre was the sort of distraction for which the British hoped, and as Jackson and his militia battled the Creeks across the Mississippi Territory in response to the massacre, the threat of foreign invasion into Alabama or Mississippi became increasingly real.

III. Jackson the General

Andrew Jackson, as major-general of the Tennessee militia, conducted a fairly short but brutal campaign against the renegade Creeks across Alabama in retaliation. The Creek War ended on March 27, 1814, at the decisive Battle of Horseshoe Bend. Four months later, the Treaty of Fort Jackson was signed to officially end the conflict, bringing the rebellious natives to heel and allocating reparations as Jackson saw fit.

As befit the current state of the country in 1814, and as it was one of the main justifications for the Creek War, the establishment of a policy of national security is evident in the treaty between Jackson and the Creek Indians. The first article of the treaty established the new territorial boundaries of the United States, removing around 22 million acres of land from Creek possession.[10] Conveniently, much of the land removed from the Creeks was either inside the state of Georgia or along the river lands of the eastern Mississippi Territory, some of the most fertile land in the South.

Taking this land from the Creeks accomplished two things that helped establish security along the southern frontier of the United States. First, removing Creek autonomy from Georgia and the eastern portion of the Mississippi Territory would allow the the state of Georgia and the territorial government of Mississippi, as well as the federal government, to gain a tighter control on the Indians living in the region. With the implementation of this treaty, the Creeks would become "protected by and subject to" the laws of the United States.[11] Second, taking away Indian land and autonomy meant they would have less interaction with Spain and Great Britain, the two most relevant threats to the United States, both of which had strong presences in south Alabama, especially along the border with Spanish Florida.

The treaty also gave the US government the right to construct military forts, trading posts, and public roads within the Creek nation's remaining territories.[12] It is ironic that in the history of Indian-settler violence over the course of American expansion much, if not all, of the violence began, at least in part, because of the encroachment or establishment of white settlers inside indigenous lands. But here, however, the American consensus was that an increased presence inside Indian territory would increase security for both white settlers and native Indians living in the western Mississippi Territory.

General Jackson, having successfully treated with the Creeks, much to the benefit of the United States, moved south towards Spanish Florida. The British had established themselves in the Spanish town of Pensacola, no doubt intending to use the town as a staging area for an attack on the nearby city of Mobile or to execute incursions the southernmost portions of the Mississippi Territory. Perceiving the threat that lay just south of the American-Spanish border, Jackson marched on the British-held Spanish city despite receiving no direct orders to do so. Taking the fort and the city proved to be relatively easy, and the British were ousted.

Jackson's invasion of Spanish Florida was relatively easy to justify; the United States was at war with the British, the British were colluding with the Spanish in Pensacola, and the United States southern frontier in Alabama was directly threatened.[13] The general's fairly brief occupation of Pensacola, while clearly done in the name of national security, foreshadowed Jackson's later invasion of Spanish Florida in 1818 during the Seminole Wars for a similar reason, which ended when Spain eventually sold Florida to the United States. Jackson's first invasion of Florida can be seen as an almost preparatory action, as if the American general was testing Spain's response to a direct military incursion into their territory. Whether or not Jackson had underlying motives, he had certainly thwarted what could have been a direct threat to American settlers and citizens living in Alabama with his victory in Pensacola, and although he would become a contentious figure in the eyes of the government because of his actions in Florida, he had ensured the security of Alabama, and thus the nation, from both European and Indian threats.

IV. Jackson the President

Jackson's reputation as a controversial public figure continued to grow during his political tenure through his specific actions involving Alabama. In one most controversial actions ever undertaken by the US government, Jackson, as president, signed the Indian Removal Act into law on May 28, 1830. Jackson played an important role in the creation and execution of this Act, both before and during his presidency. His time as the leader of the Tennessee militia during the Creek War, as well as his experience leading American forces through the South during the early years of the Seminole Wars, gave him a significant amount of credibility with the American public. They could trust Old Hickory, the man that had fought and defeated supposedly savage tribes across Alabama and Florida and protected Americans from European invasion. The Indian Removal Act was a sort of culmination of Jackson's efforts to essentially wholly take Alabama for the United States.

In Jackson's State of the Union address in 1829, he called specifically for the removal of Indians from the American southeast to the west, across the Mississippi River, to specifically designated land. This included hundreds of thousands of Cherokee, Chickasaw, Choctaw, and Creek Indians that lived within Georgia, Alabama, and Mississippi. Jackson used two main methods to convince the American public that Indian removal was necessary. One point Jackson made was that of the current condition of the Indian tribes across the South. The ever-increasing presence of white settlers in what was once Indian territory had led to a degradation in the quality of Indian life. In one of the most ironic and moving parts of the speech, while discussing the extinction of tribes across the US, Jackson argued that "Humanity and national honor demand that every effort should be made to avert so great a calamity."[14] Not able to hunt or forage like they had a

hundred years prior, combined with the continual loss of land to the US government or white settlers, tribes like the Cherokee and Creek were threatened with extinction, their whole way of life fading away. Just as Americans wanted to preserve the American way of life, Jackson used this to appeal to that sentiment, subtly relating it to an improbable but still possible chance that the native Indian could supplant or disrupt Americans' lives and their sense of security.

Of course, in southern states like Alabama, where there were still huge portions of the state designated as Indian territory, Jackson's policies appealed to the average citizen possibly more than other Americans. The Alabama elites and yeomen pushed for Indian removal for the same selfish reason. The land occupied by many of the Indian tribes in lower Alabama was located in the Black Belt, which cut a swath across lower middle Mississippi, Alabama, and Georgia and contained some of the most fertile soil in the region. Plantation owners and poor farmers alike sought to establish themselves on previously unused cropland in the Black Belt in an attempt to exploit the rich soil and warm climate for their own gain. So, Jackson's plans for Indian removal were well-received in Alabama, if a little condemned for their lengthiness. Alabamians wanted the Indian way of life removed so they could establish and continue their own lifestyle.

A more direct relation to the sovereignty and security of the American nation can be seen in Jackson's other argument. The first half of the speech is spent discussing the thing most important to almost every Southern state, especially those in the Deep South. That issue was the sovereignty of American states and the political control they maintained within their borders. This had become somewhat of a political conflict since Jackson took office. Jackson made the argument that under no other circumstances would a sovereign state of the United States allow an independent government be set up in the same manner as the Indian tribal governments tried to do (the Southern states even objected to outside involvement from other whites and so balked at the idea of Indians having legal authority within their state). As a result, Jackson "advised them [the Indians] to emigrate beyond the Mississippi or submit to the laws of those States."[15] This idea of moving beyond the Mississippi River to maintain their sovereignty and culture would become the basis for the Indian Removal Act.

The historian Michael Morris argues that in Georgia, as well as the rest of the country, politicians used this idea of state sovereignty and the threat of usurpation of authority to their own ends, that is, the expulsion of Indian tribes from the South. Morris writes that this idea of securing state sovereignty became a part of the "national agenda and a nationalist rhetoric" used by Jackson and others to remove native tribes from their land.[16] The usurpation of state sovereignty would certainly have led to conflict across the nation, especially in the South, where the idea of state sovereignty was already beginning to reign supreme. It is likely that Jackson truly believed, in keeping with national opinion, that removal was the only way to prevent American-Indian conflict, thus giving credence to his removal policy. On a subtler level, Jackson probably understood that those same Southerners who had violently expressed their displeasure at the disregard for states' rights during the nullification crisis would potentially pose a threat to American nationhood and safety if Jackson ignored Indian removal.

Despite the official voluntary policy of emigrating west of the Mississippi, Indian removal across the South would become a brutal and deadly affair. There is a great debate on the number of Indians who perished during Indian removal. A commonly accepted number, though, according to Francis Prucha, is around four thousand dead. This would place the total dead at around one-fourth of the total Indians emigrating from the American southeast to the arid plains of the Missouri Territory.[17]

It would be impossible to total the human cost of Andrew Jackson's campaigns to take and protect the South. Thousands upon thousands of Native Americans died in petty skirmishes over land ownership with white settlers, in full-scale retributive warfare against the United States, and during what were supposed to be peaceful and voluntary emigration periods. The American South today is almost totally devoid of any native peoples. As of 2014, only fourteen of the fifty American states had more than 100,000 Native Americans, with only Florida and North Carolina falling into the category of the American South. In Alabama, Native Americans represented 1.2 percent of the total population according to the 2010 census.[18]

During the first half of the nineteenth century, American security was arguably one of the most important influences on national and state policy. It was a driving factor in the War of 1812, and

it led to Jackson's direct and harsh response to the Fort Mims Massacre. The Alabama portion of the Mississippi Territory, and then later the state of Alabama, posed a serious threat to American security along its frontier. Initially, the lack of population meant European advancements into the region would remain uncontested, threatening the United States. By the 1830s, though, American Indians still threatened white settlers in the region by preventing settlers to purchase and utilize some of the most fertile soil in the region. Andrew Jackson took direct action to prevent Alabama from becoming compromised, through both direct military action in the Creek War as well as political action by speaking on state sovereignty, and was able to, at least in part, ensure the security of the United States' and its position on the world stage.

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