The Connectome: A Unifying Boundary Object in Neuroscience

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0.0. Introduction

0.1. Real, Yet Constructed

For a number of decades, philosophers, historians and sociologists of science had debated the nature of scientific phenomena. One camp – the realists – had argued that objects of scientific study want for discovery. These scholars saw scientific objects as, in their essence, akin to conventional objects, such as chairs or roses – self-evident, stable and robust. Theories about the furniture of the universe may come and go, a pure realist might have argued, but the furniture stays.

Another group – the constructionists – had claimed that scientific objects are mere inventions, which live in the minds and hearts of scientists, who themselves are shaped by historical and local circumstances. As a result, these scholars regarded scientific objects as not real and fundamentally opposed to conventional objects – thus, elusive, ever evolving and plastic.[1]

However, these feuding scholars agreed on at least one point. Inherent in their discourse was the dichotomy of real versus constructed: Scientific objects are either one or the other, but never both. Today both realists and constructionists recognize the crudeness of this dichotomy. Very few scholars of science today would deny scientific objects of some realness – and likewise, of some construction. This shift in thinking is due, in part, to work by Lorraine Daston and others, who convincingly argued that scientific objects can be both real and constructed.[2]

In line with the work of these scholars, this thesis starts from the premise that scientific objects can, and perhaps should, possess both *realness* and *construction*. But as Daston outlines, this is no conventional realness derived from self-evidence or stability. Rather she sees realness as born from action. That is, objects "may become more or less intensely real, depending on how densely they are woven into scientific thought and practice."[3]

In other words, scientists have the capacity to transform "a dispersed set of phenomena...into a scientific object that can be observed and manipulated, that is capable of theoretical ramifications and empirical surprises, and that coheres, at least for a time, as an ontological entity."[4] In doing so, researchers bring into being objects that are both tethered to reality through observed phenomena and constructed to suit the needs of scientific inquiry.

While scientific objects viewed in this way may lack the "self-evidence of a slap in the face"[5] typical of conventional objects (in this case, hands), their existence can weigh equally on our science and society. Researchers use these objects not only as rhetorical tools to obtain funding, but also as means for producing therapies for disease.

But some objects leave larger marks than others. When a particular scientific object becomes so entangled in the web of scientific practice – when researchers from all corners of a

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[1] Daston, 2-3.

[2] Daston, 3. It may be that all scientific objects bear this dual nature, but for the purposes of this thesis it is sufficient that some objects do.

[3] Daston, 1.

[4] Daston, 5.

[5] Daston, 2.

discipline acknowledge its worthiness as a subject of study – a scientific object gains the potential to reorganize and unify its discipline from the ground up.

Equipped with its duality, an object may even "flout the boundaries between scientific disciplines,"[6] and, in doing so, build a bridge uniting two disciplines. Together these über-objects may unite the whole of the sciences – an achievement that would make the 19th century positivist Auguste Comte proud.

The real-constructed ontology of objects introduces the thread that will underlie this work – duality – that is, duality in objects and in disciplines. In this work I will build upon this view of what scientific objects are to provide one way of understanding what objects can do. That is, I will show how a particular scientific object's ontological nature engenders its value in the epistemic activities of scientists.

0.2. Robust, Yet Plastic

Before I introduce my protagonist object, I must first discuss how the real-constructed ontology of some scientific objects lends itself to one of the central dualities of this work – *robustness* and *plasticity*. Susan Leigh Star and James Griesemer first coined the term *boundary object* to denote "objects which are both plastic enough to adapt to the local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites." In other words, "they have different meanings in different social worlds, but their structure is common enough to more than one world to make them recognizable, a means of translation."[7]

When an object possesses the qualities of both realness and construction, it opens the door to the possibility of a second-tier dual nature – robustness and plasticity. This duality then gives the object the potential to unify disciplines. However, boundary objects are not *ipso facto* unifying objects. At least two factors determine whether a boundary object is also an object capable of unifying a discipline:

(1) How much the object is embedded in scientific practice and
(2) the type of unity one is considering.

With respect to (1), boundary objects can take more global or local forms. If a boundary object is globalized, such that it captivates scientists from most or all walks of a discipline, I argue research efforts will likely be organized around this object – bringing unity to the discipline as a whole. But if a boundary object is more localized, it may merely provide common ground for small groups within a discipline, and thus not unite the discipline overall. Hans-Jorg Rheinberger sums up this view of the relationship between certain objects and their disciplines, likewise:

> If there are concepts endowed with organizing power in a research field, they are embedded in experimental operations. The practices in which the sciences are grounded engender epistemic objects, epistemic things as I call them, as targets of research. Despite their vagueness, these entities move the world of science. As a rule, disciplines become organized around one or a few of these 'boundary objects' that underlie the conceptual translations between different domains...For a long time in physics, such an object has been the atom; in chemistry, the molecule; in classical genetics, it became the gene.[8]

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[6] Daston, 12.

[7] Star and Griesemer, 393.

[8] Rheinberger, 220.

In this thesis I will argue that – like the atom, the molecule and the gene – the connectome is now emerging as a unifying boundary object in neuroscience. The connectome can be roughly defined as a map or network of the brain's neural connections. At its most detailed resolution (the microscale), the connectome is a wiring diagram of the all of the brain's neurons, or nerve cells, and synapses, which are spaces where two neurons transmit signals to each other via chemicals (neurotransmitters). At a less detailed resolution (the macroscale), the connectome is a map of structural links between distinct regions of the brain, which might include the frontal lobe and the cerebellum**.**

In this thesis, I will also show how scientists are coalescing a "dispersed set of phenomena" to construct the connectome, "a scientific object that can be observed and manipulated" and that is "capable of theoretical ramifications and empirical surprises."[9] And I will argue that, by possessing the qualities of both robustness and plasticity, the mere decade old connectome is mobilizing researchers from every corner of neuroscience, and in doing so, unifying the discipline.

0.3. Nay to Reductive Unity

But unity itself is a vague concept. As Carl Craver aptly points out, "the phrase 'Unity of Science' means many things to many people."[10] For Karl Popper, for example, unity denotes *methodological unity*, where all scientists share the tenets of testing hypotheses and falsification, among other aims. The underlying goal of his unity is to separate science from pseudoscience, where science "proceeds by a privileged set of principles"[11] and pseudoscience does not.

This route to unity fell out of fashion when many philosophers regarded the search for a set of scientific axioms a lost cause.[12] Like the philosophical community today, boundary objects do not favor Popper's form of methodological unity.

In 1958 Hilary Putnam and Paul Oppenheim discarded the search for methodological unity and instead argued for a form of explanatory unity. Unity in science, they said, originates from the reductive explanation of phenomena from higher-level sciences – like biology or psychology – with the laws from a proclaimed 'fundamental' science – a title often saved for physics.[13]

Thus, Putnam and Oppenheim's form of unity does share with Popper's the aim of achieving unity through reduction to some fundamental aspect of science – in this case explanation, rather than methodology. As I will explain in more detail below, boundary objects do not favor both reductive explanatory unity and reductive methodological unity precisely because they are reductive.

Craver does agree with Putnam and Oppenheim that "the unity of science serves an epistemic function."[14] But he also argues that Putnam and Oppenheim's route to unity confuses the

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[9] Daston, 5.
[10] Craver, 267.
[11] Craver, 267.
[12] Craver, 268.
[13] Craver, 268.
[14] Craver, 268.

levels of science with the levels of nature – namely, that the organization of science does not mirror the organization of nature. Even though "higher-order...phenomena can often be explained in terms of lower-order phenomena"[15] in theory, in practice researchers do not unify their disciplines or science as a whole through explanatory reduction.

Unfortunately, since "Oppenheim and Putnam's manifesto," many philosophers and historians of science have equated unity with reduction, argues Craver. Consequently, when scholars challenge the reductive unity of science, critics often misunderstand their arguments as attacks on the idea of unity in science *tout court*.[16]

The idea that unity equals reduction has also made its way into discussions concerning the unifying power of boundary objects. For example, as previously noted, Rheinberger argues that "disciplines become organized around one or a few of these 'boundary objects'"[17] and that genes are "boundary objects par excellence."[18] But in the same piece he asks, "do molecular biologists need a unified and generalized gene concept?...if we screen the pertinent literature, there appears to be no singular, unique, and rigidly determined usage of the term."[19] Thus, for Rheinberger the gene can only obtain unifying power though a rigid and reductive definition. As I will show in this thesis, boundary objects can be unifiers—albeit not reductive unifiers.

0.4. Unified, Yet Autonomous

Partially motivated to dispel this false equivalence between unity and reduction, Craver offers a third route to unity in science – namely, unity through mechanistic explanation. What he calls *mosaic unity* originates from "using results from different fields to constrain a multilevel mechanistic explanation."[20] That is, fields that comprise a discipline are unified because they all contribute to and come to agree on a particular mechanistic explanation of a phenomenon.

But fields within a discipline also remain autonomous because they ask different questions, use different techniques and make different background assumptions with regards to those mechanisms, says Craver. This duality of unity and autonomy enables explanation in the life sciences – neuroscience in particular – because the confluence of differing techniques and perspectives leads to robust explanations of its complex phenomena, he argues.[21]

To be clear, Craver's mosaic unity pertains to mechanisms – not descriptive models like the connectome. In February 2015, Craver gave a talk at Yale University, during which he argued against Philipe Hunneman's claim that mapping the brain's connectome represents "a style of explanation distinct from mechanistic explanation."

Craver admits "network models...can be used to describe features of the organization of complex mechanisms that other representational systems are ill-equipped to describe." Still, he argues networks "explain nothing at all. The explanatory force of the model comes not

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[15] Craver, 268.
[16] Craver, 230.
[17] Rheinberger, 220.
[18] Rheinberger, 225.
[19] Rheinberger, 223.
[20] Craver, 231.
[21] Craver, 231-232.

from the fact that it is a network model but from the fact that network analysis reveals something useful about the organization of a mechanism."[22] I agree with Craver on this point – the connectome does not explain the brain.

For the purposes of this work, references to unity or unification can be taken to mean mosaic unity with one important caveat. Different fields within neuroscience are unifying – and remaining autonomous – in their effort to describe and integrate the different organizational levels of the connectome – not to uncover a mechanistic explanation of brain function. In parallel with Craver's *mosaic explanatory unity,* we can call this fourth form of unity *mosaic descriptive unity*.

But as Craver points out above, descriptions "reveal something useful" about mechanisms. In other words, detailed descriptions of scientific objects facilitate the subsequent mechanistic explanations of those objects. As a result, describing the connectome can be thought of as facilitating mosaic explanatory unity. Many neuroscientists agree on this point, arguing that the connectome is "necessary, but not sufficient" for providing explanations of brain function.[23]

So far I have introduced two dualities central to this work: the robust, yet plastic connectome and a unified, yet autonomous neuroscience. This symmetry of balanced opposites in both object and discipline is no coincidence. In this thesis I will show how the connectome's robustness facilitates the unification of neuroscience. I will also show how the connectome's plasticity allows the different fields comprising neuroscience to ask their own questions and make their own assumptions – and thus remain autonomous. In this way, boundary objects can have unifying power, albeit mosaic descriptive – not reductive – unifying power.

0.5. Thesis Structure and Content

This thesis will be structured as follows. Chapter one will cover an analysis of scientific objects. First, I will explore further Daston's ontology of realness and construction in order to show how it lays the foundation for the duality of robustness and plasticity in scientific objects. In particular, I will discuss Daston and colleagues' exploration of four potential characteristics of scientific objects (salience, emergence, productivity and embeddedness) in the anthology, *Biographies of Scientific Objects*.

Second, I will provide a detailed overview of pertinent work on boundary objects. In addition to outlining Starr and Griesemer's initial conception of the idea, I will discuss Ilana Löwy's examination of the capacity for boundary objects to allow for "federative experimental strategies and disciplinary growth."[24] In order to distinguish boundary objects from their conceptual predecessors and successors, I will also include work by Joan H. Fujimura. In an effort to develop her own concept of standardized packages, Fujimura outlines how the concept of the boundary object was a response to Bruno Latour's network building concept.

Chapter one will conclude with an analysis of the connectome as a boundary object, primarily with the help of work by Olaf Sporns, who, along with Giulio Tononi and Rolf Kötter, coined the term *connectome* in 2005. In his book *Discovering the Connectome*,

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[22] http://frankeprogram.yale.edu/event/carl-craver-graphing-brains-dark-energy-network-models-and-neural-mechanisms – visited 20.07.2015.
[23] http://www.scientificamerican.com/article/c-elegans-connectome/ – visited 20.07.2015
[24] Löwy, 371.

Sporns outlines the connectome's three organizational levels in detail – the *microscale* entails connections between individual neurons, the *mesoscale* connections between collections of roughly 100 neurons and the *macroscale* connections between brain regions. Sporns also describes the functional connectome – a map of brain function. Though I will stick primarily to outlining the connectome's theoretical structure, I will also provide some historical context for the concept.

The second chapter will entail an analysis of disciplinary unity in neuroscience. I will first give an overview of Craver's argument for mosaic explanatory unity in neuroscience. In his book *Explaining the Brain: Mechanisms and the Mosaic Unity of Neuroscience*, Craver builds his argument from an analysis of explanation, causal relevance, manipulation, levels of nature and levels of science – among other topics. Once I have established a foundation in Craver's work, I will show how a boundary object – in this case the connectome – instigates mosaic descriptive unity in neuroscience.

Initially, my plan for this thesis included two more chapters. In a third chapter I aimed to drive home my argument concerning the connectome's role as a unifying boundary object in neuroscience by comparing the connectome's ontology and epistemic roles to those of the gene – the unifying boundary object of biology. In the fourth chapter, my primary aim would have been to discuss the potential duality of unity and autonomy in science as a whole using work by the 19th century philosopher Auguste Comte.

Unfortunately, due to time and monetary constraints, the discussion of the topics in these two chapters will be limited to the conclusion of this thesis. Since I have already done the research for these two chapters, I will explain how one might execute putting these arguments on paper in future research projects. I will also discuss other potential directions for future research.

Generally, this thesis should be thought of as aiming to provide one way of understanding scientific objects and their roles in disciplinary organization. Said differently, while this thesis is undoubtedly aided by historical work, it is primarily theoretical in nature. As a result, this work belongs to the so-called fields of historical epistemology and applied metaphysics.

While historical epistemology has been around for a while, Daston and colleagues created the field of applied metaphysics in their book *Biographies of Scientific Objects*. Daston describes the field in the following way:

> If pure metaphysics treats the ethereal world of what is always and everywhere from a God's-eye-viewpoint, then applied metaphysics studies the dynamic world of what emerges and disappears from the horizon of working scientists...Applied metaphysics assumes that reality is a matter of degree, and that phenomena that are indisputably real in the colloquial sense that they exist may become more or less intensely real, depending on how densely they are woven into scientific thought and practice.

What does this thesis not aim to do? Societal and cultural context must be addressed if we are to gain a full picture of how ideas are produced in science. However, given the confines of this work, I will not provide any contextual analysis of influence of technological development on the production of knowledge in science, among other influences. In short, this thesis will mainly concentrate on the birth and evolution of the ideas themselves.

This thesis also does not aim to be exhaustive or comprehensive – but representative.

Examples will be given to illustrate trends, but other examples may go against the grain of my argument and will be addressed in footnotes. While this essay does have an air of prescription in line with Craver's philosophy, it does not aim to communicate the idea that his work is the only road to understanding progress in neuroscience – there may always be other roads that currently remain uncharted.

1.0. Chapter One: Scientific Objects, Boundary Objects and the Connectome

1.1. Deconstructing Dichotomies

Much of Lorraine Daston's work centers around flipping well-known dichotomies on their head – and on more than one occasion does she begin these deconstructions with etymological insights.[25]

In *Biographies of Scientific Objects*, Daston calls into question the division of *real* versus *constructed* by showing that the meanings of *discovery* and *invention* are far from static. As explained in the introduction of this thesis, realists traditionally believe scientific objects are discovered, while constructionists argue they are invented. With *Biographies* Daston aims to "blur the distinction between invention and discovery and recall the period when these words were synonyms rather than antonyms."[26]

Sixteenth and seventeenth century uses of the term *invention* fall far from the twenty-first century tree, points out Daston. For example, *invention* took on a similar meaning to *discovery* in the following sentence cited in Oxford English Dictionary: "'That judicial method which serveth best for the invention of the truth.'"[27]

As synonyms, the "common element of novelty bound" *invention* and *discovery*, she argues. But sometime in the eighteenth century *invention* and *discovery* became antonyms, divided by the manner in which their novelty was conceived. Was "the novelty revealed, as an explorer fills a blank spot on the world map, or was it contrived, as an artisan manufactures a device?"[28]

Similarly, *realism* originally referred to the philosophical idea that abstract universals were "as real or more real than the individual particulars of sensation."[29] In other words, realness was not always so strongly associated with materiality as it is today.

After showing that the dichotomy of *invented* versus *discovered* (and by proxy *real* versus *construction*) is less frozen in time and meaning than we originally thought, Daston builds her applied metaphysics from this deconstructionist rubble. She admits the "essays in [*Biographies*] cannot by themselves undo the metaphysics that forces a choice between invention and discovery." But they can realign emphasis on what continues to tie the two terms together – novelty.[30]

Daston outlines "four principle approaches" that bring about novelty (i.e. new scientific knowledge) as it pertains to scientific objects: (1) salience, (2) emergence, (3) productivity and (4) embeddedness.[31] The first two approaches relate to how objects come about and the

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[25] In their 2007 book *Objectivity*, Daston and Peter Galison, begin dissecting the assumed polarity of *objective* and *subjective* by showing the two terms' definitions were flipped in the seventeenth century. Only until Kant, did the two terms take on the definitions they have today.

[26] Daston, 3.

[27] Daston, 3.

[28] Daston, 4.

[29] Daston, 4.

[30] Daston, 5.

[31] Daston, 6.

second two to what roles the objects play once they are created. As I will show, achieving the duality of *realness* and *construction* in scientific objects using these approaches lays the foundation for the properties of *robustness* and *plasticity* – that is, for the formulation of boundary objects.

1.2. A Foundation for Robustness and Plasticity

1.2.1. Salience

For conventional objects, process and product are intimately intertwined: What something is made of and how it is made, determines what it is (and how it can be used). For example, a table made of wood by hand, *is* a handmade wood table.

Scientific objects are no different. If a scientific object is born out the coalescence of a diversity of phenomena, the object will likely have a wide array of applications, I argue. Likewise, the variety of researchers who study specific facets of an object will likely find interest in the object as a whole.

This is the case for Daston's "collection of oddities" studied by preternatural philosophers in the early modern period. In the late sixteenth and seventeenth centuries, "two-headed cats, three suns in the sky, rains of frogs" and other oddities, became *salient* as objects of scientific inquiry, unified by their investigators' belief that "exceptions were the royal road to the discovery of nature's rules."[32] *Salience* is the first of Daston's approaches and the coalescence of previously neglected phenomena is one road to its application.[33]

Though seemingly counterintuitive, the formation of scientific objects via salience need not refer to phenomena that researchers neglected in their entirety previously. The reason behind this is rather obvious: Researchers need to have some knowledge of phenomena in order to reveal any common thread among them.

Before two-headed cats and comets were grouped together, for example, anatomists and astronomers studied them individually, says Daston. However, scientists studied the regularities within each group, not the oddities shared among them. Once preternatural philosophers unified all oddities with the idea that they revealed nature's rules, the collective object gained greater salience.[34] That is, the whole became more than the sum of its parts.

As I will show, achieving salience via coalescence comes into play for the formation of boundary objects, especially the connectome. When scientific objects come about through this approach, they gain the potential to be "plastic enough to adapt to the local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites."[35] In other words, what boundary objects are made of and how they are made, determines how scientists can use them.

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[32] Daston, 8.

[33] To be clear, singular objects can also become scientific objects via salience. As Daston writes in *Biographies*: " 'Salience' might serve as shorthand way in which previously unprepossessing phenomena come to rivet scientific attention—and are thereby transformed into scientific objects." But due to its pertinence to boundary objects, I will primarily discuss salience with respect to the amalgamation of previously separate phenomena.

[34] Daston, 16.

[35] Star and Griesemer, 393.

But objects with many parts also have the potential to splinter back into their composites. By the mid-eighteenth century Daston's oddities became fragmented yet again due to "a new metaphysics and a new sensibility." Namely, with the likes of Isaac Newton's "Rules of Reasoning" (to be found in *Principia Mathematica*), "the new metaphysics replaced the varied and variable nature of preternatural philosophy with one that was uniform and simple," Daston writes.[36] In other words, these oddities were salient as a unified scientific object in one context, but failed to stay coalesced when the context changed.

But a change in epistemological context, in addition to metaphysical context, can also dismantle a once coalesced collection of scientific phenomena. Said differently, the way scientists explain phenomena in their purview can alter the unity of a given collection scientific phenomena.

For example, in the early 20th century, biology was dominated by a reductive epistemology, which led scientists to reduce a wide array of phenomena to the gene. But in the late 20th century, biologists began to adapt systems approach to explanation, which saw the gene as only one part of a bigger whole of causative factors. The coalescence of the discipline around the gene was then challenged, as was the coalescence of phenomena caused and united by genes.[37]

1.2.2. Emergence

Daston's collection of oddities gained salience in one context, only to disappear when the context changed. Other scientific objects *emerge* wholeheartedly out of specific contexts. That is, some scientific objects emerge *ex nihilo*, argues Daston.[38] The connectome as a boundary object came about via salience, not emergence, I argue. But there are still lessons to learn from the *emergence* approach that are pertinent to the discussion of connectome – namely, lessons about the importance of the context from which boundary objects come about.

One of *Biographies* contributors, Marshall Sahlins, points to *culture* as a scientific object that was used by anthropologists *ex nihilo*. Counter to the conception of *real* objects as inherently stable and immutable, *culture*'s ability to persist as a scientific object comes from its flexibility and proteanism in definition, says Daston. For example, *culture* can be both "the paradigmatic village or island of traditional anthropology" and "the internet." Likewise, it can be "spatially compact" and "temporally contiguous."[39] This means changing contexts can create scientific objects, but it does not necessarily need to destroy them, as it did with Daston's collection of oddities.

Flexibility, or plasticity, is part of what makes a boundary object a boundary object. Similar to *culture*, the connectome has the ability to adapt to different scientific contexts. That is, it can retain its relevance in the context of different fields within their disciplines. Or as Star and Griesemer write, they are "plastic enough to adapt to the local needs and constraints of the several parties employing them."[40]

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[36] Daston, 37.

[37] In the conclusion of this thesis, I will further discuss parallels between the gene and the connectome.

[38] Daston, 9.

[39] Daston, 10.

[40] Star and Griesemer, 393.

A boundary object's ability to adapt to different scientific contexts is undoubtedly related to the environment out of which it was born. Formed from phenomena studied by a variety of researchers, boundary objects have an innate ability to adapt to different scientific contexts. This is another way of saying a boundary object's robustness feeds into its plasticity and vice versa.

But unifying disciplines takes time. As a result, boundary objects must also be able to evolve with changing temporal contexts. One of the goals of this thesis is to show how the connectome has great potential to persist through time. A boundary object's ability to endure over time can be explained by Daston's third approach: productivity.

1.2.3. Productivity

Some scientific objects come about *ex nihilo* and others through the coalescence of preexisting phenomena, but all of them "attain their heightened ontological status by producing results, implications, surprises, connections, manipulations, explanations, applications,"[41] writes Daston. So long as scientific objects produce results for scientists, they will persist through time and have the potential to unify disciplines.

A scientific object's status as a producer of results revolves around its status as a *tool* for inquiry, says Jed Buchwald, one of the anthology's contributors.[42] In this way, boundary objects like the connectome can be thought of as tools for unification for the purposes of this thesis.[43]

However, in their original paper, Star and Griesemer describe boundary objects as tools for translation between different social worlds, not for unification. But translation and unification are not mutually exclusive: Boundary objects like the gene and the atom unified their respective disciplines because they were, first and foremost, able to act as tools for translation, I argue.

In a nutshell, translation allows for communication, which allows for collaboration, which allows for unification. Said differently, some boundary objects merely facilitate translation and collaboration, while others go farther and bring about the unification of a discipline.

But like any tool, "it takes time to forge [scientific objects], time to learn how to use them, and time to learn their strengths and weaknesses," writes Buchwald.[44] It is this process of forging boundary objects as tools, which fortifies their robustness. With continued productivity, the identity of scientific objects strengthens across different temporal and sub-disciplinary contexts. With this added robustness, scientific objects become boundary objects and gain the ability to act as translators and eventually to unify disciplines. Over the next decades neuroscience will undergo exactly this process, I argue.

1.2.4. Embededness

The productivity of scientific objects is also tied to their reality – at least tangentially. The more productive a scientific object is, the more it becomes *embedded* in scientific disciples.

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[41] Daston, 10.
[42] Daston, 11.
[43] Though they may also be tools for many other purposes as well, as I will explain.
[44] Daston, 224.

And the more embedded it becomes, the more realness it possesses, says Daston.[45]

Embeddedness is the fourth and final approach Daston outlines in the introduction of her anthology. As scientific objects gain realness by *embedding* themselves into every crevice of a discipline, they also secure their ability to unify, I argue. In this way, an object's dual realness and construction lays the foundation for robustness and plasticity and for unity.

Daston describes this process in *Biographies*:

> Scientific objects may not be invented, but they grow more richly real as they become entangled in webs of cultural significance, material practices, and theoretical derivations. In contrast to quotidian objects, scientific objects broaden and deepen: they become ever more widely connected to other phenomena, and at the same time yield ever more layers of hidden structure.[46]

Daston concludes the introduction to her anthology with a "cautiously agnostic" stance on progress in science: "Science may advance in terms of scope and accuracy of prediction, but whether science thereby asymptotically approaches a reality as God might understand it is a question to handled gingerly." She goes on to discuss how, for historians, and object's ontology and epistemology are intertwined.[47]

I avidly agree with Daston on this point. I began this section on precisely this note, namely with the idea that the process by which an object – scientific or otherwise – comes about determines, or at least influences, what an object is. In other words, in the process of producing knowledge, in the process of use, boundary objects take shape. When objects come into being, they give scientists the means to produce yet more knowledge – and it is this back and forth between ontology and epistemology that brings about unification within a discipline.

In this section I have showed how the process by which scientific objects become both real and constructed relates to their potential for both robustness and plasticity, and ultimately unification. In the following section, I will reverse engineer this section and show how work on the concept of a boundary object relates back to realness and construction. First, I will show how Star and Griesemer built their concept from work by Bruno Latour. Then, I will outline work by others who argue that boundary objects can be "federative" to further drive home my argument.

1.3. Boundary Objects and Their 'Federative' Potential

I will start with a summary of Star and Griesemer's initial conception of the boundary object in their 1989 paper. Though I will make reference to the context in which the authors' birthed their concept – Berkeley's Museum of Vertebrate Zoology between 1907 and 1939 – my primary goal is to outline the boundary object's theoretical characteristics.

One of the first lines of Star and Griesemer's paper is "scientific work is heterogeneous." Simultaneously, however scientists aim "to create common understandings" and "gather information which retains its integrity across time, space and local contingencies." This is a "central tension" in science, the authors argue – how does generalizable knowledge come out

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[45] Daston, 12.
[46] Daston, 13.
[47] Daston, 14.

of a diverse scientific body?[48]

Star and Griesemer argue scientific cooperation and consensus are not imposed by nature, at least not directly. Working during a period when the social constructionist view of science was on the upswing, the authors ignored the role nature might play in contributing to the creation of scientific knowledge because they believe "consensus is not necessary for cooperation nor for the successful conduct of work."[49] Rather they thought we can only obtain representations of nature, which may have a causal relationship with nature itself, but, either way, nature is inaccessible to us.

I have already noted in the introduction of this thesis that the pure constructionist view of science is no longer commonly held among scholars of science. Likewise, I have explained in this first part of this chapter that what an object is made of influences how it can be used.

While I do not aim to argue that scientific consensus is imposed by nature, it should be clear at this point that I do not hold Star and Griesemer's view of the role of nature in science. Nature does play a role in knowledge creation – it provides scientists with the material they need to construct boundary objects, which, in turn, can facilitate the creation of unified knowledge.

Perhaps due to their social constructionist views, Star and Griesemer concentrate on how scientific cooperation among diverse actors comes about. They ignore how scientific consensus materializes because they believe it is not necessary for successful work. That is, they concentrate on how scientists and other actors "translate, negotiate, debate, triangulate and simplify in order to work together."[50]

Since these translations between diverse actors functions much like a network[51] of interacting variables, the authors argue this scientific process "cannot be understood from a single viewpoint."[52] That is, it requires an anti-reductionist, "ecological approach," where the "unit of analysis is the whole enterprise." But a pluralistic viewpoint is also not warranted, they argue, for practical and theoretical reasons.[53]

Practically, the historical record limits the authors – information is not available on the perspective of every individual who worked at the Berkeley Museum in the early 20th century. Theoretically, pluralism allows for the management of diverse views, but not their incorporation into coherent knowledge, or for Star and Griesemer, cooperation. So if neither reductionism nor pluralism is the end goal – what is left? The answer is cooperation via boundary objects, they argue. But I argue also unification via boundary objects.

A boundary object is "an analytical concept of those scientific objects which both inhabit several intersecting social worlds…*and* satisfy the informational requirements of each of them," write Star and Griesemer. Accordingly, they are:

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[48] Star and Griesemer, 387.

[49] Star and Griesemer, 388.

[50] Star and Griesemer, 389.

[51] As I will explain in the next section, this emphasis on a network is a direct influence Latour's network building model, from which Star and Griesemer derived their concept of the boundary object.

[52] As I will also explain in the following section, it's ironic that Star and Griesemer make this point because they proceed to explain this translation process from the viewpoint of only two actors. This narrative argumentation method directly limits their ability to see how a boundary object could be used in different contexts.

[53] Star and Griesemer, 389.

> [O]bjects which are both plastic enough to adapt to the local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. They are weakly structured in common use, and become strongly structured in individual site use. They have different meanings in different social worlds but their structure is common enough to more than one world to make them recognizable, a means of translation.[54]

And I argue they can also be a means of unification of disciplines. But overall, boundary objects are tools, argue Starr and Griesemer, much like the scientific objects described in *Biographies*.

In what kind of environment do boundary objects come about? Many participants within the network "share a common goal." Within the context of Star and Griesemer's history of the Berkeley Museum, it was to "preserve California's nature."[55] Having the common goal of elucidating the boundary object itself (opposed to a tangential goal like preserving nature) is a necessary, but not sufficient, criterion for the unification of a discipline, I argue. For neuroscience today, the goal is describing and integrating the different organizational levels of the brain into a coherent whole using the connectome as a framework for knowledge production.[56]

But boundary objects do not only come in one form. Star and Griesemer outline three different kinds of boundary objects that pertain to this thesis – repositories, ideal types and coincident boundaries.[57]

Repositories are "ordered 'piles' of objects which are indexed in a standardized fashion." Their purpose is to "deal with problems of heterogeneity caused by differences in units of analysis," explain the authors. "People from different worlds can use or borrow from the 'pile' for their own purposes without having directly to negotiate differences in purpose."[58] A repository is a more concrete form of a boundary object.

A notable example of a repository boundary object as it pertains to this thesis is the genome databases produced during the Human Genome Project, which I will discuss in the conclusion. Even more pertinent – one of the primary goals of the Human Brain Project is to create platforms, such as "prototype hardware, software tools, databases, programming interfaces, and initial data-sets,"[59] which neuroscientists can use for collaboration.

A second type of boundary object, an "ideal type," is more abstract than a repository and follows Star and Griesemer's initial description of a boundary object closely. It does not

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[54] Star and Griesemer, 393.

[55] Star and Griesemer, 408.

[56] For another example, within the context of biology in the early to mid 20th century, the goal was providing a mechanism for trait transmission over time. That is, the goal was providing a mechanistic and quantitative explanation for Darwin's theory of natural selection. As I will briefly cover in the conclusion of this thesis, the unification of biology in the early to mid 20th century followed the same trajectory as neuroscience is today, namely by unifying around boundary object – the gene.

[57] I'm less clear on how the fourth type of boundary object – standardized forms – applies to this thesis. Star and Griesemer describe them as "methods of common communication across dispersed work groups." The authors explain that since "natural history work took place at highly distributed sites by a number of different people, standardized methods were essential." Thus, they are "objects which can be transported over a long distance and convey unchanging information." My hunch is that standardized methods such as those explained by Star and Griesemer wouldn't be possible for neuroscience because it is a global endeavor. In other words, the distances are too large to facilitate any sort of standardized methods. However, thorough discussion of this topic is outside of the confines of this thesis.

[58] Star and Griesemer, 410.

[59] https://www.humanbrainproject.eu/platforms-overview, accessed 09/04/2015.

“describe the details of any one locality or thing” and “may be fairly vague.” For this reason, it can be adaptable to any local site. Its purpose is to serve “as a means of communicating and cooperating symbolically.” It also “incorporate[s] both concrete and theoretical data.”[60]

The connectome is also a good example of an ideal type – it can be abstract and vague, and thus, able to adapt to various fields within neuroscience. It also unites concrete data on the anatomy of the brain with theoretical data on cognitive function.

The third type of boundary object outlined by Star and Griesemer is the coincident boundary. “These are common objects which have the same boundaries but different internal contents;” for example, maps. “The result is that work in different sites and with different perspectives can be conducted autonomously while cooperating parties share a common referent.”[61]

Star and Griesemer give the example of a map of California. At the Berkeley Museum, professional biologists made ecological maps of the state filled with “life zones,” while conservationists and amateur collectors constructed more traditional maps of California that “emphasized campsites, trails and places to collect.”[62]

The connectome, likewise, is a map of the brain’s neural connections, but it can also have different internal contents. Cellular neuroscientists might be more concerned with a map of connections between individual neurons, while cognitive neuroscientists would seek to map the connections between areas of the brain.[63]

But from where did the concept of a boundary object originate? What were its predecessors and its successors? And could they be more pertinent to this thesis than the boundary object? (Spoiler: The answer to the last question is no.) In her paper “Crafting Science: Standardized Packages, Boundary Objects, and ‘Translation,’” Joan H. Fujimura provides a nice explanation of the difference between Bruno Latour’s *network building model* and Star and Griesemer’s *boundary object*.

Star and Griesemer developed their concept in response to work by Latour, says Fujimura, but their aims are different. Latour’s *network building model* primarily facilitates “fact stabilization,” whereas Star and Griesemer’s *boundary object* paves the way for “collective work across worlds with different viewpoints and agendas.”[64]

Though fact stabilization is possible with boundary objects, and, likewise, collective work with network building models, Fujimura argues that both concepts are limited by their authors’ “story-telling perspective.”[65] That is, the case studies the authors used to outline their two concepts set unnecessary constraints on how the concepts can or should be used.

For example, Latour’s presentation of the network building model in *The Pasteurization of France* “has been criticized as too Machiavellian a view in which scientific entrepreneur-generals go about waging war to conquer and discipline new allies,” writes Fujimura. This is the result of Latour’s storytelling technique, namely singling out a protagonist, Louis Pasteur,

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[60] Star and Griesemer, 410.

[61] Star and Griesemer, 410.

[62] Star and Griesemer, 411.

[63] I briefly covered these different “levels” in the connectome in the introduction. I will go into further detail on this topic in the latter portion of this chapter.

[64] Fujimura, 169.

[65] Fujimura, 172.

who attempts to “spread his theory of the microbe” across France. Others also “enrolled Pasteur’s microbe in *their* efforts” as well, says Fujimura, but their stories are marginalized.[66]

Similarly, Star and Griesemer concentrate on the story of only two individuals, Joseph Grinnell and Annie Alexander, directors of the Museum of Vertebrate Zoology at the University of California, Berkeley. Narrative argumentation is especially ironic here because the authors also use the “ecological approach,” which frames science “as a collective action from the viewpoints of all the actors and [social] worlds involved, and thereby avoid[s] the preeminence of any one actor.”[67]

Fujimura proposes her concept of *standardized packages* as an alternative to the *boundary object* and the *network building model*. She argues that, unlike the latter two concepts, standardized packages allow for both fact stabilization and collective work – not just one or the other.[68]

However, I argue it is the narrative context in which Star and Griesemer birth their concept of the boundary object that prevents them from recognizing the boundary object’s complete potential. Used in a different way, a boundary object could facilitate fact stabilization as well as collective work, I argue.

Grinnell used the museum, for example, as a means to an end – to motivate collective work on “his theory that theory that changing environments are driving forces behind natural selection, organismal adaptation, and the evolution of species.” But what if the boundary object is taken as an end in itself? What if it is the collective goal of different social groups to understand the ins-and-outs of a particular boundary object? Said differently, what if the boundary object itself is the protagonist of the story?

I argue this is precisely the difference between boundary objects that unify and those that do not. That is, when it comes to boundary objects that unify disciplines, the main motive of scientists is to illuminate the contours of the boundary object itself, not to use it as a means for cooperation to achieve some other purpose.

Said differently, seeing a boundary object as a means to an end is what limited boundary objects from facilitating fact stabilization in Star and Griesemer’s case study. But when efforts are directed at the object itself, fact stabilization, in addition to cooperation and translation, becomes possible. And fact stabilization, at least temporarily, is undoubtedly important to the unification of disciplines, I argue.

How might boundary objects become unifiers, or “federative,” as Ilana Löwy describes it? Ilana Löwy discusses the relationship between “federative” boundary objects or concepts and disciplinary growth in her 1992 case study concerning the history of immunology. She summarizes her argument as follows: “While the emphasis on well-defined scientific concepts leads to studies of coherent groups of scientists, the emphasis on loose concepts is necessary for the investigation of relations across professional and disciplinary boundaries.”[69] She then argues loose concepts, namely boundary objects, facilitate disciplinary growth in immunology in the 20th century.

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[66] Fujimura, 171.

[67] Fujimura, 172.

[68] Fujimura, 172.

[69] Löwy, 371.

But Löwy says vague concepts are not only powerful in immunology – they could facilitate the growth of any scientific discipline. Scholars of science did not always argue this point, even if they did acknowledge that vagueness could, in certain instances, bring about new knowledge. Ludwik Fleck, points out Löwy, recognized that the "variance of meaning of terms which circulate among different 'thought collectives' may lead to scientific innovation."[70]

But Fleck, and other scholars such as Thomas Kuhn and Paul Feyerabend, concentrated on the incommensurability of terms and the problems it incurred for collaboration and unification. As Löwy explains it, Fleck "viewed the variance of meaning of scientific terms as 'noise' – occasionally heuristically felicitous but entirely random result of the impossibility of accurately transferring terms from one 'thought style' to another – rather than 'signal' – a strategic tool in the construction of scientific knowledge."[71] Löwy also notes that scholars, such as Lindley Darden and Nancy Maul, discussed the "heuristic role of imprecise terms" in generating new scientific ideas, but "did not discuss their possible role in the social organization of scientific work."[72]

To make up for the limitations of her predecessors, in her paper Löwy aims to address the empirical and social functions of imprecise terms – both of which are important to the unification of disciplines. She shows how "'fuzzy' terms may remain imprecise for their whole life span and, as such, continue to play an important heuristic role in the construction of new scientific knowledge." And she also argues "'permanently imprecise' concepts may moreover favour the development of 'federative' experimental approaches and may facilitate the long-term maintenance of loose coalitions and of institutional alliances between pre-existing professional groups."[73]

In Löwy case, the fuzzy boundary concept is the "immunological self." She argues this concept appeared first in the 1910s, but failed to take hold because immunology's experimental approaches had not developed enough to make full use of the concept's potential. Löwy explains that in the 1910s immunology as a discipline experienced "a high level of technical and strategic uncertainty" simultaneously, i.e. uncertainty as it pertains to the discipline's "conceptual framework and experimental methods."[74]

As a result, immunologists traded their disciplinary autonomy for more certainty. Some gave up their titles as fundamental scientists for medicine and others gave up teleological theories of immunity for (e.g. the immunological self) for a narrower aim – the "study of specific antibodies in a test-tube." With most immunologists integrating themselves in other areas of research, unity in the discipline lost priority.[75]

But these actions ended up facilitating the federation of immunology later on. Researchers interested in immunology gathered technical skills in these other disciplines. By the 1950s they then revisited the concept of the immunological self with these technical skills in hand and the discipline was able to unify through this boundary concept.

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[70] Löwy, 373.
[71] Löwy, 373.
[72] Löwy, 373.
[73] Löwy, 373.
[74] Löwy, 390.
[75] Löwy, 390.

How and why is this the case? Löwy argues boundary concepts "are particularly effective in forging intergroup alliances among scientific domains which combine high strategic uncertainty with low technical task uncertainty." Thus, initially they may be "hampered by a low level of agreement over research goals," but boundary concepts or objects can unite these researchers, who can then share their technical skills to produce knowledge. "This precisely happened to immunologists in the 1950s," argues Löwy.[76]

And I argue this is, to a certain extent, what is occurring in neuroscience today. Thus, I agree with Löwy when she writes, "loose 'boundary' concepts play an important role in the construction of scientific knowledge and in disciplinary growth."[77]

As I will show in the following sections and chapters, neuroscientists have gathered the technical skills needed to begin to link the brain's form to its function into a organized, descriptive structure: Cellular neuroscientists have gained knowledge of the brain's anatomy; cognitive neuroscientists have developed methods for capturing the brain in action using neuroimaging (e.g. functional magnetic resonance imaging and diffusion tensor imaging) and computational neuroscientists are now finding ways to quantify and connect this data on the brain using network analysis (i.e. the connectome). Thus, it is the computational neuroscientists, with the connectome as a tool, who are leading the unification of neuroscience by providing the framework for description.

To recap, in the first sections of this chapter I showed how the process by which scientific objects become both real and constructed relates to their potential for both robustness and plasticity. As is pertinent to the thesis, first some scientific objects become *salient* via coalescence. This lays the groundwork for their *plastic* ability to catch the attention of a wide array of researchers. Over time, this diverse set of scientists investigates these objects and uses them as tools for translation and collaboration, learning their strengths and weaknesses and tweaking (or *constructing*) them accordingly. In the process, these objects *produce* results for scientists. As they produce results, these objects become more and more *embedded* in scientific disciplines. And as they become more embedded, they achieve a more *robust* reality.

I also showed that it appears that temporal context is right for the connectome to unify neuroscience, according to observations made by Löwy about immunology. In the next section, I will outline how exactly the connectome is a boundary object in neuroscience. Then, in the following chapter, I will explain in more detail why neuroscience is not unifying via reductive but mosaic unity with the help of work by Carl Craver.

1.4. The Connectome as a Boundary Object

This section will be separated into two separate sub-sections. In the first, I will outline the connectome's theoretical structure. In the second, I will give a bit of historical context for the rise of the connectome as a boundary object. In other words, I will argue the connectome conforms to Daston and Star and Griesemer's theories of scientific objects and boundary objects, respectively. I will also argue the connectome's role in neuroscience shares much with the role the "immunological self" played in immunology, as outlined by Löwy.

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[76] Löwy, 390.

[77] Löwy, 391.

1.4.1. Connectome in Theory

Olaf Sporns, Giulio Tononi and Rolf Kötter first coined the term "connectome" in their paper "The Human Connectome: A Structural Description of the Human Brain," published in *PLOS Computational Biology* in 2005. In their paper's introduction, the researchers state clearly what they aim to achieve with their new term:

> The purpose of this article is to discuss research strategies aimed at a comprehensive structural description of the network of elements and connections forming the human brain. We propose to call this dataset the human "connectome," and we argue that it is fundamentally important in cognitive neuroscience and neuropsychology. The connectome will significantly increase our understanding of how functional brain states emerge from their underlying structural substrate, and will provide new mechanistic insights into how brain function is affected if this structure substrate is disrupted. It will provide a unified, time invariant and readily available neuroinformatics resource that could be used in virtually all areas of experimental and theoretical neuroscience.[78]

This excerpt from Sporns et al.'s illustrates my thesis' argument to a near perfect degree. First off, the connectome is here presented as a dataset, or as Star and Griesemer would call it, a repository[79]. Second, the authors argue the connectome's application will reach all areas of neuroscience. This gives it the potential to unify. On top of that, Sporns et al. say the connectome will provide a unified resource for neuroscientists. Thus, in the process of fleshing out this unified dataset, neuroscientists will unify their discipline.

But scientists are no strangers to overzealousness when it comes to the potential of their research and ideas. Has the connectome begun to catch on and become as important as Sporns et al. claims? In his book *Discovering the Connectome*, published in 2012, Sporns provides a telling anecdote about the growth of the term "connectome":

> When I googled the term "connectome" (just to be sure no one else had thought of it earlier) [in 2005] I remember getting around 10 hits, none of them relevant to the brain. In fact, some of them were oddly irrelevant – I recall finding " connect-to-me " (a dating site, I believe) and " connect-home " among the search results. As of April 2012 the same Google search returns nearly a quarter million hits. ... I believe it is fair to say that the connectome and the nascent field of connectomics are beginning to influence the ways many neuroscientists collect, analyze, and think about their data.

Today[80] a Google search of "connectome" brings up about 420,000 hits – evidence that the term is only growing in use.

Before the coining of the term "connectome," neuroscience was still a busy discipline. Sporns et al argue that much work had been done at that point to understand the anatomy of the neurons, synapses, axons and the like as well as the anatomy of cerebral cortex's[81] lobes, such as the frontal or occipital lobes. Researchers did have some knowledge of the connectedness within regions of the brain, but what remained to be elucidated was the connectedness between "anatomically segregated" areas, the authors argue.[82]

Even still, back in 2005 (and still in large part today) neuroscientists had yet to organize their knowledge into "a single standardized data format" accessible "though a public database," wrote Sporns et al. The authors propose the connectome as the database to organize and

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[78] Sporns et al., 245.

[79] The connectome can also fall into other categories of boundary objects, which I will note as I go along.

[80] As of January 1, 2017. Last I checked, it was 350,000 hits in April 2016.

[81] The cerebral cortex is the outer layer of the brain.

[82] Sporns et al, 245.

further neuroscientific research with the aim of mapping "structure to function in the human brain."[83] Their "central motivating hypothesis is that the pattern of elements and connections as captured in the connectome places specific constraints on brain dynamics, and thus shapes the operations and processes of human cognition."[84]

But how will this mapping of the connectome be carried out? In their original paper, Sporns et al. break the connectome down into different components: neuronal elements and neuronal connections. They also break the connectome down into three scales: the microscale, the mesoscale and the macroscale. At the microscale, the elements and connections correspond to neurons and synapses, respectively. Distinct populations of around 80-100 neurons called cortical minicolumns and the neuronal pathways linking them fall under the mesoscale. At the macroscale, elements and connections correspond to "distinct brain regions" and "inter-regional pathways."

In his book *Discovering the Connectome*, Sporns also discusses what has been called the "functional connectome," which maps the connectivity of the "brain in motion."[85] Mapping the functional connectome entails using functional magnetic resonance imaging while the brain is in a "resting state" (with no tasks) and while conducting tasks.[86] The ultimate goal of connectomics is to link the functional connectome to the structural connectome, argues Sporns.

These different scales can also correspond to different fields within neuroscience – cellular neuroscientists study the anatomy and physiology of neurons and synapses. Behavioral and cognitive neuroscientists often use functional magnetic resonance imaging (fMRI) to link behaviors and thoughts to activity in certain brain regions, for example.

Of course, neuroscience is not limited to these disciplines – there are also fields within the discipline that concentrate on specific human phenomena. Neurolinguistics, for example, examines the role of the brain in language, while affective neuroscience studies the brain as it relates to emotion. Then there are fields such as clinical neuroscience or neuroengineering, which apply knowledge about the brain to treating diseases or designing computers, respectively. These computer systems can then be used to better understand the brain, in an epistemic cycle. And still, there are more fields.[87] The point is that all of these fields have and will continue to contribute to elucidating the connectome.

In their 2005 paper, Sporns et al. outline how the first draft of the human connectome could be carried out, namely the macroscale connectome. The authors argue this level is the most feasible in large part because a "broad range of experimental approaches exist at the macroscale,"[88] including dissection, histological staining and diffusion tensor imaging.[89]

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[83] Sporns et al, 245.

[84] Sporns et al, 249.

[85] Sporns, 109.

[86] Sporns, 120.

[87] Disciplinary boundaries in science are ever changing, and thus at least partially artificial. I discuss neuroscience in terms of the fields it comprises here more for ease of communication. Admittedly, even the boundary between neuroscience and other disciplines like physics and biology are blurred. This fact does not affect my thesis argument, however. The point is there exists a community of researchers interested in elucidating the brain (many of them call themselves neuroscientists) who are and will unify around the connectome.

[88] Sporns et al., 246.

[89] Brain tissue, or all tissue for that matter, has little inherent contrast when viewed through a light or electron microscope. Staining provides contrast so that researchers can highlight particular qualities of the biological sample. Diffusion tensor imaging maps the diffusion of molecules (primarily water) in living tissue. In doing so, it reveals details about tissue

In contrast, the authors argue attempting to map the connectome at the microlevel, namely individual neurons and synapses, “will remain infeasible at least in the near future.” There are various reasons for this difficulty, such as the fact that scientists currently do not have computers that could hold a dataset that is “several orders of magnitude larger than that of the genome,” they write. Other issues include the brain’s connective plasticity, i.e. how do you accurately map a brain in constant change? However, this issue may be solved in the future through sophisticated and dynamic models of the brain.[90]

Sporns et al. argue the microscale connectome may prove to be technically impossible and perhaps unnecessary for achieving the goal of understanding the link between brain structure and function. In fact, the connectome’s balance between realness and construction can be summed up by one quote from Sporn’s 2012 book that discusses the difficulty of mapping the connectome at the microscale: “The point of building brain models…is to advance understanding brain function, not creating *in silico* replicas that are as complex and incomprehensible as the real thing.”[91]

However, the macroscale connectome is necessary, but insufficient for reaching this goal. At some point neuroscientists will need to map the brain at the mesoscale for further detail. Why? Sporns et al. argue that minicolumns appear to “represent basic functional elements that are crucial for cortical information processing.”[92] This means minicolumns appear to play an important role in processing information.

Eventually, the researchers argue the connectome’s different scales will be integrated “by incorporating linkages between the macroscale of brain regions and pathways in more elementary mesoscale functional units.” Where possible, the connectome will also integrate microscale details.[93]

In general, mapping the connectome holds much promise, but also poses a number of hurdles for neuroscientist to overcome, the authors argued. “As experimental techniques mature, the connectome will gradually evolve through different stages of assembly,” they add. “An additional driving force is the continued innovation in data acquisition and analysis techniques, particularly in diffusion-weighted imaging.”[94]

Having work to do and hurdles to overcome are not necessarily bad things for disciplines. The more hurdles neuroscientists overcome, all the while keeping the concept of the connectome intact, the more they will unify around that time-tested concept or object. One of the hurdles Sporns outlines could actually be an asset in some cases, at least for the connectome as a boundary object that’s plastic enough to apply to multiple areas of the neuroscience. Sporns calls this issue the “parcellation problem,” or the difficulty of definitively identifying the functional units of the connectome’s scales.[95]

As I have already mentioned, Sporns and his colleagues point to neurons, minicolumns and brain regions as some of the units of the different scales. Neurons are relatively distinct

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structure.

[90] Sporns et al. 246.

[91] Sporns, 168.

[92] Sporns et al., 247.

[93] Sporns et al., 249.

[94] Sporns et al., 249.

[95] Sporns, 44.

anatomically, he says, so the parcellation problem doesn't necessarily apply to the microscale. But there is "no single universally accepted parcellation scheme…for human brain regions…posing a significant obstacle to creating a unified resource such as the connectome."[96] However, I argue Sporns et al. are wrong about this being an issue for unification.

One quality of boundary objects is their vagueness. If they are too rigid it provides the opportunity to limit the possibility of some researchers having the opportunity to use the concept of the connectome in their work. While some researchers may adhere to using the Human Brain Project definition of certain brain regions in their work, for example, others may adapt that work to their own by coming up with slightly different definitions of the brain regions.

In other words, even though Sporns shuns a reductive view of the brain in many parts of his book, he fails to recognize the limitation that would be created by reducing the connectome to one particular set of definitions of brain regions and their connections.

So how is the connectome a boundary object? Earlier on in this chapter I wrote, "If a scientific object is born out the coalescence of a diversity of phenomena, the object will likely have a wide array of applications. Likewise, the variety of researchers who study specific facets of an object will likely find interest in the object as a whole." This was in reference to Daston's *salience* criterion for scientific objects.

Along these lines, Sporns and colleagues have argued that the ultimate aim is to integrate the different scales of the connectome, and to do this it will require work by neuroscientists across the discipline.[97] Sporns et al. designed the connectome to be applicable to neuroscience as whole and this gave the object the potential to be "plastic enough to adapt to the local needs and constraints of the several parties employing" it.[98] In short, the connectome is plastic enough to apply to different scientific contexts.

But the connectome is also plastic enough to remain intact in different temporal contexts. In other words, the connectome as an object also applies to Daston's *productivity* criterion – it shows promise as being able to evolve, but remain intact, over time because it will continue to be productive as a object. This is what I meant by having work to do is not necessarily a bad thing. Sporns et al. admit as much in their 2005 paper.

As I will explain in the next section, the connectome can, in large part, do this work because Sporns et al.'s idea has come about when neuroscience had matured enough experimentally to actually be able to use the concept appropriately. In short, as long as scientists can use the connectome as a tool for deriving more questions and more answers, it will adapt to the times and remain productive. In forging this tool, in integrating the different scales of the connectome, this object will also become more and more embedded in all areas of neuroscience and the discipline will unify.

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[96] Sporns, et al., 246

[97] Admittedly, integrating information has been a trend in biology, namely the systems approach. I will discuss this overarching trend briefly in the conclusion of this thesis.

[98] Star and Griesemer, 393.

1.4.2. Connectome in History

Löwy argued that boundary concepts “are particularly effective in forging intergroup alliances among scientific domains which combine high strategic uncertainty with low technical task uncertainty.”[99] In her paper, the concept of the “immunological self” first appeared in the 1910s. But she argues it failed to take hold because immunology’s experimental approaches had not developed enough to make full use of the concept’s potential. When resurfaced in the 1950s, however, experimental approaches in immunology had developed enough to take advantage of this concept as a tool for translation and collaboration.

Marco Catani and others argue the connectome has a similar history in their paper, “Connectome approaches before the connectome.” They write, “A myriad of proto-connectome maps have been produced throughout the centuries, each one reflecting the theory and method of investigation that prevailed at the time…We argue that compared to previous attempts current connectomic approaches benefit from a wealth of imaging methods that in part could justify the enthusiasm for finally succeeding in achieving the goal.”[100]

Catani et al. support his argument by citing a number of large-scale projects aimed at understanding brain connectivity. The Human Connectome Project, for example, is a 40 million dollar National Institute of Health initiative to map the human connectome in 1200 health subjects using large scale functional and structural imaging.[101] The authors also point to the Human Brain Project, a 1 billion euro flagship project of the European Commission, which aims to simulate brain connectivity, among other endeavors.[102] Then there is the BRAIN Initiative in the United States, an initiative comparable to the Human Brain Project in proposed funding and aims.[103]

Cantani et al. argue that this “unprecedented support is in large part due to the development of new methods to image networks in the living human brain and the computational capability of processing and storing large amounts of data. The connectome approach, although new in its overarching conception, represents the culmination of converging lines of research each of which have developed over the course of many centuries.”

The main difference between previous experimental approaches and today’s imaging techniques is the ability to study the living human brain. Previous studies relied on extrapolating findings about the brains of other species to humans, as obtaining samples of human brain proved difficult.[104]

But “neuroimaging methods have inaugurated a new era in the study of functional and anatomical connectivity in the living human brain,” write Cantani and colleagues.[105] Though still in development, PET and fMRI studies, for example, “showed the existence of a ‘default mode network’…that is active during the ‘resting state,’ a condition in which the majority of the subjects engage in introspection.” Only with these new methods can neuroscience have the possibility of integrating the levels of structure with function, which is the ultimate goal

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[99] Löwy, 390.

[100] Catani et al., 2.

[101] http://www.humanconnectomeproject.org – visited 31/5/2016.

[102] https://www.humanbrainproject.eu – visited 31/5/2016.

[103] http://www.braininitiative.nih.gov -- visited 31/5/2016.

[104] Though it still does today.

[105] Cantani et al., 9.

of the connectome.[106]

Modern methods also allows for quantitative research on the brain, argue Cantani and colleagues. “A fundamental contribution of contemporary neuroimaging is related to…the possibility of quantifying parameters that give indirect measurements of the functional and anatomical strength of connections between regions,” they write. In other words, neuroimaging produces data that can be analyzed using network theory, the integration of which aids in mapping the connectome.

Cantani and colleagues also add that, “With the introduction of the concept of a brain ‘connectome’ the field moved a step farther” by integrating all the data into one map. “Current approaches to brain mapping result from the coalescence of fast paced advancements” in computing, quantitative neuropsychological testing, MRI capability and computational theories, they add. This provides support for my argument that the connectome was born out of a coalescence of different fields and their methodologies.

In sum, I have argued the connectome was formed in such a way as to lay a foundation of both realness and construction – that is via coalescence. I have also argued this foundation facilitated the connectome’s ability to act as a unifying boundary object that is both robust and plastic. Lastly, I have showed that the circumstances in which the connectome emerged also facilitates its ability to unify neuroscience, a discipline which has developed the technical ability to investigate the brain through neuroimaging: The connectome as a boundary object then provides neuroscience as a discipline with the strategy needed to describe brain structure and function. In the next chapter, I will argue that neuroscience is unifying via the connectome in a particular way, namely through mosaic descriptive unity and not reductive unity.

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[106] Sporns et al. make this explicit in their initial 2005 paper and the aim continues to be present in Sporns’ book.

2.0. Chapter Two: Mosaic Unity and the Connectome's Role in Neuroscience

In the previous chapter I argued that the duality of realness and construction in scientific objects lays the foundation for the qualities of robustness and plasticity in boundary objects in particular. I also argued that the connectome is a unifying boundary object.

In this chapter I will argue that the *robust* and *plastic* nature of the connectome pairs well with my theory of mosaic descriptive unity because this form of unity also relies on a duality: the *unified*, yet *autonomous* fields of neuroscience.

My theory of mosaic descriptive unity is based off of Carl Craver's theory of mosaic explanatory unity. In fact, I will argue with the help of Craver that mosaic descriptive unity is the precursor to mosaic explanatory unity in the practice of neuroscience.

To make my case, I will go over Carl Craver's work on explanation and unity of neuroscience in detail. This will involve a foray into what Craver rejects, namely the metaphysical underpinnings of causation and reductive explanation. I will then tie together his work with my argument for mosaic descriptive unity and the connectome as a boundary object.

2.1. Carl Craver Cares Not for Reduction and Metaphysical Questions

Before explaining how neuroscience unifies, I will outline Craver's argument for why reductive explanatory unity does not suit the discipline, and relatedly, why Craver disregards metaphysical concerns.

Very early on in his book, *Explaining the Brain: Mechanisms and the Mosaic Unity of Neuroscience*, Carl Craver distinguishes neuroscience from more fundamental sciences by arguing that neuroscience, unlike these disciplines, does not function under the premise of reductive unity.

"If one views neuroscience through the lens of explanation in physics and chemistry, one is tempted to organize multilevel explanations by sorting the different components into complete explanations at each level and then relating the levels to one another by deduction," writes Craver.[107]

But "opposed to physics or chemistry," explanations in neuroscience (1) "describe mechanisms," (2) "span multiple levels," and (3) "integrate findings from multiple fields" within the discipline, Craver says.[108] These three characteristics of neuroscience lie at the crux of Craver's argument for mosaic explanatory unity.

Still, "Fundamentalists demand that neuroscientific explanations bottom out in some privileged set of entities or causal relations," he says. "Some fundamentalists believe that neuroscientific explanations bottom out in the behavior of neurons…Other fundamentalists— molecularists – ground neuroscientific explanations in molecules." And others take reduction

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[107] Craver, 9.

[108] Craver, 2.

a step farther and argue "real" explanations come from even lower levels, such as atoms.[109]

"Wherever the bottom is," writes Craver, "that is where the real explanations are to be found," according to fundamentalists. In other words, no matter the end level, fundamentalism, or reduction, is driven by metaphysical concerns, he argues.[110]

A number of philosophers of neuroscience have used Paul Oppenheim and Hilary Putnam's reductive model[111] to provide arguments concerning the unity of neuroscience, Craver adds. Oppenheim and Putnam argued that the unity of science as a whole consists of "a chain of reductive explanations that link phenomena at the highest levels[112] to phenomena at the lowest levels[113]," he writes.[114]

Oppenheim and Putnam's model for unity in science is based off of Thomas Nagel's classical reduction model,[115] which argued that "reduction is achieved by identifying the kind of terms in higher-level theories with those of lower level theories and deriving the higher-level theories from the lower-level theories," explains Craver. "On the assumption that different fields of science have their own theories, and on the assumption that their theories describe different levels, the reduction model then provides a view of the unity of neuroscience."[116] Thus, this route to explaining unity in science is deductive and logical. Craver's mosaic unity, however, is not.

There are at least two reasons why these kinds of fundamentalist-reductive theories have become common in the philosophy of neuroscience, argues Craver. The less interesting reason is pride or ego. In other words, "Scientists in one field are convinced that they know more about the world than scientists in other fields," he writes.[117]

The role of ego in the unification of disciplines will be discussed briefly in the conclusion of this thesis, where I will outline areas for future research. In particular, I will discuss how the unification of neuroscience around the connectome parallels the unification of biology in the early 20th century around the gene, both in in the structure of the unification and the attitudes of some scientists during unification. But for the most part, I will leave ego unexplored, as it is outside the confines of this thesis.

Another more pertinent reason for employing reductive theories of unification stems from a view of the history of neuroscience, says Craver. Some scholars "believe that science exhibits a trend toward explanation in terms of ever more fundamental ontological units," he writes. But he argues there is actually not much evidence from the historical record to support this theory and over the years many other philosophers of neuroscience have come to admit this as well.[118]

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[109] Craver, 11.
[110] Craver, 12.
[111] Oppenheim and Putnam's model was outlined in the 1958 paper, "The unity of science as a working hypothesis."
[112] For example, the organization and interactions of and within societies.
[113] For example, elementary particles.
[114] Craver, 17.
[115] Craver is referring to Nagel's 1961 book, *The Structure of Science: Problems in the Logic of Scientific Explanation*.
[116] Craver, 17.
[117] Craver, 12-13.
[118] Craver, 14.

As a result, some philosophers, such as Kenneth F. Schaffner,[119] have attempted to keep reductive explanatory unity alive in neuroscience by calling it a "regulative ideal" in the discipline; that is "an ideal end point that guides the search for explanations even if that end point is never achieved in practice," says Craver. Schaffner also admits that reduction is largely peripheral to the practices of neuroscientists, both past and present.[120]

But Craver argues that reduction is "so peripheral to the practice of neuroscience that it is misleading to think of it as a regulative ideal for integrating neuroscience."[121] As a result, "There is no reason (absent separate metaphysical arguments) to take the developmental trajectory of physics as a projectable trend to be read onto the development of all sciences," says Craver, and that includes neuroscience.[122]

Olaf Sporns, who coined the term "connectome," could not agree with Craver more. For example, Sporns ends his book, *Discovering the Connectome*, stating, "I think we'll find that the complex architecture of the connectome and its variable dynamics fundamentally resist reductionist explanation."[123]

Sporns sees the structural connectome – the static, anatomical micro-, meso- and macroscale connectomes – as necessary, but not sufficient for explanation in neuroscience. He argues that the "dynamics of functional networks," or the functional connectome, "invalidate any simple-minded attempt to reduce brain function to brain wiring."[124]

Sporns also makes no mention of any metaphysical concerns in his book, which supports Cravers argument that neuroscientists disregard these concerns when conducting research and forming theories about the brain. "Questions about the metaphysics of properties and causation are…not relevant to what experimental scientists ought to do or to what explanations they ought to seek," he writes. For this reason, "Nor are they relevant to which explanations a neurophilosopher ought to endorse."[125]

In other words, Craver is not aiming to address whether neuroscientists get at the *reality* of the brain and nervous system, but rather how they *construct* knowledge about the brain based on observations of and experimentation with neurological phenomena. "We can make significant progress in the philosophy of neuroscience without settling…perennial metaphysical disputes,"[126] he writes.

This desire for metaphysical answers leads philosophers of neuroscience to misunderstand explanation in neuroscience in two ways, says Craver. For one, fundamentalists, as previously noted, strive to address the metaphysical by arguing that lower levels of nature explain higher levels, but not the other way around. Second, also due to their metaphysical concerns, fundamentalists argue that "levels of nature" correspond to "levels of science" [127] because they believe scientists are (or at least should be) *directly* getting at the real world,

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[119] Craver's predominately talking here about Schaffner's 1974 paper, "The Peripherality of Reductionism in the Development of Molecular Biology."

[120] Craver, 18.

[121] Craver, 18.

[122] Craver, 38.

[123] Sporns, 179.

[124] Sporns, 178.

[125] Craver, 226.

[126] Craver, 227.

[127] Craver, 171.

instead of just creating representations of nature.

Let's start with the confusion over correspondence between levels of nature and science. What falls under these two different categories of levels? "Levels of nature relate items in the world, such as activities, entities, properties, and states," says Craver.[128] Levels of science do not correspond to the real world, but rather constructs of science. Craver breaks levels of science down into two categories – products and units. Products of science entail descriptions and theories, whereas units of science include fields, paradigms and research programs. A fundamentalist might argue that the levels of activities correspond directly to levels of descriptions, for example.

But Craver says there is no tidy correspondence between levels of nature and levels of science in the practice of neuroscience. In fact, he argues it makes no sense to interchange these different types of levels in the same sentence, as some reductionists have done. For instance, Oppenheim and Putnam write in their 1958 manifesto, "It has been contended that one manifestly cannot explain human behavior by reference to the laws of atomic physics. It would indeed be fantastic to suppose that the simplest regularity in the field of psychology could be explained directly – that is, 'skipping' intervening branches of science—by employing subatomic theories."[129]

In this passage, Oppenheim and Putnam switch from discussing phenomena of nature (i.e. human behavior), to describing scientific products (i.e. explanations and theories), to referring to scientific fields (i.e. psychology and atomic physics). But a neuroscientist or psychologist in practice would never attempt to explain human behavior in this way because they do not have the same goals as Oppenheim and Putnam, which is to neatly order and correspond levels in science to levels in nature. In other words, reductive philosophers' desire to consider the metaphysical drives them away from the actual practice of neuroscience.

If philosophers acknowledge that ordered explanation is not a goal in science, they will also be able to see that 'higher level' disciplines like neuroscience may have different criteria for successful explanation than lower level disciplines like physics. In neuroscience, "Single fields increasingly reach across multiple levels of nature, and different fields often approach items at the same level of nature from different perspectives," writes Craver.[130]

Said differently, explanation in neuroscience is multilevel and "oscillates up and down in a hierarchy of mechanisms," says Craver.[131] Higher-level mechanisms can be used as parts of explanations for lower-level mechanisms. In short, they are not reductive. Craver also argues philosophers of neuroscience who argue for reductive explanation to quell metaphysical concerns are misleading neuroscientists into ignoring explanations that may occur at higher levels.

Craver then takes his argument a step further towards the normative: "The suggestion…is not merely that the central nervous system *can* be explained at different levels, but that an adequate explanation of many phenomena in the central nervous system *must* bridge phenomena at multiple levels." For this reason, Craver argues, no single level in

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[128] Craver, 171.
[129] Craver, 175.
[130] Craver, 176.
[131] Craver, 9.

neuroscientific explanation, the molecular or the cognitive, takes precedent.[132]

Again, Sporns could not agree with Craver more on this point. Connectomics is “an extension of systems biology to the brain,” says Sporns.[133] Accordingly, like systems biology, connectomics “must integrate data from disparate sources and across levels of organization” for successful explanation.[134] Akin to Craver, Sporns also writes that no scale or level of the connectome (i.e. micro, meso, macro) is “privileged over others in the sense that system behavior cannot be fully reduced to processes occurring at one scale only.”[135]

Thus, by concentrating on “norms implicit in the practice of neuroscience,” Craver says he abandons “traditional metaphysical projects concerning the nature of causation.” By “traditional” he primarily means Hume’s metaphysical analysis of cause and effect. In fact, Craver writes, “From my perspective, causation requires normative regimentation, not metaphysical demystification.”[136]

Sporns agrees on this point as well. According to him, regimentation in his discipline can come out of “normative datasets” that a multitude of researchers can use to search for statistical patterns by which they develop models of brain structure and function. “A major driving force behind efforts to collect and share large data sets is the growing realization that understanding the complexities of brain and behavior requires the integration of scientific findings across a broad array of methods, approaches, and systems,” Sporns writes. In fact, he says, “future success of connectomics will depend on broad availability of data in open-access repositories and archives.”

This is another way of saying that, in order to map the connectome, neuroscientists need to be using the same datasets, i.e. it is easier to build a house when everyone is using the same materials. Perhaps indicative of Craver’s observations of neuroscientists’ main goals, Sporns does not directly address any metaphysical concerns in his book *Discovering the Human Connectome*. Rather, his concerns are more pragmatic, i.e. how can all neuroscience get on the same page and what are the technical hindrances of viewing the brain through the lens of the connectome.

However, this does not mean the connectome is only constructed. As I have explained previously, the connectome is real because of the phenomena (materials) used to construct it are real. Scientists may not have direct access to the complex workings of the brain, as Star and Griesemer argue, but rather only a sliver of that complexity at a time. But as Craver argues, an “explanation [or description] is more likely to be correct if it is consistent with multiple theoretically and causally independent techniques and perspectives.”[137] Star and Griesemer miss this point, on the other hand, because they believe “consensus is not necessary for cooperation nor for the successful conduct of work.”[138]

Craver also argues against metaphysical concerns for another reason. The search for that secret connection between cause and effect, he says, distracts from “the aspects of causation that are most important for an account of explanation” in neuroscience. Many cause and

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[132] Craver, 10.
[133] Sporns, 23.
[134] Sporns, 7.
[135] Sporns, 5.
[136] Craver, 64.
[137] Craver, 19.
[138] Star and Griesemer, 388.

effect relationships in neuroscience are not exemplified by connection (i.e. contact), for example. In some cases, it is the absence of a specific neurotransmitter that leads to the activation of a certain neural mechanism, he explains.[139] On a similar note, a lack of connectivity between two brain regions could be just as causative for a phenomenon as a plethora of connections, especially when it comes to diagnosing disease.

Already in analyzing what Craver rejects, we can see his view of neuroscience parallels work by Daston, Star and Griesemer and Sporns. All of these scholars and scientists do not center their work on how or whether scientists get at the reality of nature, as I noted in the first chapter of this thesis. Instead, they concentrate on how science is conducted in practice – on the manner in which scientists themselves construct scientific knowledge. As will become clear later on in this chapter, Craver's view of neuroscience also allows for robustness and plasticity in neuroscientific explanation.

2.2. Craver's Take on Causation and Explanation

Instead of centering his argument on the metaphysics of causation, Craver concentrates on the *causal relevance* of particular components – "activities" and "entities" – to one another and within specific mechanisms. Activities might include phosphorylation or cellular binding, and entities could range from a dopamine molecule to a synapse to a specific kind of memory formation.[140]

Though Craver does not say it explicitly, causal relevance, from my reading of the text, is akin to correlation; at least in as far as the observable phenomena are concerned. In other words, if two components are often witnessed in parallel, a scientist can declare that those two components are causally relevant to one another. Through experimentation, neuroscientists uncover what entities are causally relevant to one another. With a number of experiments, scientists can then piece together the array of components that are causally relevant to one another into a mechanistic explanation.

Craver also argues that neuroscientists are aware of what does not count as an explanation of a particular phenomenon. For example, "Neuroscientists know that merely finding that a brain region regularly lights up…during a cognitive task"[141] is not, on its own, a mechanistic explanation for that phenomenon – this correlation between cognitive and brain activity is only one correlation that contributes to the piecing together of an entire mechanism.

Craver is talking about the use of fluorescent magnetic resonance imaging, or fMRI, when he uses the phrase "lights up." This technique allows neuroscientists to infer activity in a certain region of the brain by measuring blood flow in that region. That measure itself is not direct, as fMRI actually measures the movement of water molecules in the brain and then infers blood flow, making any conclusion based on these images a double inference. But there are multiple reasons why fMRI correlations, while a valuable tool in the discipline, do not qualify as legitimate explanations.

For example, Craver highlights another limitation of one instance of causal relevance, or correlation, using fMRI. He writes, "The brain region…might be a component in a different

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[139] Craver, 64.
[140] Craver, 64.
[141] Craver, 60.

phenomenon that is experimentally inseparable from the one under study." He gives an example: "the volume of blood flowing to the visual cortex is tightly correlated with reading, but this does not mean that increasing blood flow explains my ability to read," Craver explains. This mere "neural correlate" is "too weak to be taken seriously as an account of explanation." But this does not mean uncovering neural correlates cannot be used to figure out the mechanisms for phenomena, he adds.[142]

Yet again Sporns agrees with Craver wholeheartedly. In his original 2005 paper where he first coined the term "connectome," Sporns writes "the mechanistic interpretation of neuroimaging data is limited, in part due to the severe lack of information on the structure and dynamics of the networks that generate the observed activation patterns." The key word here is "mechanistic," namely that neuroimaging data, including fMRI, cannot be the end for explanation in neuroscience; it is only a tool, a means to an end when it comes to neuroscientific explanation, but not an end in itself.

For this reason, Sporns argues, neuroscientists need a "theoretical framework for conceptualizing cognition as a network phenomenon," i.e. the connectome.[143] That is, they need the normative regimentation of the connectome.

To get more specific, Craver distinguishes two types of mechanistic explanation – etiological and constitutive. The former explains an event by describing what comes before it (i.e. its antecedent causes); the latter explains a phenomenon by describing the "underlying mechanism." Craver argues the constitutive explanation plays a major role in neuroscience and he develops a "normatively adequate account" of it in order to eventually argue for his theory of mosaic explanatory unity.

Craver also notes that there are two traditions of constitutive explanation – the reductive tradition and the systems tradition. Craver rejects reductive constitutive explanation for many of the reasons noted previously. But to reiterate, he argues it is not sufficient to explain a phenomenon by reducing a theory about it to a lower level theory and that reduction does not account for the practice of neuroscience. Likewise, Sporns argues that the theoretical underpinning of connectomics is grounded in systems, not reductive, thinking, as previously noted.

Unlike reductive explanations, "systems explanations are not peripheral to the practice of neuroscience," argues Craver.[144] The systems tradition "construes explanation as a matter of decomposing systems into their parts and showing how those parts are organized together."[145] This is the "engineer's ideal," says Craver, namely Fred Dretske "constructivist's model of understanding." This view of explanation comes with a convenient tagline: "If you can't make one, you don't know how it works."[146]

This engineering view of explanation is no accident, adds Craver. It is driven by one of the disciplines' ultimate goals. Neuroscientists are "driven not merely by intellectual curiosity about the structure of the world, but more fundamentally by the desire (and the funding) to cure diseases, to better the human condition, and to make marketable products," says Craver.

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[142] Craver, 60.

[143] Sporns et al., 245.

[144] Craver, 109.

[145] Craver, 110.

[146] Craver, 109. He's referring to Dretske's 1994 paper, "If You Can't Make One, You Don't Know How It Works."

"The search for causes and explanations is important in part because it provides an understanding of where, and sometimes how, to intervene and change the world for good or for ill."[147]

When it comes to the connectome, Craver is undoubtedly correct about neuroscientists desire to not only explain, but also control and modify the brain. On numerous occasions Sporns notes how connectomics will help neuroscience as a whole uncover the causes and cures for neurological and psychological disease.[148]

For example, Sporns writes in his 2012 book that "discovering the human connectome will give us new insights and tools for asking better questions about how the structure of the brain gives rise to its functional operations, in both health and disease."[149] Why? "Alterations of large-scale brain networks have been found to be associated with virtually all neurological or psychiatric conditions studied so far,"[150] Sporns points out.

In the conclusion of their original 2005 paper, Sporns and colleagues also write, "The human connectome could potentially have a major impact on our understanding of brain damage and subsequent recovery," adding, "The effects of developmental variations or abnormalities, traumatic brain injury, or neurodegenerative disease can all be captured as specific structural variants of the human connectome."

In other words, Sporns and colleagues argue that, like normal brain function, neurological and psychological disease can be explained within the framework of connectomics, supporting the connectome's robustness within the discipline. Sporns and his colleagues also argue that, "The functional consequences of network perturbations will allow a better understanding of structural causes of dysfunction, and may permit the design of strategies for recovery based on network analysis, and thus "open new avenues for therapy and prevention." This supports Craver's argument that neuroscientists are interested in both understanding the brain and changing it for the better. And as Sporns argues, this goal can be reached by thinking about the brain within the framework of the connectome.

In order to manipulate the brain to cure or treat disease, the neuroscientist as engineer needs to understand the brain in action. That is, he or she must understand not only how the pieces are put together, but also how they interact over time. Or as Craver puts it, it is *active* organization that matters most when it comes to explaining via mechanisms. Opposed to other organizations structures, mechanisms are not "static…patterns of relations," he says. Instead, they entail patterns of generation, stimulation and production, for example. In fact, he writes, "There are no mechanisms without active organization, and no mechanistic explanation is complete or correct if it does not capture correctly the mechanism's active organization."[151]

The active organization of components is what makes mechanisms more than the sum of their parts. "I argue that mechanisms, by virtue of their organization, are able to do things that their parts cannot do individually," writes Craver. "They can respond to inputs that the parts alone cannot detect. They can produce behaviors that their parts alone cannot produce."

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[147] Craver, 93.
[148] Sporns, 146.
[149] Sporns, 29.
[150] Sporns, 134.
[151] Craver, 136.

Mechanistic explanations come from understanding and describing the organization and interaction of activities and entities, says Craver.[152]

Ultimately, understanding how the connectome's connections taken together are more than a collection of parts is the aim of connectomics, argues Sporns. Like systems biology, the "overarching goal" of connectomics is to account for emergent neurological phenomena," he writes.[153] In other words, the goal is to link structure to function, or the structural connectome to the functional connectome.

Active organization also "distinguishes mechanistic models from taxonomic schemes," writes Craver. For example, the periodic table used widely by physicists and chemists does employ organization, but it is not a mechanism.

Similarly, biologists use the Linnaean system – domain, kingdom, phylum, class, order, family, genus and species – to organize species according to their phenotypic traits and evolutionary development. Still, the Linnaean system is not a mechanism, and thus not an explanation of biological phenomena.

In fact, Craver states that "several kinds of scientific achievement unify without explaining." He points specifically to taxonomies, the Linnaean system and periodic table, in particular. He goes on to say, "The development of a taxonomy of kinds is crucial for building scientific explanations." Why? "Taxonomies are often useful because they arrange items according to explanatorily relevant features," says Craver. "Sorting is preparatory for, rather than constitutive of, explanation."

Likewise, the connectome, in its structural form, is not a mechanism or explanation of neurological phenomena, I argue, but it is a means of organizing components in neuroscience that can unify the disciplines as well as set the stage for mechanistic explanations. Sporns agrees. He writes, "Cataloguing system components and their relations is only a first step toward the ambitious goal of understanding how their dynamic interactions give rise to integrated functional states."[154]

Again, in this section I showed that Sporns and Craver are on the same page when it comes to what the connectome can and cannot do for neuroscience. In sum, they both see the limitations of neuroimaging – it is a means to an end, but not an end in itself. In other words, it is a tool that can be used to contribute to uncovering mechanistic explanations, but it is not an explanation itself. They both also see the limitations of the structural connectome on its own – it is preparatory for mechanistic explanation, but still it does not qualify as an explanation itself. Mechanistic explanation requires neuroscientists to understand the brain's "active" (in Craver's words) or "dynamic" (in Sporns' words) organization.

2.3. Craver's Mosaic Explanatory Unity

Craver begins the final chapter of his book reiterating his disapproval of unity by reduction, as it pertains to neuroscience. "Philosophers of neuroscience traditionally envision the unity of neuroscience as being achieved through the stepwise reduction of higher-level theories to successively lower level, and ultimately fundamental, theories," he writes.

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[152] Craver, 227.

[153] Sporns, 11.

[154] Sporns, 9.

Instead, he argues unity in neuroscience comes about when diverse researchers "collaborate to build multilevel mechanistic explanations."[155] Diversity is a trait specific to neuroscience and part of the reason why reduction does not work well in the discipline. For example, researchers who have different explanatory goals, vocabularies and techniques make up the Society for Neuroscience, he points out, which was established in 1969.[156]

In fact, the society's website states the its mission is to, "Advance the understanding of the brain and the nervous system by bringing together scientists of diverse backgrounds, by facilitating the integration of research directed at all levels of biological organization." Today, the society has nearly 38,000 members in over 90 countries. For comparison, in 1969 it had 500 members.[157]

Sporns views connectomics and its corresponding scientific object, the connectome, similarly. "The connectome offers a common operational goal for a broad spectrum of neuroscientists working across different scales and systems," he writes. "Connectomics is an inherently transdisciplinary endeavor that brings together anatomists, neurophysiologists, radiologists, geneticists, and computer scientists."[158]

But since these different fields have different priorities and use different techniques, their findings each place constraints on the range of possible mechanistic explanations for a specific phenomenon, explains Craver. These constraints from diverse fields make up "the tiles that fill in the mechanism sketch to produce an explanatory mosaic," Craver says. "To the extent that different fields have independent perspectives and techniques, the ability of a hypothesized mechanism to satisfy their diverse constraints simultaneously counts as an impressive epistemic success."[159]

But why does Craver call his theory "mosaic" unity in the first place? It's a useful analogy, of course. "The findings in different fields of neuroscience are used, like the tiles of a mosaic, to elaborate this abstract mechanism and to shape the space of possible mechanisms," he writes.[160]

Craver's theory parallels Daston's view of scientific objects. Like Daston's scientific objects, Craver's mosaic unity comes about, in part, because of the "material" with which neuroscience is made, as I have discussed previously. "What something is made of and how it is made, determines what it is (and how it can be used)," as I write in the first chapter of this thesis.

In other words, neuroscience unifies as Craver outlines because, unlike other disciplines, it is a multifield research program – it is composed of diverse pieces that come together like a mosaic. "Its departments, journals, societies, and textbooks include perspectives from anatomy, biochemistry, computer science, radiology, developmental, evolutionary, and molecular biology, electrophysiology, experimental psychology, ethology, pharmacology, and psychiatry," writes Craver.[161]

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[155] Craver, 19.
[156] Craver, 229.
[157] https://www.sfn.org/about/mission-and-strategic-plan - visited 04/09/2016
[158] Sporns, 21.
[159] Craver, 18-19.
[160] Craver, 228.
[161] Craver, 228.

But how do these different fields interact to produce explanation in neuroscience? This brings us to perhaps the most important section of Craver's book as it pertains to my thesis. "The different fields that contribute to the mosaic unity of neuroscience are *autonomous* in that they have different central problems, use different techniques, have different theoretical vocabularies, and make different background assumptions," Craver says. But "they are *unified* because each provides constraints on a mechanistic explanation."[162]

Here we have the third level duality of my thesis – unity and autonomy. First we had *realness* and *construction* of scientific objects generally. Then we had the *robustness* and *plasticity* of unifying boundary objects. And now we have the *unity* and *autonomy* of fields within a unifying discipline. In the first chapter of this thesis, I showed how the first tier duality, realness and construction, gave way to the second tier duality, robustness and plasticity. But there is also a relationship between the second tier duality and this third tier duality of unity and autonomy, which I will outline in the next section.

2.4. Mosaic Descriptive Unity

Unlike reductive unity, "Individual fields do not surrender their autonomy through" mosaic explanatory unity, writes Craver. Why? It is because "their ability to contribute novel constraints on a mechanism requires that they maintain their autonomy," he argues. "Because different fields approach problems from different perspectives, using different assumptions and techniques, the evidence they provide makes mechanistic explanations *robust*,"[163] and I argue it makes descriptions robust as well.

To elaborate on his point, when researchers from different fields contribute to an explanation (or a description such as a connectome), it will more likely withstand examination by multiple different lines of evidence from different fields over time. In other words, it will be robust. It will also more likely be applicable to the different fields that created it. That is, it will be plastic. Thus, the autonomy of individual fields necessitates the robustness and plasticity of explanations. This same model can be applied to description.

Pertaining to my thesis, the description of the connectome is robust and plastic because the autonomous fields of neuroscience must each contribute to that description. But since each field with neuroscience must contribute to the connectome, the connectome as a descriptive "goal" also unifies the discipline. This is another way of saying the connectome as a boundary object and neuroscience as a discipline co-create each other in a feedback loop. The connectome accommodates the unified, yet autonomous structure of neuroscience because it is composed of multiple scales, from the neuron to cognition, all of which must be linked together. Thus, it applies to all fields of the discipline and all fields must contribute to its description.

As noted previously, Craver argues that taxonomies (or descriptions) are a precursor to mechanistic explanation, which is very pertinent to my thesis argument. Craver states, "Taxonomies are often useful because they arrange items according to explanatorily relevant features" adding, "Sorting is preparatory for, rather than constitutive of, explanation." He also writes "several kinds of scientific achievement unify without explaining."[164]

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[162] Craver, 231, my italics.
[163] Craver, 231-232.
[164] Craver, 42.

As I pointed out in the introduction to this thesis, Craver gave a lecture back in February 2015 at Yale University in the United States, during which he argued that network models like the connectome "can be used to describe features of the organization of complex mechanisms that other representational systems are ill-equipped to describe."[165]

But how exactly is descriptive mosaic unity a precursor to explanatory mosaic unity? Craver says there is a "space of possible mechanisms" that "contains all the mechanisms that could possibly explain a phenomenon." This space is infinite. But neuroscientists never start with the infinite space of possible mechanisms. Rather, they begin with "a restricted space shaped by prior assumptions about what kinds of components are likely to be included" and "what kinds of organization are likely to be relevant." [166]

In other words, neuroscientists reduce this space by figuring out what kinds of components do and do not make up specific mechanisms, argues Craver. Descriptions like the connectome shape these prior assumptions concerning components of mechanisms, I argue. Therefore, neuroscientists first unify around descriptions of components they believe to be pertinent to mechanistic explanations before they unify around the mechanisms themselves.

For example, in their original 2005 paper introducing the connectome, Sporns and colleagues write, "To understand the functioning of a network, one must know its elements and their interconnections." They see the brain as a network as exemplified by the connectome, which will provide "mechanistic insights" in the form of a "unified" neuroinformatics resources "used in virtually all areas of experimental and theoretical neuroscience."[167]

But let us use Craver's work to get more precise. What kinds of components are we talking about? Some constraints "show that some set of possible mechanisms is impossible given what is known about the components and their organization,"[168] what Craver calls spatial constraints. "Researchers in different fields often investigate different forms of spatial organization and are uniquely suited to provide certain spatial constraints," adds Craver.[169]

For example, whereas cognitive neuroscientists more equipped to uncover spatial constraints pertinent to the macrolevel and functional connectome, cellular neuroscientists may be better equipped to uncover constraints pertinent to the microlevel connectome. They each do this by *localizing* certain components in certain areas of the brain through the use of network models, i.e. the connectome.

Once these components are localized, explains Craver, "one can then begin to describe the connections*"* between these components.[170] "The mosaic unity of neuroscience is built, in part, through the effort to combine spatial constraints at and across levels into an adequate description," he adds.[171]

In his book, *Discovering the Connectome*, Sporns makes a similar argument. He writes, "Computational models of biological systems need to capture phenomena on different

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[165] http://frankeprogram.yale.edu/event/carl-craver-graphing-brains-dark-energy-network-models-and-neural-mechanisms -- Accessed 12/11/2016.
[166] Craver, 247.
[167] Sporns et al., 245.
[168] Craver, 247.
[169] Craver, 251.
[170] Craver, 252.
[171] Craver, 253.

temporal and spatial scales and thus require integration of physical and biological processes across different levels of organization."[172] He adds, "Connectomics culminates in the construction of quantitative computational models that embody neurobiological mechanisms at multiple levels of organization."[173] In other words, the mosaic unity of neuroscience is built through the effort to describe the connectome, a multiscale, unifying boundary object.

Craver also discusses specifically how researchers integrate all of their findings from different levels of organization in neuroscience. Integration occurs, he says, when researchers are both "upward-looking" and "downward-looking." That is, researchers show how lower level phenomena in the brain relate to higher-level phenomena and vice versa.[174] In Sporns' language this means, "no single scale [i.e. level; e.g. microscale] occupies a privileged position" within the connectome and that "processes at all scales contribute to global functional outcomes that become manifest in cognition and behavior."[175]

By integrating descriptions, that is scales of the connectome, researchers fully unify their discipline. For this reason, researchers are constantly collaborating and consulting each other to make sure their descriptions at lower levels parallel those at higher levels and vice versa. Or as Sporns writes, "The need for understanding the multiscale nature of the connectome requires growing cooperation and collaboration among scientists who work at different scales in the brain."

"The relative autonomy of different fields affords each of them the theoretical and technical independence to provide a check on the findings in other fields and so heighten one's confidence that the explanation is correct," says Craver.[176] In other words, no one level, no one field takes precedent. Or as Sporns explains, "cross-validation and convergence onto a common description of brain connectivity" is a "goal" in connectomics.[177]

For example, opportunities for cross validation and collaboration include comparing data on the same regions of the brain using different imaging techniques, like tract tracing with diffusion imaging, explains Sporns. Both techniques aim to trace the microscale connections of the brain; the former by labeling physical tissue with different "tracer" chemicals and the latter by tracing water molecules with MRI based images. These microscale techniques can then be cross-validated with other techniques, like fMRI, which is used to evaluate connections at the macrolevel.[178] In short, fields stay autonomous while describing the connectome because each of their perspectives and techniques only add to the connectome's robustness and plasticity.

To sum up, the unity of neuroscience does not come about via reductive explanation. Reduction is driven by metaphysical concerns that neuroscientists themselves do not bother with, and these metaphysical concerns then misconstrue the means to successful explanation. Successful explanation entails multilevel mechanistic explanation, which is cross-validated by neuroscientists from all walks of their discipline. Description is a precursor to explanation in neuroscience, and, likewise, mosaic descriptive unity is a precursor to mosaic explanatory unity. Description acts as a precursor by limiting the realm of possible mechanistic

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[172] Sporns, 9.
[173] Sporns, 21.
[174] Craver, 257.
[175] Sporns, 40.
[176] Craver, 269.
[177] Sporns, 107.
[178] Sporns, 107-108.

explanations for a given phenomena. Or as Craver puts it in the final chapter of his book, "The mosaic unity of science is *constructed* during the process of collaboration by different fields in the search for multilevel mechanisms," and I add, descriptions such as the connectome.

4.0. Conclusion

In this conclusion, I will first summarize my thesis argument. I will also go over areas of future research, which will include what I would have argued in detail in two additional chapters had I not had time and monetary constraints as well as how this thesis could be expanded into doctoral work.

4.1. Summary of Thesis

In this thesis I have argued that the connectome is a unifying boundary object in neuroscience. In the first chapter, I showed that the qualities of *realness* and *construction* of scientific objects pave the way for the qualities of *robustness* and *plasticity* of boundary objects, a specific kind of scientific object. These two sets of qualities make up the first and second tier dualities of my thesis argument. The third tier duality, the *unity* and *autonomy* of neuroscience's fields, comes about through the collaboration of researchers from all walks of the discipline to describe the connectome, I argued in the second chapter.

Much of my work in the first chapter was influenced by Lorraine Daston's book *Biographies of Scientific Objects*, which aimed to flip the dichotomy of *real* and *constructed* on its head. Scientific objects can, and perhaps should, possess both of these qualities, she and others argued. Scientists can take a dispersed set of *real* phenomena and *construct* scientific objects to suit their theoretical and experimental needs. But unlike a black and white realness derived from stability or self-evidence, this grayscale realness depends the extent to which certain scientific objects permeate scientific thought and practice.

Through Daston's work I laid the foundation for my thesis argument, but through Susan Leigh Star and James Griesemer's work on boundary objects I erected my argument's scaffolding. Star and Griesemer argued that some scientific objects are *plastic* enough to apply to a diversity of scientific contexts (e.g. different fields within a discipline) but *robust* enough to preserve a common identity across these contexts. I showed that objects made up of a collection of once unassociated phenomena allow for the qualities of robustness and plasticity because they are pertinent to an array of researchers united in their effort to elucidate this now coalesced object. In short, in the first chapter I also argued that some real and constructed scientific objects are boundary objects.

However, while some boundary objects are only locally integrated in a small niche of research activities, some are widely integrated across all fields of discipline. When researchers from all corners of a discipline acknowledge a specific boundary object's worthiness as a subject of study, that object gains the ability to unify that discipline. Thus, in the last section of the first chapter I argued that the connectome, roughly defined as a map of the brain's connections, is a *unifying* boundary object in neuroscience.

Since it is composed of multiple scales, the connectome is plastic enough to apply to multiple fields within neuroscience. For example, whereas a cellular neuroscientist might be interested in the microscale connectome (connections between individual neurons), a cognitive neuroscientist might be interested in the macroscale connectome (connections between brain regions). But the connectome is also robust enough to maintain its identity across fields, since it can also be thought of generally as a map of the brain's connections. According to Olaf Sporns, who with others coined the term *connectome*, the ultimate goal is to unify the connectome's different scales, which will take collaboration among a diverse set of researchers.

But the time for unification must also be right. At the very end of the first chapter I also argued via work by Ilana Löwy and Marco Catani that the historical circumstances from which the connectome emerged facilitates its ability to unify neuroscience. Löwy argued that boundary objects are most effective in bringing groups of scientists together when a certain area of research is advanced in its techniques, but lacking in its strategy; in other words, when researchers have the required tools, but are not sure how to use them. This is precisely the predicament in which neuroscientist currently find themselves, argued Catani. The connectome can provide that much needed strategic direction, he also argued.

In the second chapter, I continued my argument by showing how the *robustness* and *plasticity* of the connectome feeds the *unity* and *autonomy* of the neuroscience's fields. This third tier duality comes about through the process of describing the different scales of the connectome. But the second and third tier dualities exist in a feedback loop, I argued: The *robust* and *plastic* nature of the connectome elicits the *unity* and *autonomy* of the fields comprising neuroscience and the *unity* and *autonomy* of these fields then generates a *robust* and *plastic* connectome.

I linked the second and third dualities using work by Carl Craver, who argued for a specific form of disciplinary unity in his book, *Explaining the Brain: Mechanisms and the Mosaic Unity of Neuroscience.* As the title suggests, Craver advocates for the mosaic unity of neuroscience and in the process explains why no form of reductive unity suits the discipline.

Craver argues mosaic unity arises in neuroscience from using findings from different fields to construct multilevel, mechanistic explanations. In other words, the fields that make up neuroscience are *unified* because they all have a common goal, but *autonomous* because they each approach that goal by using different techniques and by asking different questions. This duality of *unity* and *autonomy* in neuroscience lends itself to *robust* explanations of the discipline's complex phenomena, Craver adds.

In contrast, Craver argues reductive unity, the kind exposed by the likes of Hilary Putnam and Paul Oppenheim, for example, cannot provide the discipline's fields with this dual *unity* and *autonomy* for multiple reasons. For one, reductive unity is historically peripheral to the practice of neuroscience. That is, neuroscientists themselves have not been and are not currently concerned with reducing cognitive phenomena to cellular phenomena. In fact, Sporns argues in his book *Discovering the Connectome* that mapping the structural connectome is only the beginning. The ultimate step will be to link the structural connectome to the functional connectome, argues Sporns, and showing how they influence each other.

Neuroscientists are also not concerned with the metaphysics of cognition, while reductive unity is driven by metaphysical concerns, argues Craver. Likewise, in his work, Sporns makes no mention of the underlying metaphysics of the brain, only how scientists can construct robust descriptions and explanations of neural phenomena. This concern for the metaphysical drives philosophers away from what neuroscientists themselves consider routes to successful explanation and description, Craver argues, namely multilevel (or multiscale in Sporns' language) explanation and description, where no one level takes precedent.

But Craver's mosaic unity pertains to *explanation*. In the second chapter, I argued for my own theory of mosaic *descriptive* unity. The connectome is, after all, a description of the brain, not an explanation of it; Sporns admits as much. With Craver's help I also showed how mosaic descriptive unity sets the stage for mosaic explanatory unity. In other words, I showed how elucidating the *static* organization of components (a description) is the precursor to understanding how those parts *actively* interact to produce neural phenomena (a mechanism). Thus, descriptions like the connectome can facilitate the elucidation of neural mechanisms, I argued with the help of Craver, by constraining the realm of possible mechanisms for a particular phenomenon.

Given time and monetary constraints of my own, I was not able to further drive home my thesis argument by drawing parallels between how the fields of neuroscience are unifying around the connectome today and how the fields of biology unified around gene in the early 20th century. I would have accomplished this in a third chapter with the help of work by Vassiliki Betty Smocovitis and Evelyn Fox Keller. These constraints also prevented me from drawing conclusions from this my thesis research about the unity of science as a whole, which I would have argued in a fourth chapter.

However, I already did much of the research for these chapters while writing a paper for a tutorial course with Prof. Bert Theunissen on the history and philosophy biology. Thus, in the next sections, I will briefly go over how this research could be adapted to further support my argument that the connectome is a unifying boundary object in neuroscience. I will also propose a theory for how science as a whole may be unified.[179]

4.2. The Gene and the Connectome

I saw the first inklings of parallels between early 20th century biology and early 21st century neuroscience, or cognitive science more broadly, after reading a paper by Vassiliki Betty Smocovitis, an old professor of mine at the University of Florida, and watching a TED talk by Sebastian Seung, a computational neuroscientist at Princeton University.

In her 1992 paper called "Unifying Biology," Smocovitis argues that biology grounded itself in the mechanistic thinking of physics and chemistry with genetics, while simultaneously preserving its autonomy from these more matured disciplines with evolutionary theory.[180] This view of biology's unification contrasts with the philosophy of those who brought the unification of science to the fore in the late-19th and early 20th century – the logical positivists of the Vienna Circle. Their "Unity of Science Movement" was based on the belief that all the sciences could be *reduced* to "physicalist terms," writes Smocovitis.[181]

The logical positivists, including Rudolph Carnap and Ernst Mach, influenced the likes of William Bateson, a biologist who Smocovitis calls an "ultramechanistic materialist."[182] Bateson argued that biology would only unify if it was completely rid of "vitalistic thinking."[183] But other biologists, such as Theodosius Dobzhansky, who Smocovitis credits

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[179] I feel as though I need to qualify this last statement with the fact that I also didn't write the fourth chapter because it stood on the least sturdy grounds argumentatively, compared to the other chapters. For one, I only looked at biology and neuroscience in detail, which means that with further research I could find that the theory could very well not apply to other disciplines. This possibility for future research will be discuss at the very end of the conclusion.

[180] Smocovitis, 3. Sound familiar? I'll address this fourth tier duality of unity and autonomy *between* disciplines (not *within* them) in the next section.

[181] Smocovitis, 6.

[182] Smocovitis, 38.

[183] Smocovitis, 4.

as playing perhaps the most influential role in biology's unification, balanced the need for mechanism in biology with genetics and the need for emergence[184] from the physical world with evolutionary theory (i.e. through the evolutionary synthesis).[185]

Though Smocovitis does not center her work on the linguistic and sociological characteristics of biology, from reading her paper I noticed that biologists at the time not only emulated the terminology of physical sciences, but also justified their novel methodologies through rivalry with the physical sciences.

For example, in 1906 Bateson coined term *genetics* and to him and to many other biologists at the time, the suffix of this new field was of great importance to the development of their discipline, argues Smocovitis. "Unlike the '-ologies,' which were logocentric or descriptive sciences, genetics was an '-ics' word, meant to emulate physics and other exact sciences," she writes.[186] Once genetics and evolution combined to synthesize evolutionary genetics and unify the discipline as a whole, the evolutionary biologist Julian Huxley also made the claim that biology was "a science that could...rival the unity and legitimacy of physics."

Similarly, in his 2010 TED talk, "I am my connectome," Seung voices a tone of rivalry with biology. Seung opens his speech with the following:

> We live in a remarkable time, the age of genomics. Your genome is the entire sequence of your DNA...The headlines tell us that genes can give us scary diseases, maybe even shape our personality, or give us mental disorders. Our genes seem to have awesome power over our destinies. And yet, I would like to think that I am more than my genes...I think some people agree with me. I think we should make a statement...I am more than my genes. What am I? I am my connectome.[187]

And if it was not already obvious, Sporns coined the terms *connectome* and *connectomics* in direct emulation of the terms *genome* and *genomics*.[188]

Thus, in the paper I submitted to Prof. Theunissen, I argued, among other things, that early 21st century discourse in neuroscience exhibits similar linguistic and sociological characteristics to early 20th century biology, signaling neuroscience's unification.

This paper's argument was also guided by work by Evelyn Fox Keller, who writes in her book *The Century of the Gene*, that the linguistic features a discipline adopts can be powerful enough to guide research for a century. "The words [scientists] use play a crucial (and, more often than not, indispensable) role in motivating them to act, in directing their attention, in framing their questions, and in guiding their experimental efforts. By their words, their very landscapes of possibility are shaped," she writes.[189]

If I had written a third chapter to this thesis, I would have included this work, in addition to arguing that, like the connectome, the gene was a unifying boundary object in biology in the

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[184] It's worth noting that, similar to Dobzhansky, Sporns leaves room for the emergence of psychological/cognitive phenomena from the biological world in *Discovering the Connectome*. He writes "alterations in neural circuitry contribute to the emergence of new behaviors or cognitive capacities" (pg. 4). At the end of his book he also says, connectomics "will illuminate how the connections between neural elements enable integrative and emergent neural processes, adding, "I think we'll find that the complex architecture of the connectome and its variable dynamics fundamentally resist reductionist explanation" (pg. 179).

[185] Smocovitis, 42.

[186] Smocovitis, 14, footnote 39.

[187] https://www.ted.com/talks/sebastian_seung/transcript?language=en -- visited 31/12/2016

[188] http://www.scholarpedia.org/article/Connectome -- visited 29/12/2016

[189] Fox Keller, 139.

first half of the 20th century. I would have done so with the help of work by Hans-Jorg Rheinberger, who argued "the historical and disciplinary trajectory of gene representations" is "an exemplar of a boundary object."[190]

Like the connectome, the gene can take on a variety of definitions depending on its application; thus, it is plastic. For example, Rheinberger argues that a molecular geneticist might see genes "as informational elements of chromosomes," while an evolutionary biologist might see genes as "the products of mutated, reshuffled, duplicated, transposed, and rearranged bits of DNA" that have "evolved through differential reproduction, selection, or other evolutionary mechanisms," he writes. However, a development biologist might see genes "as hierarchically ordered switches that, when turned on or off, induce differentiation. And so on.[191]

Also like the connectome, the gene sustains a common identity across all particular instances of its use; thus, it is robust. Rheinberger argues the gene can maintain this common identity because of the vague general definition as a "material entity" that is "carrier of information." He adds, "The spectacular rise of molecular biology has come about without a comprehensive, exact, and rigid definition of what a gene is." The gene, like all boundary objects, needs to have this generally vague definition because they exist at the frontiers of knowledge, he says. Too precise of a definition will stifle research, he adds.[192]

Lastly, in the third chapter I would have used work by Smocovitis to show how the gene and the connectome parallel each other with regards to the manner in which they unified their respective disciplines; namely, through mosaic descriptive unity. Work across all fields of biology in the first half of the 20th century culminated in the description of the structure of DNA. Likewise, with massive (and expensive) brain mapping projects like the European Commission's Human Brain Project and the Obama Administration's BRAIN Initiative, researchers from all walks of neuroscience are directing their efforts towards describing the connectome.

Along the way, I would have pointed out cases where Sporns himself compares the connectome and connectomics to the genome and genomics. A passage from the introduction of his book *Discovering the Connectome* illustrates this parallel perfectly:

> Understanding integrative processes from the interactions of neural elements is a central research focus of connectomics, an extension of systems biology to the brain. A corollary of adopting this perspective is that brain function cannot be fully reduced to the connectome or wiring diagram, just as knowing an organism's genetic material does not furnish a complete account of its biological form and physiology…Alas, despite the ever-increasing volume of genomic data, a principled understanding of how the genome underpins biological function is still in its infancy. Nevertheless, in ways that are subtle and complex, both genome and connectome carry important information about the natural history of the human species and the biological substrate of our individuality. Gaining access to the basic inventory of genetic components and a growing understanding of the complex networks they set in motion has transformed the biological sciences. In a similar vein, discovering the human connectome will give us new insights and tools for asking better questions about how the structure of the brain gives rise to its functional operations, in both health and disease.[193]

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[190] Rheinberger, 219.

[191] Rheinberger, 225.

[192] Rheinberger, 222.

[193] Sporns, 23.

In the introduction of his book, Sporns also quotes James Watson, who uncovered the structure of DNA with Francis Crick. Sporns writes, "The connectome is not a blueprint of 'who we are,' no more so than the genome, which was supposed to deliver the 'book of life' that explained 'the chemical underpinnings of human existence.'"[194] Here, Sporns references Watson's 1990 article in the journal *Science*, which was a plug for the Human Genome Project.[195] At the time Watson was the head of the project, a position he held until 1992.[196]

This is the one case in this thesis where it is pertinent to discuss ego as an instigator of reductive thinking. Similar to Watson and genome, Seung reduces the cause of human identity to the connectome, in his TED talk, "I am my connectome." Seung also later went on to write the book *Connectome: How the Brain's Wiring Makes Us Who We Are*. He argues in this book and elsewhere the connections between individual brain cells store human identity. If only we can map the brain at the "appropriate resolution," he argues, then we will know who we really are.[197]

But researchers came to realize at the end of the Human Genome Project that the genome could not reveal "who we are," as Watson claimed. While the sequencing of the human genome did greatly expand our understanding of trait transmission in health and in disease it did not ultimately answer the question of true human nature. Likewise, I argue the completed connectome, regardless of resolution, will also not reveal the nature of human identity. Reductive thinking may help researchers to obtain funding and sell their books, but it will not help them elucidate the nature of human mind. Sporns himself argues as much, Craver argues as much – and so do I.[198]

4.3. An Homage to Auguste Comte

Still, one may wonder if the relationship between the gene and connectome goes deeper than mere analogy. Might their rise parallel each other, in part, because their disciplines themselves are connected?

If I had written a fourth chapter of this thesis, I would have argued that the relationship between biology and neuroscience can be thought of as functioning much like generations of a family: Children found their personal ideologies in the ideologies of their parents, but later grow up to formulate their own views of the world. In this metaphor, the parents symbolize 20th century biologists and the children represent 21st century neuroscientists. In this picture of scientific progression, it is not the logical positivists with their reductive unity of science who emerge as victors, but the much forgotten father of positivism himself: Auguste Comte.

In the mid-19th century Comte outlined his law of the classification of the sciences in *Course*

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[194] Sporns, 23.

[195] Specifically, Sporns is quoting: Watson JD. 1990. The human genome project: Past, present, and future. *Science* 248: 44 - 49.

[196] https://www.nih.gov/about-nih/what-we-do/nih-almanac/national-human-genome-research-institute-nhgri -- visited 29/12/2016

[197] http://www.cnn.com/2012/03/01/tech/innovation/brain-map-connectome/ -- visited 29/12/2016

[198] Much of my thinking about reduction in neuroscience was influenced by Sporns and Craver. But I also have to mention a book by Jan Slaby, at the Free University in Berlin and others. Called *Critical Neuroscience: A Handbook of the Social and Cultural Contexts of Neuroscience*, the book's diverse contributors are unified in their belief that reducing personhood to the brain is not only unsound empirically, but also detrimental to culture and society. Thus, "The goal of critical neuroscience is to create a space within and around the field of neuroscience to analyze how the brain has come to be cast as increasingly relevant in explaining and intervening in individual and collective behaviors, to what ends, and at what costs."

on Positive Philosophy. First, he separates science into six fundamental disciplines – mathematics, astronomy, physics, chemistry, physiology and social physics – the last two of which correspond to biology and sociology, respectively.[199] Starting with mathematics, the sciences are associated with one another in an exhaustive scale that goes from the general to the specific and from the simple to the complex.

Comte argues this classification also represents the order and manner in which each discipline develops: Astronomy grounds itself in mathematics to unify as a discipline, chemistry in physics, and so on. He also reasons that while the latter discipline depends on a former discipline for unification, the inherent diversity of the sciences precludes the possibility of reductionism of one field to another:

> The positivist clearly sees that the tendency towards reductionism is fed by the development of scientific knowledge itself, where each science participates in the evolution of the next; but history also teaches us that each science, in order to secure its own subject matter, has to fight invasions by the preceding one.[200]

Ultimately, Comte's aimed to preserve "the diversity of the sciences without thereby losing sight of their unity."[201] Thus, nearly two centuries before Craver proposed his mosaic unity, Comte argued for a duality of *unity* and *autonomy* between scientific disciplines.

To be clear, Comte's unity and autonomy *between* scientific disciplines does not form in the same manner as Craver's mosaic explanatory unity and my mosaic descriptive unity *within* disciplines forms. On the one hand, mosaic unity originates from a concerted effort by researchers in different fields to explain mechanisms or describe a central scientific object, respectively. On the other hand, Comte's unity originates from one discipline grounding itself in the former discipline. The younger discipline then goes on to produce its own unique methodology, in which a yet younger discipline will ground itself, and so on.

Thus, I would have supported an argument for the *potential* duality of *unity* and *autonomy* among all disciplines by outlining the development of biology and neuroscience in the 20th and 21st centuries. Admittedly, since my analysis would have primarily been limited to these two disciplines, more research would be needed to drive home this argument for science as a whole.

So what support do I have for this fourth tier duality? Using work by Smocovitis I would have shown how biologists in the first half of the 20th century grounded their discipline's methodology for *describing* the gene (a boundary object par exemplar) in the physical sciences culminating in the discovery of the *structure* of DNA. At the same time, biologists produced a view of evolutionary change, namely the evolutionary synthesis, which distinguished biology from physics and chemistry. Then, in the late 20th century biologists completely transcended the physical sciences to produce their own unique methodology for *explaining biological function* of living things; namely, with genomics and the systems approach.

Likewise, I would have shown that today neuroscience is following a similar trajectory. Organized in their effort to map the connectome, neuroscientists are grounding their methodology for *description* in biology's methodology for *explanation*, namely in systems

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[199] http://plato.stanford.edu/entries/comte/ – visited 20/07/2015. The Stanford Encyclopedia of Philosophy page on Comte uses the terms 'biology' and 'sociology,' while Ferre's translation of Comte uses 'physiology' and 'social physics.'
[200] http://plato.stanford.edu/entries/comte/ – visited 20/07/2015.
[201] http://plato.stanford.edu/entries/comte/ – visited 20/07/2015.

biology. As I alluded to previously, Sporns specifically argues in his book *Discovering the Connectome*, "Beyond semantic similarities [with the term *genome* and *genomics*], there are several reasons why the connectome belongs in the family of complex biological systems and why connectomics represents an extension of systems biology into the realm of neuroscience."[202]

Thus, I would have argued that a *description* of the connectome's *structure* will lead to general principles of brain organization that gives neuroscience autonomy from biology, much like the theory of evolution gave biology autonomy from the physical sciences. Likewise, farther into the future, neuroscientists may also produce their own methodology for *explaining cognitive function*, much like biology produced its methodology for *explaining biological function* with the systems approach.

Distilled into a general theory, I would have argued that a more mature discipline's methodology for *explanation* lays the foundation for a younger discipline's methodology for *description*. Within this framework for understanding scientific progression, is the idea that disciplines unify twice – once to around a methodology for *structural description* and a second time around a methodology for *functional explanation*.

Many scholars have criticized Comte for the simplicity of his scientific classification, arguing scientific inquiry is much more complicated and messy than his step-wise picture. However, Comte fully admits that "the different subdivisions of each science, which we are led to separate in the theoretical order, are in reality developed simultaneously and under the mutual influence of each other."[203]

Like Comte, I would not have aimed to argue that science is perfectly structured and that younger disciplines, like biology, cannot and do not at some point influence developments in what many consider more mature disciplines like physics. In other words, I am not claiming historical progression perfectly mirrors theoretical organization.

4.4. The Value of Vagueness

Upon returning to this last chapter's argument after first formulating it last year, it has become evident that I would have needed to do more research to fully flesh it out. For example, I am now asking myself what role the gene plays in biology today as researchers in the discipline endeavor to not only *describe* biological *structure*, but also *explain* biological *function*. I am also wondering whether the gene perhaps acts as a reference, or starting, point for systems biologists or whether they largely ignore it. If the gene has become less important in biology, might the cell then be acting as a unifying boundary object in the discipline? Or perhaps boundary objects only unify disciplines when scientists organize in an effort to describe, and not when they endeavor to explain.

Reaching farther back into history to look at the roles of the atom in physics and the molecule in chemistry would undoubtedly shed light on the role of boundary objects in the unification of disciplines. I would also have to reach in the future to analyze what could possibly act as boundary objects in psychology and sociology. This research would also be needed in order to sufficiently support an argument for *unity* and *autonomy* in science as a whole.

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[202] Sporns, 7.

[203] Comte, 48.

Obviously, this work is much too extensive to comprise a master's thesis. But in the future I would be interested in formulating it into a PhD dissertation. In fact, last year I contacted Martin Kusch at the University of Vienna to inquire about the potential to apply to its DK program (The Sciences in Historical, Philosophical and Cultural Contexts) and he said my "topic would be excellent all around" for the program and I "would no doubt be a strong applicant."

But sometimes life and other pursuits get in the way. At the moment I am currently living and working in Philadelphia, Pennsylvania as a science writer with FactCheck.org, which is run out of the University of Pennsylvania. Since my job entails analyzing how American politicians misconstrue scientific information, I have also become interested in exploring how scientific reductive rhetoric of the likes of Crick and Seung functions in political, cultural and social contexts. If I was to pursue this route in the future, working with scholars in the field of critical neuroscience would make more sense, including Jan Slaby in Berlin and Suparna Choudhury at McGill University in Montreal.

These projects, along with my master's thesis work, were and are worthy of pursuit for a number of reasons. To start, my master's thesis supports the utility of Star and Griesemer's boundary object for understanding the production of knowledge in yet another discipline. Scholars have written much on the nature of the gene as a boundary object and unifier in biology, yet I was the first to analyze the connectome's role in neuroscience in this way.

My thesis also attests to the value of vagueness generally in science, as argued by Rheinberger.

> …it is not necessary, indeed it can be rather counterproductive, to try to sharpen the conceptual boundaries of vaguely bounded research objects while in operation. As long as the objects of research are in flux, the corresponding concepts must remain in flux, too…it is not the task of the epistemologist either to criticize or try to specify vague concepts in the hope of helping scientists clarify their convoluted minds and do better science with them…Instead of trying to codify precision of meaning, we need an epistemology of the vague and the exuberant.

Rheinberger also writes that boundary objects in particular "operate on and derive their power from a peculiar epistemic tension: To be tools of research, they must reach out into the realm of what we do not yet know." In this way, boundary objects "move the world of science," he says.[204]

While some scientists may be aware of the value of vagueness, I am not certain that all do. I am even less certain that most politicians and members of the public understand this. Time and again as a science journalist I have witnessed members of these groups, particularly the latter two, fundamentally misunderstand the relationship between vagueness and precision, certainty and uncertainty in scientific research.[205]

Whether I was to pursue a PhD in critical neuroscience or in the structure of scientific unity,

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[204] Rheinberger, 220-223.

[205] A perfect example would be some American politicians disbelief in the science behind climate change. Repeatedly, they argue they won't act on the issue unless the theory of climate change is "proven," i.e. 100% certain. In the 21st century, this should no longer be a valid argument. It should be understood by everyone that, while some uncertainty and vagueness may exist, climate change is well supported by the scientific literature. Admittedly, American politicians may be motivated to make these claims for reasons that have nothing to do with the epistemology of science, but at the very least, they should not be permitted to make this particular argument anymore.

the ultimate value and purpose of my work would be to engage researchers, politicians and members of the public in understanding how both precision and vagueness, certainty and uncertainty function in the production of scientific knowledge. I agree with Rheinberger that there needs to be an “epistemology of the vague,” but that work also needs reach into the realm of those who do not know its value.

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