ARTICLES

TURNING THE WORLD UPSIDE DOWN: HOW FRAMES OF REFERENCE SHAPE ENVIRONMENTAL LAW

BY

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Models and representations help us understand complex phenomena. The Mercator map presents a familiar, two-dimensional view of our three-dimensional world, for example, but it can distort as much as it clarifies. In the natural sciences, too, there are very different ways of framing reality. The classic method developed by Leonard Euler measures a system from a fixed point. A competing method developed by Joseph Louis Lagrange measures from the perspective of a particle moving within the system. These Eulerian and Lagrangian methods of measurement dominate the physical sciences and provide different, though equally valid, measures of how the system operates. This Article explores how our frame of reference shapes our understanding and application of environmental law. Using examples from the Clean Air Act, Clean Water Act, and other statutes, we argue that environmental law is just as sensitive to Eulerian and Lagrangian frames of reference as fluid mechanics or cartography, and that this sensitivity predetermines how we conceive of environmental problems and solutions far more than we realize. Understanding the implicit but fundamental importance of frames of reference can help explain emerging challenges such as water pollution from fracking, air pollution hot spots, and epigenetic sensitivities to pollution.

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I. INTRODUCTION 2
II. REFERENCE FRAMES IN FLUID DYNAMICS 9
III. REFERENCE FRAMES IN THE LAW 15
IV. WHAT DO REFERENCE FRAMES MEAN FOR ENVIRONMENTAL LAW? 22

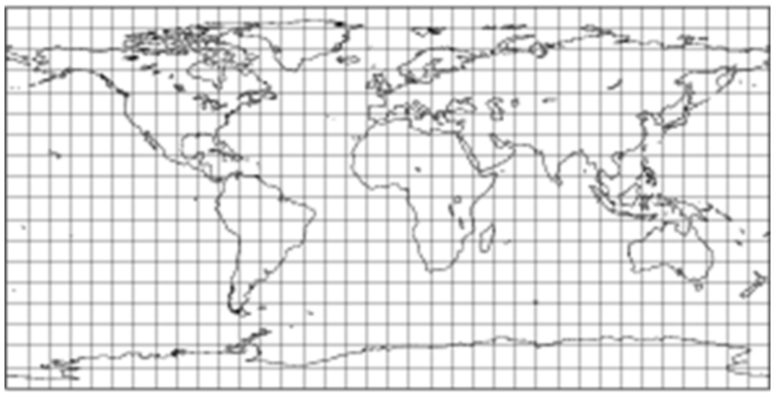
I. INTRODUCTION

In 1569, the Flemish geographer, Geradus Mercator, published a new type of map. His innovation placed the Equator as its standard parallel, making lines of latitude and longitude intersect at right angles to one another.[1] Previous cartographers had realized that the Earth was round and placed continents as best they could but, as the *Mappa Mundi* of 1449 shown below makes clear, their maps were of no practical use with regard to the ocean.[2]

1 JOHN P. SNYDER, U.S. GEOLOGICAL SURVEY, MAP PROJECTIONS—A WORKING MANUAL 38–39 (1987), *available at* http://pubs.usgs.gov/pp/1395/report.pdf.

2 Wikimedia, *Walsperger - Mappa Mundi*, http://commons.wikimedia.org/wiki/File:Walsperger_-_Mappa_mundi.jpg (last visited Feb. 22, 2014).

The Mercator Projection was particularly well-suited to its time because it allowed navigators to determine lines of constant true direction—the compass direction on the map connecting two points was the same compass direction that a ship would follow at sea.[3] At a time of maritime empires, far-flung voyages, and exploration, this map was just what captains needed to cross an ocean. Mercator's vision has endured and remains the standard map on classroom walls around the world, the conventional and accurate means to portray the surface of the Earth.[4]



At least that's the story, but it's not really true.

While maintaining accurate geographic direction between lines of latitude and longitude, the Mercator Projection map quickly starts to distort areas and shapes once one moves north or south from the Equator.[5] Consider, for example, the exchange on the popular TV show *The West Wing* White House staffers C.J. Cregg and Josh Lyman with Professor Sayles and his well-intentioned colleagues in the Organization of Cartographers for Social Equality, who want the White House to replace the Mercator Projection map in classrooms with the more accurate Peters Projection map:

> SAYLES: [Showing the Mercator Projection map on the screen] Here we have Europe drawn considerably larger than South America when at 6.9 million square miles South America is almost double the size of Europe's 3.8 million.
>
> HUKE: Alaska appears three times as large as Mexico, when Mexico is larger by .1 million square miles.

3 *See* SNYDER, *supra* note 1, at 39 ("The major navigational feature of the projection is found in the fact that a sailing route between two points is shown as a straight line, if the direction or azimuth of the ship remains constant with respect to north.").

4 Wikimedia, *World in Equidistant Cylindrical Projection with Grids*, http://commons.wikimedia.org/wiki/File:World_in_equidistant_cylindrical_projection_with_grids.png (last visited Feb. 22, 2014).

5 *See* Nick Stockton, *Get to Know a Projection: Mercator,* WIRED, July 29, 2013, http://www.wired.com/wiredscience/2013/07/projection-mercator/ (last visited Nov. 22, 2013).

SAYLES: Germany appears in the middle of the map when it's in the northernmost quarter of the Earth.

JOSH: Wait, wait. Relative size is one thing, but you're telling me that Germany isn't where we think it is?

FALLOW: Nothing's where you think it is.

C.J.: Where is it?

* * *

FALLOW: When Third World countries are misrepresented they're likely to be valued less. When Mercator maps exaggerate the importance of Western civilization, when the top of the map is given to the northern hemisphere and the bottom is given to the southern . . . then people will tend to adopt top and bottom attitudes.

C.J.: But . . . wait. How. . . Where else could you put the Northern Hemisphere but on the top?

SAYLES: On the bottom.

C.J.: How?

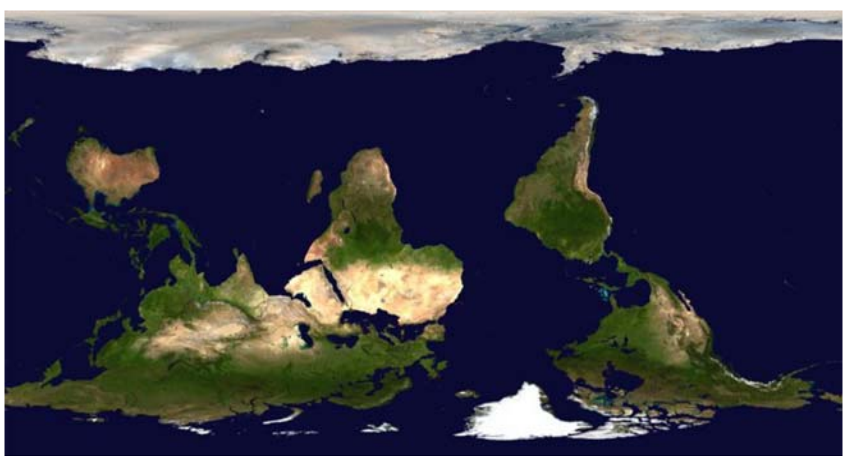
FALLOW: Like this.

[The map is flipped over.]

C.J.: Yeah, but you can't do that.

FALLOW: Why not?

C.J.: 'Cause it's freaking me out.[6]



[7]

6 *The West Wing: Somebody's Going To Emergency, Somebody's Going To Jail* (Warner Bros. broadcast Feb. 28, 2001).

C.J. is understandably upset when her world is turned upside down, but there is no obvious reason why the map should have north on top or, for that matter, be centered along the Equator. Indeed, the first question posed by professors in introductory geography courses often is the simple yet disarming, "Why is north up?"[8] The Mappa Mundi shown on the first page of this Article, for example, had south on top. Or imagine a map with the North Pole at the middle, projected outward from the Arctic.[9] This projection is disorienting. Finding Alaska takes some time.

In the past, this projection was largely irrelevant or a simple curiosity. The melting of the ice cap along with the continued discovery of natural resources at the North Pole, however, has made this projection increasingly relevant for understanding rapidly evolving geopolitics. More broadly, conceptualizing the world as centered on Western Europe and the Atlantic (as the typical projection implies) may be less relevant as the global economy pivots toward South Asia,[10] or, potentially, as there is greater global commerce across the North Pole than across the North Atlantic.[11]

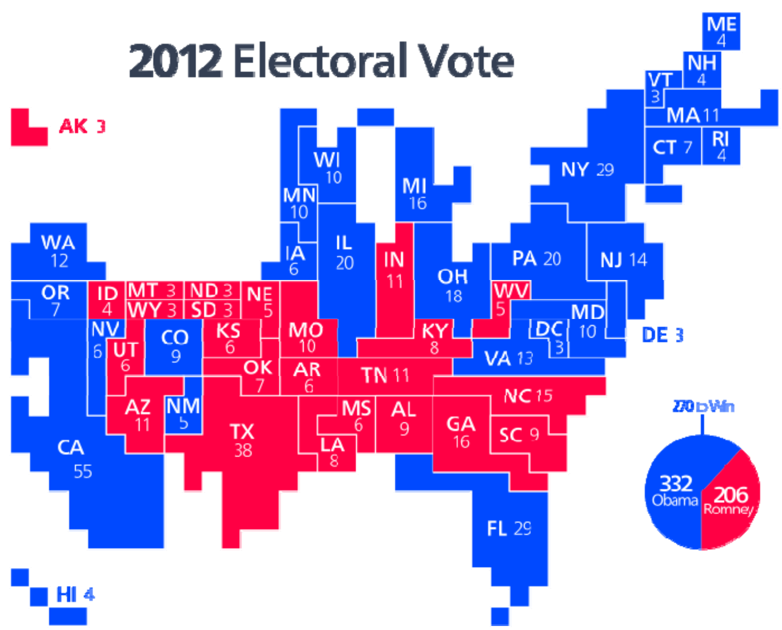
7 Wikimedia, *World Upside Down*, http://commons.wikimedia.org/wiki/File:World_upside_down.jpg (last visited Feb. 22, 2014).

8 *See generally* Jeremy W. Crampton & John Krygier, *An Introduction to Critical Cartography*, 4 ACME: AN INT'L E-JOURNAL FOR CRITICAL GEOGRAPHIES 11, 12–13 (2005), *available at* http://www.acme-journal.org/vol4/JWCJK.pdf (providing an overview of the field of critical cartography).

9 Wikimedia, *Blankmap-ao-090N-North Pole*, http://commons.wikimedia.org/wiki/File:Blankmap-ao-090N-north_pole.png (last visited Feb. 22, 2014).

10 *See* LAURENCE C. SMITH, THE WORLD IN 2050: FOUR FORCES SHAPING CIVILIZATION'S NORTHERN FUTURE 41 (2010); Daniel Tencer, *World's Economic Centre of Gravity Shifting Back to Asia at Unbelievable Speed: McKinsey Institute*, HUFFINGTON POST CANADA, July 5, 2012,

Most often we use maps to represent the physical size of geographic space scaled to some projection, but a map need not just be a spatial projection of geographic relations. A map is a model—a representation of the spatial distribution of natural, political, economic, or any other type of information or data. The size of a projected area on a map may be scaled by income or by race rather than actual geographic area.[12] Within the United States, voting maps for political elections scaled by population indicate far different relations than the more typical projection of geographic scale.[13]



Maps powerfully provide a great deal of data in an accessible manner; but they cannot reflect reality. At its most obvious, geographic maps do not fully reflect the world because something is inevitably lost when projecting a three-dimensional object on a two-dimensional surface. More subtly, map projections inherently depend on a sequence of often unarticulated, or even unrecognized, assumptions. The geographic map not only loses some physical accuracy depending on the projection system, but also smuggles in

http://www.huffingtonpost.ca/2012/07/05/world-economic-center-of-gravity_n_1651730.html (last visited Feb. 22, 2014)

11 *See* SMITH, *supra* note 10, at 156–57.

12 Twisted Sifter, *40 Maps That Will Help You Make Sense of the World*, http://twistedsifter.com/2013/08/maps-that-will-help-you-make-sense-of-the-world/ (last visited Feb. 24, 2014) (showing various types of maps; with over 939,000 Facebook "likes" and 23,400 tweets, this site has gone viral).

13 Wikimedia, *Cartogram–2012 Electoral Vote*, http://commons.wikimedia.org/wiki/File:Cartogram%E2%80%942012_Electoral_Vote.svg (last visited Feb. 24, 2014).

a series of normative assumptions that are much less obvious—hence Professor Fallow's concerns about the primacy of Northern Hemisphere countries over the Global South.[14] Maps both clarify and distort.

Despite their limitations, maps also create opportunities. The way they frame the world allows questions to be asked that might otherwise be ignored or unseen. Looking at the Mercator map, for example, tells us virtually nothing about the North Pole. A polar projection, by contrast, immediately brings into stark relief the complicated jurisdictional conflicts among the northern countries.[15] These conflicts are invisible on a Mercator projection, where the North Pole is distorted out of all recognition.

These same challenges and opportunities are also present in the natural sciences. There, in addition to space, scientists must combine temporal and spatial information to develop an understanding of the biophysical dynamics that shape the distribution of natural resources, organisms, communities, and chemicals. In these cases, the projection or presentation of temporal and spatial information forms the basis for not just presenting information, but also how that information might be abstracted into relations that form the basis of analytical reductions, from simple correlations and analytical equations to complex computational models.

How objects move through space and time has been fundamental to the intellectual development and scientific theory of physical processes. Two eighteenth century mathematicians—Leonard Euler and Joseph Louis Lagrange—made seminal contributions to how movement is conceived in the natural sciences, specifically in the field of fluid mechanics.[16] They are not popular names today, but their different ways of framing the world still dominate how scientists conceptualize and measure physical phenomena.

Central to both of these mathematicians' early work was conceptualizing the seemingly simple problem of water flow and the velocity of water "parcels." Euler developed a theory of fluid mechanics that began with a clearly defined system of Cartesian coordinates—a mathematical description of the space of interest.[17] This theory allowed him to develop a powerful system of equations that could describe the distribution of force and velocity within a particular region of fluid.

In contrast, Lagrange's formulation of mechanics was not tied to any one coordinate system—rather, any convenient independent variable could

14 *The West Wing*, *supra* note 6.

15 *See* Steve Connor, *Arctic Ice-Melt Will Bring Frosty Relations as Nations Navigate Across North Pole*, INDEPENDENT, Mar. 4, 2013, www.independent.co.uk/environment/climate-change/arctic-icemelt-will-bring-frosty-relations-as-nations-navigate-across-north-pole-8519915.html (discussing tension between northern countries caused by global warming).

16 J.S. Calero, *The Genesis of Fluid Mechanics*, 1640–1780, 22 STUDIES IN HIST. & PHILOSOPHY OF SCI. 401 (2008).

17 *See* JAMES F. PRICE, LAGRANGIAN AND EULERIAN REPRESENTATIONS OF FLUID FLOW: KINEMATICS AND THE EQUATIONS OF MOTION 1 (2006), *available at* http://www.whoi.edu/science/PO/people/jprice/class/ELreps.pdf (discussing the distinction between the theories of Euler and Lagrange).

be used to describe the system (e.g., distance along a river channel).[18] Lagrange focused on specific actors within the larger system and analyzed how those specific actors (e.g., parcels of water) behaved wherever they might be. He then calculated the characteristics of the fluid that caused the particular movements of the object of interest.[19]

In simple terms, Euler's approach framed the system as a black box with inputs and outputs: a flux. The fluid moved in and out of that region and, by studying the characteristics of the collection of fluid parcels at the entry and exit, one could quantify the forces exerted within that region that might cause the changes observed at the boundaries. Lagrange's reference frame looked *inside* the box, tracing specific actors within the system: a flow. While the Eulerian and Lagrangian reference frames were derived from mathematics and physics for fluid mechanics, they have been adopted by natural scientists as the basic reference frames for the analysis of the movement of objects within the environment. [20]

A simple example of these different frames of reference can be seen in monitoring traffic. The standard approach is to use road-cams above bridges. This is an Eulerian approach, measuring flux from a fixed position. The new smart phone application, Waze, by contrast, allows each Waze user to transmit his or her location or speed on the road at that moment.[21] This is a Lagrangian framing, following individual actors rather than measuring a flux at a fixed point. Both frames provide an accurate view of traffic, but from very different perspectives.

The debates surrounding the Mercator Projection or the Eulerian and Lagrangian approaches take place in very different fields, but they are asking the same basic question: What is the most effective reference frame for conceptualizing, understanding, and analyzing space and movement in the natural world? While largely underappreciated, such basic conceptualizations are the first step in any analysis of a system, necessary priors to identifying the parts of the system, how those parts interact, what the boundaries of the system are, and how the parts move relative to each other. There is a tendency to assume that this reference frame or conceptualization *is* reality. The Mercator Projection must show the Earth as it really is. The Northern Hemisphere clearly is in the top half of the world, or at least should be.

But this easy acceptance blithely sidesteps the problem that there are very different, though equally valid, conceptualizations of the system, including when the Northern Hemisphere is on the bottom of the map.

18 *Id.*

19 Martin W. Doyle & Scott H. Ensign, *Alternative Reference Frames in River System Science,* 59 BIOSCIENCE 499, 500 (2009).

20 *Id.*

21 Waze's website states it is "one of the world's largest community-based traffic and navigation app[s]. Join other drivers in your area who share real-time traffic and road info, saving everyone time and gas money on their daily commute." *Waze*, https://www.waze.com (last visited Feb. 24, 2014).

Because in all systems there are constraints on what can be observed, measured, and modeled, the reference frame chosen a priori determines the data collected or the modeling approach taken. As a result, one may well ask whether reconceiving the system in a different reference frame leads to different assumptions about the way the system works. Would a different reference frame or a different map projection allow us to ask fundamentally different questions, suggesting completely different data and modeling choices?

Using the Lagrangian and Eulerian reference frames as a model, this Article explores how our frame of reference shapes our understanding and application of environmental law. We are particularly interested in whether environmental law in the United States is predisposed toward Eulerian or Lagrangian reference frames and how, in turn, these reference frames influence the law.

Our thesis is that environmental law is just as sensitive to frames of reference as fluid mechanics, cartography, and any other discipline that studies natural phenomena, and that this predetermines how we conceive of environmental problems and solutions far more than we realize. Geographers and fluid mechanics scientists understand this point. We argue that environmental lawyers should, as well.

II. REFERENCE FRAMES IN FLUID DYNAMICS

The first day of fieldwork in many introductory stream hydrology classes starts the same way: A class of students is taken to a river and asked to measure how fast the water is moving.[22] This task is not so easy as may first appear. Because natural rivers have a large amount of variety in their shape, there are many different velocities of water in a river from one bank to the other. The challenge then is how to represent and measure velocity in a way that captures this variability.

One option is to set up at a particular point in the river and measure the velocity of water moving past that location. This would mean using a velocity meter, and measuring velocity at different widths and depths in that spot. The class would then take the different measurements of velocity, perhaps average them together, and have a quantification of velocity at that particular place. This approach first requires choosing a particular place and then measuring the movement of many water parcels as they pass by. The reference frame is a static place and the movement of objects past it. The data collected reflects the conceptualization of the system.

An enterprising group of students, though, might employ a quite different though equally valid approach by taking a bag of oranges—which have the same buoyancy as water—dumping the bag into the river and

22 *See, e.g.*, COLLEGE OF ENGINEERING, UNIV. OF MASS. AMHERST, LAB EXERCISE #1: STREAM FLOW 1 (2010), *available at* http://www.ecs.umass.edu/cee/reckhow/courses/370/Lab1/Stream%20flow%20lab.pdf (providing students with details regarding their first lab exercise, a field trip to measure stream flows).

having each student follow a particular orange for some period of time. The distance traveled divided by time would be the velocity of the particular orange, and thus a quantification of the particular water pathway that carried that orange. All the different velocities of oranges could be averaged to give a single quantification of the streamflow velocity of the river. This approach requires choosing to *not* be fixed in a particular space, and instead to follow particular objects.

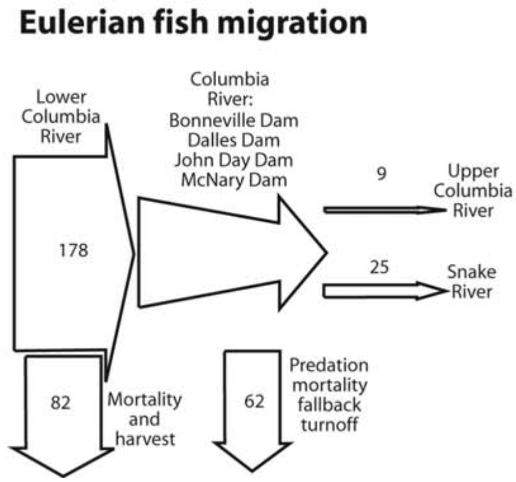
Both groups of students are measuring the river velocity, though their answers and methods are very different. The Eulerian reference frame used by the first group is based on measuring the flux of objects through or within a spatially bounded area. The Lagrangian reference frame used by the second is based on tracking specific, identifiable objects through time. The methods are a function of the different conceptualizations of space and movement.

Eulerian and Lagrangian reference frames permeate the natural sciences, particularly the study of environmental phenomena. In researching sediment or chemicals in rivers, the standard practice has been to establish measuring stations and quantify the flux of materials or solutes past that location.[23] The study of sediment and chemical transport phenomena is predominantly Eulerian and can use the changes in fluxes to infer processes that are occurring there. This approach to sediment and chemical solute study is entirely reasonable, as the objects of interest are difficult to distinguish from each other, making the Lagrangian approach logistically difficult.

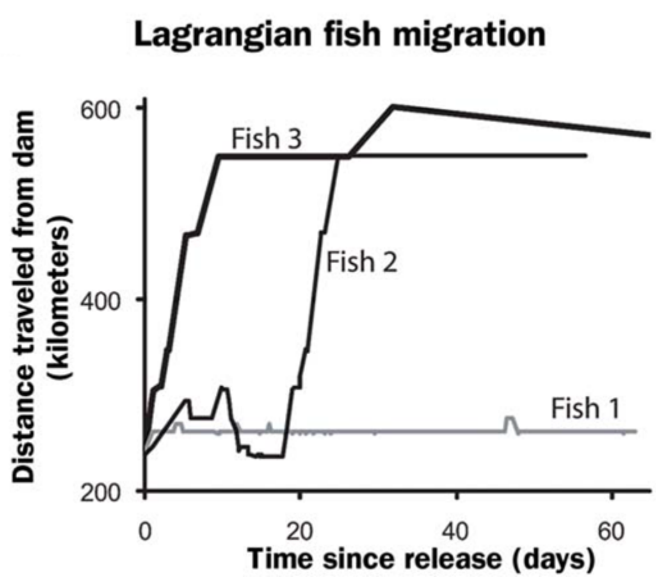
In the study of fish migration in river corridors, such as the anadromous salmon, it is possible to utilize both reference frames more easily. In rivers with declining or endangered populations of salmon, fish observation stations have been established in which the number of fish of a particular species migrating past the observation point are quantified; changes in this flux are used to infer the changes in quality of conditions and viability of the species as a whole. This method is shown in the figure below.[24]

[23] *See* U.N. ENV'T PROGRAMME & WORLD HEALTH ORG., WATER QUALITY MONITORING: A PRACTICAL GUIDE TO THE DESIGN AND IMPLEMENTATION OF FRESHWATER QUALITY STUDIES AND MONITORING PROGRAMMES §§ 3.6–3.7 (Jamie Bartram & Richard Balance eds., 1996), *available at* http://www.who.int/water_sanitation_health/resourcesquality/waterqualmonitor.pdf (explaining sampling site and sampling station selection processes).

[24] Doyle & Ensign, *supra* note 19, at 501.



Alternatively, transponders attached to individual fish can record fish position through time and space to follow their movement through a river, which allows observers to identify the specific limitations to fish survival.[25]



Using the Eulerian reference frame, we might learn that there is a downward trend in salmon populations along a particular reach. Using the

[25] *Id.* at 502.

Lagrangian reference frame, we might learn that over a week, eight out of ten salmon tracked tended to avoid areas with little riparian shading. Much like simply measuring water velocity, neither reference frame produces the *correct* answer any more than the other; they both produce answers particular to their respective reference frames.

There are also subtler effects of reference frames in the natural sciences that are quite important, yet rarely recognized. First, reference frames, once chosen, can permeate into a discipline's preconceived notions and perspectives, and shape foundational thinking.

Consider the perspectives of famed father and son, Aldo Leopold—godfather of conservation and author of the *Sand County Almanac*—and Luna Leopold—godfather of stream hydrology and winner of the National Medal of Science. In describing rivers, Luna Leopold observed: "It has been said that streams are the gutters down which flow the ruins of continents."[26] In contrast, Aldo Leopold used a Lagrangian frame, describing rivers through the tortuous path of an individual atom, named X, whom he follows through a bur-oak, acorn, deer, and Indian, then on to a plover and into the soil again. He writes:

> Next he entered a tuft of side-oats grama, a buffalo, a buffalo chip, and again the soil. Next a spiderwort, a rabbit, and an owl. Thence a tuft of sporobolus.
>
> . . . .
>
> One year, while X lay in a cottonwood by the river, he was eaten by a beaver, an animal that always feeds higher than he dies. The beaver starved when his pond dried up during a bitter frost. X rode the carcass down the spring freshet, losing more altitude each hour than heretofore in a century. He ended up in the silt of a backwater bayou, where he fed a crayfish, a coon, and then an Indian, who laid him down to his last sleep in a mound on the riverbank.[27]

Luna and Aldo Leopold's descriptions are both accurate, but they present dramatically different conceptions of the physical system.

Entire disciplines are in fact predisposed to adopt one or the other. For instance, compare two branches of ecology: behavioral ecology and ecosystem ecology. Behavioral ecology is rooted in the observation of individual organisms, the evolutionary history and adaptation of that species, and its behavior within particular environmental settings.[28] One might point to the studies of MacArthur's mapping of the movement of individual warblers through a forest as a starting point of this branch of ecology.[29] That is, behavioral ecology is based largely on a Lagrangian reference frame.

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26 LUNA B. LEOPOLD ET AL., FLUVIAL PROCESSES IN GEOMORPHOLOGY 97 (1964).

27 Aldo Leopold, *Odyssey*, AUDUBON MAG., May–June 1942, *available at* http://mag.audubon.org/articles/conservation/archives-aldo-leopolds-odyssey.

28 *See* PAUL COLINVAUX, ECOLOGY 2, at 154–56 (1993).

29 *Id.*

In contrast, ecosystem ecology is focused on the stores and fluxes of nutrients and energy through an ecosystem—a place.[30] Ecosystem ecology sets aside the particulars of the organisms within the ecosystem and instead quantifies the effect of the ecosystem itself on energy and nutrients (or other chemical compounds) as they move through or are stored within that ecosystem. One might point to the essential work of Likens in quantifying the budgets of elements into and out of lakes or entire watersheds as quintessential ecosystem ecology.[31] The particulars of the organisms or movement within the site of the organisms, and certainly the behavior of organisms, was only relevant insomuch as it affected the fluxes being measured. Ecosystem ecology has as its base, an Eulerian reference frame.

It is not that one reference frame is more accurate than the other. It is that each reference frame is appropriate for the core questions being asked within that particular discipline and, as well, that each discipline is predisposed to utilizing a particular reference frame on topics that emerge. That is, almost regardless of the issue of interest, ecosystem ecologists will be predisposed to framing the issue and corresponding research questions via Eulerian reference frames while behavioral ecologists will likely frame questions in Lagrangian reference frames.[32]

Reference frames within the natural sciences tend to be presupposed—like map projections—and thus, the constraints and biases that they embody are passed on via their application, often without critical thought or reevaluation. Some scholars have suggested that these presupposed reference frames have restricted scientists' ability to make novel insights or push the intellectual boundaries of their fields. Stuart Fisher, a prominent theoretical ecosystem ecologist whose early work adopted the Eulerian view of streams for ecosystem ecologists,[33] has contended that a conceptual step is needed to move ecosystem ecology forward. Specifically, he suggested that the discipline needs to blur ecosystem boundaries rather than

30 *See id.* at 1, 10.

31 *See generally* G.E. Likens et al., *The Calcium, Magnesium, Potassium, and Sodium Budgets for a Small Forested Ecosystem*, 48 ECOLOGY 772 (1967) (providing an example of Gene E. Likens' work on ecosystem budgets within six watersheds of the Hubbard Brook Experimental Forest in West Thornton, New Hampshire).

32 For instance, since the late 1980s there has been considerable growth in analyzing spatial patterns in landscape ecology. Of interest now in ecology is how the spatial structure of the landscape, such as habitat fragmentation, may affect ecological processes. As this new crosscutting approach to ecology has grown, behavioral ecologists and ecosystem ecologists have engaged it via their predilection for a particular reference frame. Behavioral ecologists have adopted Lagrangian reference frames to study how individual organisms (or species) might move through fragmented landscapes while ecosystem ecologists have adopted an Eulerian reference frame (often of the same studied landscape types) to quantify how fragmentation affects the fluxes of nutrients. *See* Monica G. Turner, *Landscape Ecology in North America: Past, Present, and Future*, 86 ECOLOGY 1967, 1967–69, 1971–72 (2005).

33 Stuart G. Fisher & Gene E. Likens, *Energy Flow in Bear Brook, New Hampshire: An Integrative Approach to Stream Ecosystem Metabolism*, 43 ECOLOGICAL MONOGRAPHS 421, 421 (1973).

accentuate them.[34] To do so, to break the dominant paradigm in ecosystem ecology, he proposed a simple exercise of:

> . . . following water from the hill slope and into the channel as one way of doing this—essentially adopting a more Lagrangian view of stream ecosystems. Following a particle or organism through space may be an efficient way of deconstructing preconceived boundaries or notions of processes, and potentially eliciting alternative research questions and agenda.[35]

What Fisher's 'call to creativity' shows is that preconceived reference frames take on a role almost in and of themselves in shaping many disciplines, and that to break out of the myopia that may develop over time, natural scientists may need to be intentional in altering their reference frames in order to generate new research questions and move the discipline forward.

The second subtle effect of reference frames is that they affect which questions are asked or what the scope of an entire research discipline might be. That is, once a reference frame has become predominant in a discipline, entire classes of questions or research agenda may be ignored, or even appear nonsensical. For instance, the field of river geomorphology is the study of the shape of the earth's surface with particular focus on rivers.[36] The shape of the earth is set by the location of rock and sediment, and so erosion, transport, and deposition are the primary foci of geomorphology.[37] The primary growth phase of the science of geomorphology was in the mid-twentieth century, and many of the leading geomorphologists were trained initially as hydraulic engineers.[38] The reference frame that they adopted to study sediment movement was Eulerian, and they applied hydraulic principles to the study of sediment as the fluxes of sediment into and out of river reaches of interest and the physical flow characteristics that change the sediment loads.[39] Thus, traditional Eulerian sediment transport and river geomorphology sit almost exclusively in the realm of physics and mechanics.

However, if instead of fluxes of sediment we were to focus on a particular sediment particle, the most striking thing that would emerge would be that as the sediment particle is transported from its mountain origin to its oceanic finality, the vast majority of its time is spent not in

34 Doyle & Ensign, *supra* note 19, at 507.

35 *Id.*

36 *See* KENNETH J. GREGORY & ANDREW S. GOUDIE, THE SAGE HANDBOOK OF GEOMORPHOLOGY 1 (Kenneth J. Gregory & Andrew S. Goudie eds., 2011).

37 *See* Jeff Warburton, *Sediment Transport and Deposition, in* THE SAGE HANDBOOK OF GEOMORPHOLOGY 326 (Kenneth J. Gregory & Andrew S. Goudie eds., 2011).

38 *See* Andrew Goudie, *Geomorphology: Its Early History, in* THE SAGE HANDBOOK OF GEOMORPHOLOGY 23, 25 (Kenneth J. Gregory & Andrew S. Goudie eds., 2011). *See, e.g.*, ANN L. RILEY, *River Scientists*, *in* RESTORING STREAMS IN CITIES: A GUIDE FOR PLANNERS, POLICYMAKERS, AND CITIZENS 111, 112 (1998).

39 KEITH J. TINKLER, A SHORT HISTORY OF GEOMORPHOLOGY 203 (1985).

motion, but as sediment deposited. As sediment is transported downstream, it is often deposited in bars or on floodplains, where it might sit for centuries or millennia.[40] While deposited, sediment particles undergo a variety of geochemical processes that can change their basic characteristics (i.e., chemical weathering).[41] Thus, a Lagrangian approach to sediment transport and river geomorphology inevitably leads to the realm of chemistry.[42] That is, the normative questions of a discipline can flow directly out of a presupposed reference frame.

III. REFERENCE FRAMES IN THE LAW

At one level, the idea of legal reference frames is obvious. The simplest and most pervasive use is line drawing. Law by its very nature is binary. Statutes and the common law create boundary lines. You are either in or out, subject to the law's strictures or not. Consider jurisdiction. The government cannot enforce against a pollution source beyond the reach of the court. A Los Angeles resident cannot sue a Chinese power plant under the Clean Air Act, even if she can trace the movement of its air pollution across the Pacific. The same is true for standing. A person can sue in court, as can a corporation.[43] A tree and a Lorax, alas, cannot.[44] Proximate causation serves as the line in negligence. Judges need to draw a line to keep some damage claims out of court. As Justice Cardozo memorably observed and Mrs. Palsgraf ruefully learned, negligence is not in the air.[45]

Our focus is on a less obvious act of framing, though equally prevalent. Our concern is how we measure the physical system, how we conceive of the legally significant action in the environment. Under the Clean Air Act, what is the proper frame for measuring pollution? Should we trace, for example, emissions from a specific smokestack to the impact on an individual receptor or measure ambient air concentrations in the general airshed? Is the proper frame for the Endangered Species Act the impact of actions on an individual or on a population? These framing decisions are different from jurisdictional scope. They bring into question the nature of the system itself—the collection of particular actions, actors, and areas we seek to regulate. In the paragraphs below, we consider whether Eulerian and Lagrangian frames of reference map onto environmental law. It turns out the fit is very close indeed.

40 *See* ALISTAIR F. PITTY, INTRODUCTION TO GEOMORPHOLOGY 229–30 (1971).

41 *See generally* DOROTHY MERRITTS ET AL., ENVIRONMENTAL GEOLOGY: AN EARTH SYSTEM SCIENCE APPROACH 164 (1998) (discussing the general process of chemical weathering and the products that result).

42 ROBERT H. MEADE, TRANSCONTINENTIAL MOVING AND STORAGE: THE ORINOCO AND AMAZON RIVERS TRANSFER THE ANDES TO THE ATLANTIC, *in* LARGE RIVERS 45, 47 (Avijit Gupta ed., 2007).

43 *See* Citizens United v. Fed. Election Comm'n, 558 U.S. 310, 342–43 (2010) (holding that corporations have First Amendment free speech rights).

44 *See* DR. SEUSS, THE LORAX (1971) ("I am the Lorax. I speak for the trees. I speak for the trees, for the trees have no tongues." And sadly neither does the Lorax in the court system.).

45 Palsgraf v. Long Island R. Co., 162 N.E. 99, 99 (N.Y. 1928).

Let's start with the Clean Water Act. One of the basic divisions in this law is the distinction between point source and nonpoint source pollution, basically pollution flowing from pipes versus from fields and roads.[46] The regulation of point sources is largely framed through a Lagrangian approach. National Pollutant Discharge Elimination System (NPDES) permits are required for individual sources and establish specific control technologies the sources must employ. Whether the sum of point sources causes overall water quality problems to the larger river or lake is not immediately considered.

Contrast that with nonpoint source pollution, which is treated within an Eulerian frame. The Total Maximum Daily Load (TMDL) program seeks to calculate the overall fluxes or pollutant budget into a water body.[47] Indeed, the very term TMDL refers to the overall pollutant load that a water body can accept while meeting water quality limits—Eulerian in all but name.

The Water Quality Standards program—where individual NPDES permits are revised based on meeting the TMDL[48]—represents a hybrid approach, where the Eulerian frame of the water body is combined with the Lagrangian frame for allocating contributions from each individual source.

One can also see different reference frames at work in the wetlands mitigation banking program. Starting with President George H.W. Bush, every subsequent President has adopted a "No Net Loss" strategy for wetlands.[49] This has been achieved through the section 404 program of the Clean Water Act, which authorizes the Secretary of the Army to "issue permits, after notice and opportunity for public hearings for the discharge of dredged or fill material into navigable waters at specified disposal sites."[50] These permits, administered principally through the Army Corps of Engineers (Corps)[51] and known ubiquitously as "404 permits," should be issued using a "sequencing" approach. The first preference is to require the applicant to avoid filling wetland resources, followed by minimization of adverse impacts to those wetlands that cannot reasonably be avoided,

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46 Clean Water Act, 33 U.S.C. § 1362(12)–(14) (2006).

47 *Id.* § 1313(d)(3).

48 EPA, EPA-823-B-12-002, WATER QUALITY STANDARDS HANDBOOK, ch. 7, at 1, 7 (1994), *available at* http://water.epa.gov/scitech/swguidance/standards/handbook/chapter07.cfm.

49 *See* 40 C.F.R. § 257.9 (2013) (establishing the "no net loss" policy); JAMES SALZMAN & J. B. RUHL, "NO NET LOSS": INSTRUMENT CHOICE IN WETLANDS PROTECTION 1 (2005), *available at* http://ssrn.com/abstract=796771; OBAMA FOR AMERICA, BARACK OBAMA: SUPPORTING THE RIGHTS AND TRADITIONS OF SPORTSMEN (2008), *available at* http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0CC8QFjAB&url=http%3A%2F%2Fobama.3cdn.net%2F75994105496e31ff83_guzfmvkls.pdf&ei=xXqVUqetO8ndoATauIDIAQ&usg=AFQjCNGYvmXmy0onfnkDozaTuBihjgFTwQ&bvm=bv.57155469,d.cGE&cad=rja (stating the campaign promise to continue the wetlands "no net loss" policy); Louis Jacobson, *Partial Progress on Several Elements of Wetlands Protection*, POLITIFACT, Nov. 29, 2012, http://www.politifact.com/truth-o-meter/promises/obameter/promise/282/support-wetlands-protection/ (last visited Feb. 22, 2014) (assessing the campaign promise to continue the wetlands "no net loss" policy).

50 33 U.S.C. § 1344(a) (2006).

51 *Id.* § 1344(b).

followed by the least desirable option of providing compensatory mitigation for those unavoidable adverse impacts that remain after all minimization measures have been exercised.[52] This latter option is essentially an offset program: For X acres of wetlands impacted, Y acres had to be conserved or restored.

In the early years of wetlands mitigation, the Corps took a Lagrangian perspective for implementing the compensatory mitigation requirements.[53] Each project was considered individually and mitigation required onsite, in-kind restoration. The success of restoration was assessed as matching the restoration against the harm on that particular site; impact and offset were definitively linked. While attractive in theory, the project-by-project compensatory mitigation approach was widely regarded as having failed miserably in terms of environmental protection.[54] Whether onsite or nearsite, the piecemeal approach complicated the Corps' ability to articulate mitigation performance standards, monitor success, and enforce conditions. Many developers went through the motions of so called "landscape mitigation"—planting what was required or regrading where required to meet the minimum letter of the permit—then moved on.[55]

In light of these problems, the Corps and EPA started shifting compensatory activities from onsite to offsite mitigation, thus opening the door to wetlands mitigation banking.[56] This approach allows a developer who has mitigated somewhere else in advance of development to draw from the resulting bank of mitigation "credits" as the development is implemented and wetlands are filled.[57] The concept progressed beyond this personal bank model, as large commercial and public wetlands banks, not tied to a particular development, sell mitigation credits to third party developers in need of compensatory mitigation.[58] Wetland mitigation banking now resembles a commodity market, with freewheeling, entrepreneurial wetlands banks offering for sale (and profit) finished, offsite wetlands as credits to anyone who is in need of mitigation for their 404 permits.[59]

52 *See* Memorandums of Agreement (MOA); Clean Water Act Section 404(b)(1) Guidelines; Correction, 55 Fed. Reg. 9,210, 9,211–12 (Mar. 12, 1990).

53 *See, e.g.*, Doyle & Ensign, *supra* note 19, at 500; Michael J. Bean & Lynn E. Dwyer, *Mitigation Banking as an Endangered Species Conservation Tool*, 30 ENVTL. L. REP. NEWS & ANALYSIS 10,537, 10,538 (2000).

54 Bean & Dwyer, *supra* note 53, at 10,538.

55 Keith Bowers, *What Is Wetlands Mitigation?*, LAND DEV., Winter 1993, at 28, 33 (1993).

56 *See* James Salzman & J.B. Ruhl, *Apples for Oranges: The Role of Currencies in Environmental Trading Markets*, 31 ENVTL. L. REP. NEWS & ANALYSIS 11,438, 11,456 (2001).

57 William W. Sapp, *Mitigation Banking: Panacea or Poison for Wetlands Protection*, 1 ENVTL. LAW 99, 108 (1994) ("In a single-user bank, the 'banker' and the 'user' are the same entity.").

58 ENVTL. LAW INST., WETLAND MITIGATION BANKING 120–23 (1993) (describing four types of commercial and public mitigation banks).

59 *See* William W. Sapp, *The Supply-Side and Demand-Side of Wetlands Mitigation Banking*, 74 OR. L. REV. 951, 968–73 (1995) (explaining economies of scale in mitigation banking and profitability to mitigation bankers).

Onsite, project-by-project mitigation was classic Lagrangian, in that the credits were the object being tracked. Mitigation success was tied to the success of the specific restoration project replacing the losses from the original wetland. The move to wetlands mitigation banking required a significant intellectual shift to an Eulerian frame of reference. To mitigate under wetlands banking, a developer need only buy a credit from a bank somewhere else in the same watershed.[60] "No net loss" shifted from no net loss of that particular wetland to no net loss of *cumulative* wetlands.[61] The problem became viewed as managing a flux, balancing overall gains and losses of wetlands.

Once a credit is approved by the Corps for compensatory mitigation, it loses its individuality. The permittee/buyer does not care if it is a good restoration or a bad restoration. This is particularly true for in lieu fee programs, in which the arrows linking impact to compensation are malleable. They don't point to each other, they essentially point to a great credit silo where deposits and debits are inventoried, and the particular credits are churned from individuals to homogeneity. The nuance of a particular ecosystem is completely subsumed into a large spreadsheet in the cloud balancing the books of natural capital.

This is true for other restoration markets as well. To gain the efficiencies of scale and engage a sufficient number of buyers and sellers, market designers necessarily abandon the importance of individuality to allow the gains of the market to operate.[62] Fungibility, an Eulerian perspective balancing cumulative impacts and cumulative credits, must dominate over a Lagrangian frame, which necessitates tracking a specific credit to a specific offset, essentially one-to-one trading.[63]

Outside the mitigation context, there are other examples of how wetlands regulations are couched in different reference frames, and how these differences influence legal interpretation. The Eulerian/Lagrangian

60 ENVTL. LAW INST., BANKS AND FEES: THE STATUS OF OFF-SITE WETLAND MITIGATION IN THE UNITED STATES 27 (2002), *available at* http://www.eli.org/sites/default/files/eli-pubs/d12_08.pdf.

61 *See, e.g.*, Compensatory Mitigation for Losses of Aquatic Resources, 73 Fed. Reg. 19,594, 19,601 (Apr. 10, 2008) (codified at 40 C.F.R. pt. 230) (stating that offsite mitigation may better support the no net loss goal for wetlands than onsite mitigation).

62 *See, e.g.*, Shirley Jeanne Whitsitt, *Wetlands Mitigation Banking*, 3 ENVTL. LAW. 441, 469 (1997) (discussing the importance of avoiding defining service areas for credit ventures too narrowly in order to increase demand for credits).

63 In the book *Nature's Metropolis*, Historian William Cronon provides a fascinating account of the same transition in the development of wheat futures markets in the 19th century. Cronon follows a bushel of wheat through the market from farm to final sale. When transported by river, the bushel remained in a bag and therefore distinct. It had to be priced by its individual quality. However, once trains and grain elevators became popular, wheat was bulked and rated into classes (taken out of bags from farmers and put in bulk onto trains and eventually into grain elevators), making it easier to handle and price. In the process, it lost its individuality. WILLIAM CRONON, NATURE'S METROPOLIS: CHICAGO AND THE GREAT WEST 142–47 (1991). The shift from individual to bulk identification of commodities could equally well be described as a shift from Lagrangian to Eulerian frames.

distinction is perhaps most clearly evident in *Rapanos v. United States*.[64] This case raised the issue of whether isolated wetlands connected to navigable waters through streams and conduits should also be considered navigable waters subject to regulation under the Clean Water Act.[65] While the implications of the split verdict in *Rapanos* have remained murky,[66] the oral arguments were crystal clear in setting out the choice between an Eulerian and Lagrangian frame of reference.

The lawyer for Rapanos argued that a specific, hydrologic link must be established between the navigable water and the body of water upstream subject to regulation.[67] This was, in essence, a hardline Lagrangian tack. In his questioning, Justice Souter recognized the implications:

> The functional reason [to regulate adjacent wetlands upstream of a traditionally navigable water] is that if you put the poison in the adjacent wetland, it's going to get into the navigable water. Exactly the same argument can be made as you go further and further up the tributaries, and it seems to me that once you concede, as I think you have to, that there can be a regulation that goes beyond literally navigable water at the point at which the . . . pollutant is added, then you have to follow the same logic right up through the watershed to . . . any point at which a pollutant, once added, will eventually get into the navigable water.[68]

For Souter, a Lagrangian approach would require developing tracers from specific upstream sources to navigable waters, at which point they could be subject to regulation. This, however, would impose a significant logistical challenge on the regulators: "You mean . . . in every case then . . . a scientist would have to analyze the molecules . . . and trace them up, and so long as they . . . could trace it [sic] to a specific discharge, they could get at it [to regulate], but otherwise they couldn't?"[69] The Solicitor General made a similar argument:

> One way of [establishing a connection between navigable waters and distant water bodies] . . . would be this impossible sort of process of trying to fingerprint or DNA test oil spills in a tributary to figure out, yes, that's the guy that got it to the navigable waters. And the one thing we know is that there were some efforts to try to regulate pollution that way before 1972 and they were a dismal failure.[70]

Instead, the Government argued that the upstream wetlands and tributaries should be classified based on their characteristics and location,

64 547 U.S. 715 (2006).
65 *Id.* at 729.
66 Clifton Cottrell, *The "Wetlands Adjacent to Non-Navigable Waters" Less Traveled: Clean Water Act Jurisdiction and the Fifth Circuit*, 43 TEX. ENVT'L L. J. 19, 32 (2012).
67 *See Rapanos*, 547 U.S. at 739–40.
68 Transcript of Oral Argument at 6, *Rapanos*, 547 U.S. 715 (Nos. 04-1034, 04-1384).
69 *Id.* at 8.
70 *Id.* at 57.

from which their connection to downstream waters could be inferred. This approach is essentially Eulerian: The cumulative landscape upstream results in some net pollution level downstream. This line of thinking does not require a specific Lagrangian link to be made from downstream water to an upstream wetlands or tributary. Rather, it requires a broader systems view for water pollution and the landscape processes. In fact, this was the central vision behind Justice Kennedy's controlling concurrence:

> Through regulations or adjudication, the Corps may choose to identify categories of tributaries that, due to their volume of flow (either annually or on average), their proximity to navigable waters, or other relevant considerations, are significant enough that wetlands adjacent to them are likely, in the majority of cases, to perform important functions for an aquatic system incorporating navigable waters.[71]

This is a classic Eulerian framing, looking to the large-scale attributes rather than tracing individual pollutants. It is worth noting in this regard that one of the essential elements of the Government's defense of its categorical approach was the logistical impossibility of tracing specific molecules of a pollutant to a specific polluter upstream.[72] This had been the case prior to the Clean Water Act's adoption in 1972 and, the Government contended, it remains relevant and dominant today.[73] We return to this point in the last Part of this Article.

Or consider the aftermath of the *Rapanos* decision. The EPA has recently released a study of peer reviewed, scientific literature on the physical, biological, and chemical linkages between isolated waters and navigable waters.[74] EPA is also preparing a rule on this topic for submission to the White House.[75] While the details of the rule are still unknown, reports indicate that it will rely on "connectivity" between specific water bodies and navigable waters in order to assert federal jurisdiction.[76] The Government will therefore rely on the flow connecting the waters rather than the mere category of the water body itself. If so, the Clean Water Act may soon take on a stronger Lagrangian frame of reference.

The dichotomy between Eulerian and Lagrangian frames of reference extends far beyond the Clean Water Act. In the Clean Air Act, for example,

71 *Rapanos*, 547 U.S. at 780–81 (Kennedy, J., concurring).

72 *See* Transcript of Oral Argument, *supra* note 68, at 8.

73 Though this may be changing. EPA, *Clean Water Act Definition of "Waters of the United States"* http://water.epa.gov/lawsregs/guidance/wetlands/CWAwaters.cfm (last visited Nov. 24, 2013) [hereinafter Draft Rule Article].

74 EPA, EPA/600/R-11/098B, CONNECTIVITY OF STREAMS AND WETLANDS TO DOWNSTREAM WATERS: A REVIEW AND SYNTHESIS OF THE SCIENTIFIC EVIDENCE 1-1 (2013).

75 Draft Rule Article, *supra* note 73.

76 Indeed, the title of EPA's draft report is "Connectivity of Streams and Wetlands to Downstream Waters: A Review and Synthesis of the Scientific Evidence (Sept. 2013 External Review Draft, EPA/600/R-11/098B)." Notification of a Public Meeting of the Science Advisory Board Panel for the Review of the EPA Water Body Connectivity Report, 78 Fed. Reg. 58,536, 58,536 (Sept. 24, 2013).

the use of "bubbling" treats the facility as an Eulerian system of smokestacks. If the net emissions of a facility do not increase, there is no need to revise the facility's permit.[77] A Lagrangian approach would focus on the emissions of each discrete stationary source. This is equally evident in the acid rain trading program in Title IV.[78] A Lagrangian approach would follow emissions from Midwestern power plants up the coast until they ended up as acid deposition in the Northeast, and then regulate individual sources. Instead, just as occurred with wetlands mitigation banking[79] and the Chicago wheat exchange,[80] the Clean Air Act renders sulfur dioxide pollution fungible and establishes a nationwide cap to reduce net emissions.[81] This approach, which ensures a viable trading market, makes little sense from a Lagrangian perspective but perfect sense from an Eulerian view.

Or consider the Endangered Species Act (ESA),[82] where Eulerian and Lagrangian frames of reference also are evident. Under the ESA, a species may be listed as "endangered" if it is in danger of extinction in all or a significant portion of range.[83] But should this judgment be made in reference to the current range—a static, Eulerian snapshot—or the species' historic range, which has been shrinking for decades or even centuries—a Lagrangian frame moving over time? Migratory corridors provide a different context. In tracking migratory birds, biologists usually look at populations at both the nesting and wintering grounds, measuring whether there has been mortality in the migration between the two.[84] This is an Eulerian frame of reference. But what about how the birds got there? Tracing individual birds' paths would be Lagrangian. For example, the wind power industry has faced criticism in light of the concern that whooping cranes will attempt to avoid windmills resulting in longer migration patterns, meaning they have less energy when they arrive.[85] The Lagrangian frame would suggest the same number of birds as the Eulerian frame but have a different understanding of their condition because of the route they took, and thus, different implications for whether the ESA is relevant to wind farms.

77 This is the rule affirmed in *Chevron, U.S.A., Inc. v. Natural Resources Defense Council, Inc.*, 467 U.S. 837, 854 (1984). The rule was originally described in the Federal Register, 46 Fed. Reg. 50,766 (Oct. 14, 1981).

78 *See* Clean Air Act, 42 U.S.C. § 7651(b) (2006) (laying out Congress's purpose in creating an allocation and transfer program for emissions).

79 *See supra* notes 57–62 and accompanying text.

80 *See supra* note 63 and accompanying text.

81 42 U.S.C. § 7651c(a) (2006).

82 Endangered Species Act, 16 U.S.C. §§ 1531–1544 (1973).

83 *Id.* § 1532(6).

84 *See, e.g.,* Kevin C. Fraser et al., *Continent-Wide Tracking to Determine Migratory Connectivity and Tropical Habitat Associations of a Declining Aerial Insectivore*, PROC. OF THE ROYAL SOC'Y BIOLOGICAL SCI., Dec. 2012, at 4,901–02, *available at* http://rspb.royalsocietypublishing.org/content/279/1749/4901.full.

85 *See, e.g.,* U.S. FISH & WILDLIFE SERV., WHOOPING CRANES AND WIND DEVELOPMENT–AN ISSUE PAPER 18 (2009).

We could go on, but the point is clear. Lagrangian and Eulerian frames of reference are commonplace in environmental law. As a descriptive matter, this seems quite obvious. The key question is why it matters.

IV. WHAT DO REFERENCE FRAMES MEAN FOR ENVIRONMENTAL LAW?

The realization that much of environmental law can be described in terms of Eulerian and Lagrangian reference frames is interesting, but we believe it raises two important questions. The first is why we see different frames in the law. What drives the choice of an Eulerian frame in some settings and a Lagrangian frame in others?

One reason is conceptual. There are certain environmental problems that are best considered as a flux rather than as a set of individual actors. Indeed, tracing individuals may lose the property of the system that we care about. It may be sufficient, for example, to focus only on the population level of a species or the overall concentrations of a global pollutant. The more important reason, though, is practical.

In many instances, it is infeasible or impossible to trace individuals. That was Justice Souter's concern in the *Rapanos* oral argument—scientists cannot trace molecules back to a specific discharge, so that cannot be the basis for regulation.[86] The Solicitor General reinforced this point, arguing that this approach had been tried in the past and failed.[87] The same would be true for air pollution. What we really care about is the impact of air pollution on an individual, but it is too difficult to trace the source of pollutants in a mixed airshed and the susceptibility of individuals.

This was also evident in our earlier discussion of salmon research and the choice between studying the movement of fish populations or tracing the path of individual salmon.[88] The Eulerian approach is most suitable for small, indistinguishable or interchangeable objects with little individuality that might influence their behavior and movement. It is the natural reference frame for flux-based questions and problems. But it imposes limitations. Because the Eulerian reference frame views the system as a black box, it is not able to provide insight into what happens *within* the boundaries at which measurements are taken.

The Eulerian approach deliberately obscures internal processes: The processes and effects are inferred based on the output from the area bounded for the study. Moreover, the results are entirely dependent on the sampling locations chosen and which boundaries are assumed to exist.[89] The investigator must select the study areas and the sampling locations a priori, and the representativeness of these sites is essential to the insights gained from the data. Results vary as a function of where boundaries are drawn.

86 Rapanos v. United States, 547 U.S. 715, 728–29 (2006).

87 *Id.*

88 *See* discussion *supra* Part I.

89 For a general discussion on the central role of monitoring in environmental law, see Eric Biber, *The Problem of Environmental Monitoring*, 83 U. COLO. L. REV. 1 (2011).

Temporally, the resolution of data collection or the timing of collection biases the utility of the data. Measuring the flow of traffic under a bridge may not show where the real bottlenecks are.

The Lagrangian reference frame, in contrast, works well for objects that exhibit individual behavior. But it is limited by the ability to observe a number of objects by the availability of appropriate tracer technology—either physical transponders or chemical isotopes—and particularly the ability to trace objects over long periods of time: In most cases, the efficacy of a tracer diminishes over time. Consequently, most Lagrangian studies involve large objects, such as large birds or rare radioactive elements.[90] Salmon are much easier to track and follow individually than are sediment particles, but there are only so many salmon that could be sufficiently monitored with transponders, and so insight must be shaped by a small number of observations. If individuals behave similarly, then the Lagrangian approach would reveal insights into typical behavior—the more idiosyncratic each salmon is, the more problematic it is to understand the group as a whole from the observations of the few.

The central importance of monitoring capacity in choosing reference frames is clearly the case for water pollution. As Stephenson and Shabman describe:

> A point source is one where it is technically and financially feasible to trace the pollutant back to an originating location [and therefore Lagrangian]. In contrast, a nonpoint source is often characterized by the following conditions: a lack of monitoring technology for linking pollutants to their source; costs for tracking pollutants to their source in excess of available resources; or political opposition from nonpoint sources who could face . . . limits . . . . For one or more of these reasons, nonpoint sources are beyond the reach of the CWA and NPDES permits for point sources are the only CWA-authorized instrument limiting pollutant discharges. This is the case even though, in many places, nonpoint source loads are the reason water quality standards are not met [and therefore measured through an Eurlerian reference frame].[91]

Put simply, because of monitoring limitations, most of our environmental laws have Eulerian reference frames. But this begs a second question: What if the technology changed? What if you *could* trace everything and identify everyone's sensitivity? What would environmental law look like then?

To give a preview of what might lie in store, realize that we are seeing rapid development of very lightweight transponders, chemical tracers, DNA tracing, and even cell phones.[92] These technological advances have all led to

90 Doyle & Ensign, *supra* note 19, at 500–01.

91 Kurt Stephenson & Leonard Shabman, *Rhetoric and Reality of Water Quality Trading and the Potential for Market-Like Reform,* 47 J. AM. WATER RESOURCES ASS'N 15, 17 (2011).

92 For a discussion of how technological advances in monitoring were influencing environmental law in 2003, see Daniel C. Esty, *Environmental Protection in the Information Age*, 79 N.Y.U. L. REV. 115 (2004). *See also* Dave Owen, *Mapping, Modeling, and the Fragmentation of Environmental Law*, 2013 UTAH L. REV. 219, 251–81 (discussing spatial

a surge in the use of Lagrangian techniques in the study of environmental and even sociological phenomena. Consider, for example, the startup company, BaseTrace.[93] Founded by recent Duke graduates, BaseTrace has developed tracers that can be mixed in hydraulic fracturing fluids. The tracers contain readily identifiable DNA strands that will stay in the fluid no matter where it goes.[94] As a result, it may soon be possible—indeed, easy—to establish definitively whether a particular fracking site's fluids contaminate drinking water supplies through DNA fingerprinting. The company's product has generated a great deal of interest in the venture capital community.[95]

New technology is changing the possible frames of reference. If adopted, the BaseTrace technology will allow Lagrangian analysis of fracking fluids and potentially change the contours of liability. But we can go even further. Given the pace of technology, it is not farfetched to assume that we may be able to trace the specific path of virtually anything—from water parcel to organism—in the coming decades.

As tracers have become more robust in other fields, they have also enabled the Lagrangian approach over longer periods of time, which leads to the primary advantage of the Lagrangian approach over the Eulerian approach in natural science—the boundaries of the system are not presupposed. By following an individual object through space and time, it is possible that boundaries initially thought present may be more permeable than imagined.[96] For instance, the development and application of stable isotopes has allowed ecologists to identify and quantify the movement of chemicals and organisms between regions that had typically been considered distinct; there is now substantial understanding of the interaction between water in stream channels and groundwater.[97]

To assess how this might change environmental law, in particular, consider two examples from the Clean Air Act[98] described below. The first concerns the challenges posed by advances in genomics.

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mapping's effects, or lack thereof, on environmental law and spatial mapping's ability to solve problems posed by environmental law).

93 BaseTrace, *Home*, www.basetrace.com (last visited Feb. 22, 2014).

94 BaseTrace, *About Our Technology*, www.basetrace.com/technology (last visited Feb. 22, 2014).

95 Amanda Jones Hoyle, *Through Challenge, Early Stagers Getting Help,* TRIANGLE BUS. J., July 12, 2013, http://www.bizjournals.com/triangle/print-edition/2013/07/12/through-challenge-early-stagers.html (last visited Feb. 22, 2014).

96 *See, e.g.*, Randall Kochevar, *Following a Dream, and Tuna, with Electronic Tagging,* STANFORD REP., Feb. 25, 2004, http://news.stanford.edu/news/2004/february25/aaas-blocksr-225.html (last visited Feb. 22, 2014) (discussing how marine biologist Barbara Block tagged and tracked individual Bluefin tuna, demonstrating that they migrate from the eastern coast of the United States all the way to the Mediterranean, therefore making clear that conservation efforts for the stock must take place in both jurisdictions).

97 *See generally* STREAMS AND GROUND WATERS (Jeremy B. Jones & Patrick J. Mulholland eds., 2000) (explaining the "surface–subsurface exchange processes in streams" and demonstrating the "robust understanding" of these processes in the field).

98 Clean Air Act, 42 U.S.C. §§ 7401–7671q (2006).

Under the Clean Air Act, National Ambient Air Quality Standards (NAAQS) must be set at a level "requisite to protect the public health" with "an adequate margin of safety."[99] The question this begs, of course, is: Who is the public? Based on *Lead Industries Association v. EPA*, [100] CAA amendments,[101] and agency policy,[102] the EPA has set its NAAQS at levels protective of sensitive subgroups with "significantly higher probability of developing a condition, illness, or other abnormal status" from pollutant exposure than the rest of the population.[103]

When revising the ozone air quality standard in 1979, for example, the standard was aimed "not only on the most sensitive population group, but also on a very sensitive portion of that group (specifically, those persons who are more sensitive than 99 percent of the sensitive group, but less sensitive than 1 percent of that group)."[104] When developing the NAAQS for lead in 1978, the level was set so it would protect 99.5% of children, defined as the most sensitive population group.[105]

While this approach is highly protective, it also poses a challenge in light of recent advances in genetics. As Gary Marchant has written:

> It has long been observed that individuals differ in their response to exposures to air pollutants such as ozone and particulate matter, but it is only in recent years that the genetic basis of this variable response has been identified.
>
> . . . .
>
> . . . [I]ndividuals with a genetic condition called α_1-antitrypsin deficiency are prone to developing chronic obstructive pulmonary disease ("COPD"), especially when exposed to tobacco smoke or airborne particulate matter. Similarly, many genetic variants have been identified that appear to predispose an individual to developing asthma, which in turn makes the individual more susceptible to adverse health effects from air pollution exposures.
>
> This growing data set indicates that there are significant genetic susceptibilities to ambient air pollutants in the general population. The issue then presented is whether and how this information can and should be used to better protect genetically susceptible individuals. . . . [W]e are reaching the point of scientific understanding where we can start utilizing genetic

99 *Id.* § 7409(b)(1).

100 *See* 647 F.2d 1130 (D.C. Cir. 1980) (holding that the Administrator did not exceed his authority by promulgating the standards based on protecting children from "subclinical" effects of lead exposure which had not been shown to be harmful to health).

101 40 C.F.R. § 50.2 (2013).

102 *See* Am. Lung Ass'n v. EPA, 134 F.3d 388, 389 (D.C. Cir. 1998) ("Congress defined public health broadly. NAAQS must protect not only average healthy individuals, but also 'sensitive citizens' . . . [who are] particularly vulnerable to air pollution.").

103 EPA, EPA-600/8-77-017, AIR QUALITY CRITERIA FOR LEAD 13-11 (1977).

104 Revisions to the National Ambient Air Quality Standards for Photochemical Oxidants, 44 Fed. Reg. 8,202, 8,215 (Feb. 8, 1979).

105 *Lead Indus. Ass'n*, 647 F.2d at 1144–45.

> information to tailor our environmental and public health policies to better protect susceptible individuals . . . .[106]

The CAA operates as an Eulerian system if our concern is about ambient concentrations and their effects on populations. A truly Lagrangian approach would regulate from specific source to specific individual. If we can now identify hypersensitive individuals and trace the pollutants back to their source, does the CAA require setting the NAAQS at the level necessary to protect them? Marchant argues that this is the direction we are necessarily heading. He concludes that:

> It is probably a matter of when, not whether, genetic information will play a major role in our air pollution protection programs. As we continue to control and reduce air pollution exposures, the remaining health effects will be increasingly clustered in vulnerable people who have a genetic or other susceptibility that makes them particularly sensitive to air pollution.[107]

This plays into our second example—microclimates under the Clean Air Act (CAA). As Professor Ann Carlson has demonstrated, microclimates can be created by proximity to mobile sources and these pose serious challenges for the Clean Air Act.[108] Diesel engines, in particular, can create hot spots in tightly bounded locations near highways and intersections where the air quality is well in excess of the NAAQS standards.[109] And this occurs in air quality control regions that are regarded as in attainment. As a result, the poor local air quality is effectively masked by the stamp of approval for the airshed.

Carlson does not use the vocabulary of Euler and Lagrange, but their applicability is evident in her description below:

> The concept of "ambient" as implemented under the CAA is applied to precisely the opposite of microclimates. Instead, attainment is measured for large geographic areas—designated by the Environmental Protection Agency after consultation with individual states—even though those areas may have very different air quality within their jurisdictional borders.
>
> Using a small number of monitors to measure ambient air quality over a large geographic area, by definition, simply ignores many microclimates. . . . [The Southern California air quality district] uses 35 monitoring stations around its almost 11,000 mile basin to measure air quality, a number higher than required by federal regulation. The stations cannot, obviously, measure the quality of

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106 Gary E. Marchant, *Genetic Susceptibilities: The Future Driver of Ambient Air Quality Standards?*, 43 ARIZ. ST. L.J. 791, 796–98 (2011).

107 *Id.* at 807.

108 Ann E. Carlson, *Microclimates and Air Pollution* (forthcoming 2014).

109 *Id.* at 2.

the air across the potentially thousands of microclimates that exist within its borders.[110]

Due to awareness of this problem, there has been pressure from environmental justice groups to place additional monitoring stations in hotspots,[111] increasing the granularity of what is essentially an Eulerian reference frame. Perhaps surprisingly, EPA has blocked these efforts.[112] Carlson reports that "EPA regulations prohibit using microclimate monitoring to establish ambient limits and the agency has opposed requiring the monitoring of near road microclimates for certain air pollutants. The Ninth Circuit upheld EPA's regulations prohibiting the use of monitors near pollution hotspots to establish ambient levels in *Physicians for Social Responsibility v. EPA*."[113]

Let's now consider what would happen in the two preceding technologies if the technology changed. What would environmental law look like if you could trace the sources of every pollutant and their impact on every receptor? What if you could identify everyone's sensitivity? Would this allow us to pivot from an Eulerian to Lagrangian reference frame, and would this pivot matter for environmental law?

Let's reconsider the airshed with microclimate hotpots. The air quality monitors currently operate in an Eulerian frame. We can add more monitors and gain greater granularity, but the frame is still stationary. It's like adding more road cams to monitor traffic. To make the Lagrangian pivot, we need to let the monitor move. The first easy Lagrangian move would be to use a mobile lab and drive around the city. With this stream of data coming into an EPA database, officials could map the hotspots at different resolutions in time and space. But why stop with moving labs? Why not allow people to buy small air samplers they can put on their cars and go about their daily lives, monitoring the impacts when and where they are encountered? The data resolution would increase dramatically.

110 *Id.* at 5, 8.

111 *See* Elena Craft, *12-Step Program for TCEQ to Clean Up Air Pollutant "Hotspots" in Texas*, TEXAS CLEAN AIR MATTERS, (Apr. 22, 2010), http://blogs.edf.org/texascleanairmatters /2010/04/22/12-step-program-for-tceq-to-clean-up-air-pollutant-hotspots-in-texas/ (discussing increasing the number of air monitor sites in hotspot areas as part of numerous steps to mitigate pollutant concentrations).

112 Carlson, *supra* note 108, at 8. As Carlson's article explains, EPA is in a difficult position: Choosing between more accurate measurements of air quality locations throughout the airshed versus using current locations to true measure the overall ambient pollutant levels. Both approaches are problematic. The current framing masks hotspots. But it doesn't make sense to consider an entire airshed out of compliance because of a small number of hotspots, either. *Id.*

113 Physicians for Soc. Responsibility v. EPA, No. 12-70079 (9th Cir. Oct. 26, 2012) ("A coalition of environmental groups is currently suing EPA over its failure to mandate near road monitors in southern California to establish ambient limits."). *See* Petitioners' Opening Brief at 4, Physicians for Soc. Responsibility v. EPA, No. 12-70016 (9th Cir. May 18, 2012); Brief for Respondent United States Environmental Protection Agency at 1–3, ; Approval of Air Quality Implementation Plans; California; South Coast; Attainment Plan for 1997 PM2.5 Standards, 76 Fed. Reg. 69,928, 69,928, 69,946 (Nov. 9, 2011) (quoting Carlson, *supra* note 108, at 8 n. 17).

But why just cars? As technology improves, we could have small backpack sensors or even cell phone apps coupled with phone-mounted microsensors that monitor local air quality. This would provide data on our daily lives as we actually move. We would not have data from presupposed monitoring stations but rather from the places that people *actually* encounter in their daily lives. Now, we don't have to presuppose where pollution happens. The boundaries are defined in real data from the time and place people are really living. It may turn out that the worst hotspots are actually indoors, beyond the reach of the Clean Air Act,[114] or in places we never considered. The presupposed line between the clean indoors and the dirty outdoors—the presupposed line between EPA and Occupational Safety and Health Administration—may become blurred when presupposed reference frames are dissolved through emerging technologies.

Imagine, for example, what nuisance would look like if you could trace discrete pollutants that an individual had inhaled or ingested to their original sources and you knew the individual's specific susceptibilities. This would describe a classic Lagrangian system but might also describe a sort of "frictionless common law." The challenges of causation would disappear. There would still be obstacles, of course, in establishing whether the conduct was reasonable and whether the interference was substantial, but one of the main barriers to common law actions in the pollution context would be removed.

And there is one further, big Lagrangian legal pivot worth considering. What if we had not only personal, mobile air quality data but we *also* knew the genetic susceptibility of the person with the sensors? This is a truly Lagrangian system, tracking both individual pollutants and the characteristics and responses of the receptors. Let's assume, for example, that people know they are genetically more susceptible to lung cancer from fine particulates and their sensors tell them they are entering a high particulate area. Does this rise to the level of moving to the nuisance?

Does this have implications for EPA regulation? A Lagrangian frame of reference suggests that the most efficient means to protect people from the environmental harms of modern society may be to change the behavior of *both* polluting sources *and* receptors. One can then well ask whether we should be regulating the polluters for the 99.5% sensitive population when we can demonstrate that none of that 0.5% live in the target area or could easily avoid it. Put simply, could EPA become not a regulator of sources, but a regulator of individual movement? Through this vantage, environmental law demands more explicit sociological and ethical considerations than the more traditional scientific and economic vantages.[115]

114 CENTERS FOR DISEASE CONTROL AND PREVENTION & U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT, HEALTHY HOUSING REFERENCE MANUAL 5-1 (2006), *available at* http://www.cdc.gov/nceh/publications/books/housing/housing_ref_manual_2012.pdf.

115 For a discussion of how monitoring personal information raises privacy issues, see generally Katrina Kuh, *Personal Environmental Information: The Promise and Perils of the Emerging Capacity to Identify Individual Environmental Harms*, 65 VAND. L. REV. 1565 (2012).

The implication of this thought experiment is that changing technology can facilitate changing reference frames, and in so doing, change basic notions of duty and causation. Given recent developments, this could soon be a very real scenario. It is too early to know if, as C.J. feared,[116] such developments will turn our legal worlds upside down. But at a minimum it will challenge our basic notions of the settled contours of environmental law.

116 *The West Wing*, *supra* note 6.

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