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Dynamic interactions of neurological states: Reflections on implications for learning engineering

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Abstract

Point of view: Each of the creators is a university researcher or professor of engineering; Linda is Eurasian/Latina and transgender, with a background in metallurgical engineering and materials science and engineering acquired in United States institutions; Nicola is a cis-gender woman, with a background in environmental engineering and educational research, who moved to the U.S. from Australia after completing her doctoral studies. Ruth is a cis-gender woman, born and raised in the U.S., of Western-European ancestry, with an educational background in biology and educational psychology. Although these identities do not represent the totality of what has shaped our view, we believe they have strongly influenced our experience of the field of engineering.

Value: This piece raises what we believe are important questions about our current education for engineers that are arising from the implications of recent neuroscience findings.

Summary: According to the National Society of Professional Engineers’ (NSPE) creed, engineers are members of a profession who “dedicate [their] professional knowledge and skill to the advancement and betterment of human welfare.” Although the educational process of developing one's engineering cognition has regional differences, by and large it derives from a core content that requires mechanical reasoning about the physical world. Results emerging from cognitive neuroscience imply that regions of the brain that function for mechanical reasoning have antagonistic relationships with regions that are active during moral and social reasoning, and vice versa. Their findings raise important questions for engineering education: How are we ensuring the balanced cognitive development necessary for the social and moral reasoning required of our profession? Can integrating Phenomenal activities with Physical activities serve holistic developmental aims? Can we envision integrative alternatives to present incarnations of engineering curricula? The intent of this paper is to offer reflections and speculations on the implications of these emerging neuroscientific findings on the dynamics of brain functioning for learning engineering.

Introduction

Over 20 years ago, renowned systems theorist Ervin Laszlo wrote about the limitations of specialization, or “atomistic” (versus “systems” or “integrative”) thinking:

“The unfortunate consequence of... speciality barriers is that knowledge, instead of being pursued in depth and integrated in breadth, is pursued in depth in isolation. Rather than getting a continuous and coherent picture, we are getting fragments - remarkably detailed but isolated patterns.” (p. 2-3, Laszlo 1996)
It would seem that Laszlo’s call for the integration of knowledge was ahead of his time, for it is only now that there is substantive support for such work. One example is a recent Dear Colleague Letter (DCL) published by the National Science Foundation, entitled “Growing Convergence Research at NSF,” which outlines a vision for “the deep integration of knowledge, techniques, and expertise from multiple fields to form new and expanded frameworks for addressing scientific and societal challenges and opportunities” (National Science Foundation 2017). The need for convergence approaches is also underscored in a report published by the National Academies, “A New Vision for Center-Based Engineering Research” (National Academies 2017). The work we present in this paper sits squarely in this new domain of convergence research. Specifically, we offer reflections on the potential to integrate neuroscientific studies with engineering education research.

We are not the first scholars to consider the implications of neuroscience for the social sciences. As discussed by Jack et al. (2017), the use of neuroscientific findings and theory in the field of organizational behavior has increased rapidly over the past 15 years. More recently, scholars are beginning to explore connections between neurobiological processes and learning environments (Owens and Tanner 2017). In this paper, we offer speculations and reflections on possible implications of a study by Jack et al. (2013) that indicates an antagonistic relationship between the region of the brain that is active in mechanical reasoning and the region that is active in moral and social reasoning.

Our goals in writing this paper are twofold. First, we wish to begin to explore the questions that lie at the convergence of the neurosciences and engineering education. We hope to achieve this goal through writing this paper and then engaging experts in the neurosciences to serve as Reflectors on this article. Second, we wish to catalyze a conversation in the engineering education community, and education community more generally, on possible neurological implications of educational programs that focus predominantly on mathematics and science (i.e., mechanical reasoning) and contain implicit judgments regarding the relative (lesser) value of “softer,” social aspects of students’ professional formation (Cech 2014).

What follows is a brief summary of the Jack et al. (2013) article that served as the basis for our exploration. First, we describe functional magnetic resonance imaging (fMRI)—how it works and what it measures, and current understandings of those measurements. We then summarize the Jack et al. (2013) article and provide reflections on two themes: (1) the relationship between structure and behavior, and (2) implications of inhabiting and managing neurological states.

**Primer on fMRI**

Before we begin our discussion of the implications of Jack et al. (2013)’s interpretations of their findings, we explain fMRI, the technique on which their findings are based. Those who are not interested in this detail may want to skip to the section titled, *Summary of Jack et al. article: Mutually antagonistic neurological stances.*

**What is fMRI measuring?**

Functional magnetic resonance imaging (fMRI) has emerged over the last 20 years as a technique used to study the function of the human brain, primarily focused on changes in Blood Oxygen-Level Dependent (BOLD) signals that are associated with neuron activation. As in MRI, fMRI generates magnetic field pulses, thousands of times the strength of the earth’s magnetic field, as probes that pass through the tissue of the subject’s brain. These probes are spatially arranged in known patterns and directed through a two-dimensional slice of the brain as conceptually depicted in Figure 1.

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1. A layman’s description of MRI can be found in Berger (2002).
Because protons in the nuclei of all atoms have a tiny magnetism, their magnetic orientation aligns with the probe in accordance with their magnetic property. A second, radio frequency (RF) electromagnetic field pulse disrupts the magnetic alignment of the protons in the nuclei of atoms of interest. When the RF pulse is off, these magnetic orientations recover to their original alignment with the magnetic probe field. In doing so, they induce a small electromagnetic pulse—an echo—of the original pulse. In this way, the data collected during an fMRI are a series of echoes created by the protons in the nuclei of atoms of interest.

The echoes collected in fMRI are blood oxygen-level dependent. The theory is that activated neurons uptake oxygen from blood while they are functioning; their surrounding microvasculature senses the activity and “dilates in order to divert more oxygenated blood to the active area.” (p. 202, Marina et al. 2016). Thus an increased BOLD signal of each volumetric pixel—or voxel—is inferred to indicate involvement of the adjacent neurons. However, we note that this firing does not specify functionality; for example, a firing neuron can be inhibitory in its effect.

The spatial pattern of the magnetic field probe is used to analyze the echoes, producing a 2-D map of the intensity of BOLD signals originating from in the 2-D brain slice. The slices of 2-D maps of BOLD signals from the voxels are mathematically combined into a 3-D representation. This BOLD representation is inferred to indicate the activation (or deactivation in some cases) of neurons associated with cognitive tasks performed by the subjects during the fMRI study; positive BOLD signals above the resting state are presumed to indicate neuron firing.

Converting the BOLD signals to brain images

Generally, a number of assumptions go into the mathematical manipulations of the raw echo data to assign an event-related BOLD signal to a voxel. This often includes a presumed mathematical model of how the BOLD signal changes when the neuron is activated in response to the test stimulus. However, in Jack et al. (2013), they assessed the difference in fMRI signals induced by the stimulus task—this was a direct measure that did not involve a presumed model of the BOLD signal.

Prior to analyzing the fMRI data, the raw data is altered to account for noise, movement, and other spurious signals, which can constitute 90 percent of the overall signal (Friston)

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2. Typical spatial resolution is a cube with side dimension 1-1.5 mm.
3. The mathematics of the analysis is the Fourier transform. It is conceptually explained in Elster (2018). A more detailed description can be found in Gallagher, Nemeth, and Hacein-Bey (2008).
4. For a detailed explanation of the math, see Kumar, Welti, and Ernst (1975).
5. For a detailed mathematical description of how the event-related BOLD data is extracted, see Friston et al. (1998).

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Figure 1. Conceptual image of a 2-D slice that is probed during fMRI. The magnetic field line pattern is controlled. It enables the spatial location (i.e., the specific video pixel, or “voxel”) of the originating fMRI signals in the brain.
And, in the case of comparing differences across subjects, corrections are made for differences in brain size and shape from subject to subject. The process of inferring differences between subjects’ responses to stimuli above the resting state employs statistical inference methods. These methods evaluate the probability that the differences in the BOLD signals are due to something other than random variation. The statistically-significant magnitudes of change in BOLD signals of a voxel relative to those around it are on the order of 1 percent in the case of the Jack et al. (2013) research.

With so many assumptions and inferences required to go from raw data to a brightly colored image as seen in Figures 2 or 3, it is useful to keep in mind that fMRI results are representations based on our best models—models that are conditioned by what we seek to understand. And there are cases when the same neural image was used as evidence to bolster opposing arguments about the condition of a brain-injured patient (Koch 2012). Additionally, while our best science can discern the signs of neurological activity presuming the accuracy of the BOLD model, it cannot differentiate between the type of activity—whether it is functioning to inhibit or activate the particular brain region (Owens and Tanner 2017).

Meaning of the brain images

Jack et al. (2013) represented the statistically-significant differences in 3-D BOLD results onto a commonly-used brain atlas (Talairach and Tournoux 1988). This atlas includes a tag for each voxel that indicates its presumed anatomical region of the brain (Lancaster et al. 1997). The process of assigning an anatomical region requires judgment at border regions. The colored “blobs” seen on these atlases, for example Figure 3, with red being the end of one spectrum and blue being the other, underscore two principles of brain functionality: specialization and integration (Friston 2003). Cells in the brain are apparently specialized for certain cognitive functions. When needed, these regions of functionality simultaneously connect (i.e., integrate) in a network.
Summary of Jack et al. 2013 article: Mutually antagonistic neurological stances

Jack et al. (2013) proposed that various fMRI data, including theirs, suggest a model of at least three “cognitive stances”: Physical, Phenomenal, and Intentional (see Figure 4). Each of these stances exhibits a network of neurological activation, evidenced through blood oxygen-level dependent fMRI signals, in response to a specific task. These networks are distinct physical regions of the brain; the “analytic network [i.e., Physical stance] is slightly left dominant and the empathic network [i.e., Phenomenal stance] slightly right” (Jack 2018). Jack et al. (2013) inferred the networks to be responsible for the cognitive function associated with their activation by the experimental task stimulus (see Appendix 1); however, they experimentally addressed only the Physical and Phenomenal stances.

The Physical stance shows activation during reasoning about objects in the physical world and their mechanical cause-and-effect relationship; others have named this cluster of firing neurons the Task Positive Network (TPN). The Phenomenal stance is active during reasoning involving relationships between people (“moral concern”), emotion, and experience; others have called this same neural network the Default Mode Network (DMN). Both
networks, or stances, show a mutually inhibitory response to one another akin to a see-saw, such that when one is activated, the other is deactivated. We note that these studies involve highly-controlled environments with tasks designed to isolate and activate only the hypothesized networks.

Jack et al. (2013)'s proposed Intentional stance is "an emotionally disengaged form of social cognition," which recruits functions from both Physical and Phenomenal stances to "guide a deliberate plan of action" (p. 396). Thus, they model these three cognitive stances as having a relationship to one another as depicted in Figure 4, where the Physical and Phenomenal are mutually inhibitory during their activation and the Intentional provides access to both Physical and Phenomenal during its cognitive work of planning in ways that dehumanize people. Jack et al. posited that the Intentional stance activates the neural network associated with mechanical reasoning without emotion. The Intentional stance was originally identified by Gallagher et al. (2002) to describe mentalizing about the mental states of others. Jack et al. noted their hypothesized Intentional stance is consistent with studies involving cognition that objectifies people, and consistent with patterns involving deception (Christ et al. 2008). Although salient, yet outside the scope of this paper, Jack, Dawson, and Norr (2013) explored their hypothesis that the Physical stance (i.e., TPN) is activated in cognition about inanimate objects in a separate study. Jack, Dawson, and Norr (2013) identified “distinct and overlapping neural signatures associated with mechanistic and animalistic dehumanization” (p. 327): “the perception of humanness is associated both with increased activity in the DMN…and with decreased activity in the TPN.” These results support their hypothesis that the Physical stance is activated, and the Phenomenal stance deactivated during dehumanizing perceptions of people. In this paper, we focus on the relationship between the Physical and Phenomenal stances that were empirically investigated in Jack et al. (2013).

With reference to the antagonistic relationship between the Physical and Phenomenal stances, we provide this quote from Anthony Jack, who served as a reflector for this submission (Jack 2018):

"The fact that attention demanding analytic tasks, such as mechanical reasoning, tend to deactivate brain regions essential for social, emotional and moral cognition might be fairly characterized as one of the most clearly established findings in cognitive neuroscience. This work is broken down in greater detail in many of my more recent articles. In addition, there are behavioral studies by researchers with no interest in the brain which clearly show that analytic thinking negatively impacts ethical thinking and behavior. These studies provide powerful convergent evidence, since they were in no way motivated or informed by neuroscience – they are observations about patterns of human behavior made by behavioral economists and psychologists without reference to the underlying neural mechanism which explains why they occur. Since the authors do not appear to be aware of much of this literature, large parts of the article are quite tentative in tone. Nonetheless, in the section titled "Reflections on implications for learning engineering", the authors provide an excellent and incisive summary of exactly why our understanding of the brain should be a serious cause for concern for those who are concerned about educating ethical engineers."

**Reflections on implications for learning engineering**

**Theme 1: The relationship between structure and behavior**

It is well-known that our actions in the physical world can alter our biology; consider exercise and its effects. It goes without saying that our behavior, such as weightlifting, can alter our structure, such as muscle mass. In turn, structure determines behavior—greater muscular strength produces a greater ability to do things that require muscles. Structure and behavior exist in a reinforcing relationship to one another, as shown in Figure 5. In
biological terms, this relationship represents a self-replicating, or autopoietic, system. An autopoietic system is a system which creates the conditions for its own replication (Varela, Maturana, and Uribe 1974).

Figure 5. Causal loop diagram. Structure reinforces (R) behavior and vice versa.

By analogy, the activity of learning similarly results in neurological restructuring and strengthening of synapses. Owens and Tanner (2017) described this learning process at the neurological level and provided insights as to how the quality of a learning environment could influence this process. For example, they explained how punitive classroom testing structures, such as surprise quizzes, can undermine the biochemical process of learning. Specifically, the process of reinforcing or making new synaptic connections between neurons is mediated by chemicals; the learning process can therefore be inhibited by other chemicals, such as cortisol, which the body releases when under stress or in a state of fear.

The Jack et al. (2013) findings suggest that the neurological basis for reasoning about the physical world is distinct from and in tension with the neurobiology activated for reasoning involving social and moral dimensions. Combining their result with the self-replicating nature of learning, the possibility emerges that cognitive behavioral practices, too, can build and reinforce particular structures at the neurological level. That is, can we alter our own neurobiology by simply thinking—might this “doing” (i.e., thought) affect our “being” at the molecular/cellular level? Supporting evidence of this possibility can be found in several other studies. For example, practitioners who adopted a daily, 30-minute practice of managing one’s attention exhibited increases in the concentration of gray matter of their brainstems over the course of eight weeks (Singleton et al. 2014); They also reported greater psychological well-being. And the recent book, Altered Traits (Goleman and Davidson 2017), explores how meditation changes our biology in greater depth.

If we connect the dots of these separate studies and consider their implications for engineering, one possibility is that practices of chronically and disproportionately activating the neural networks of the Physical stance, as typically required in core engineering courses, strengthen the Physical stance neuronal connections while simultaneously weakening the cognitive abilities of the Phenomenal stance—moral, emotional, and social reasoning. This tendency is captured in the aphorism (Shatz 1992), “Neurons that fire together, wire together.”

Further, is it also possible that our “being” in turn creates our “doing”? If the sustained “doing” of the cognitive Physical stance often required of engineering students strengthens these TPN neurological structures, would these same structures then condition one’s subsequent thought and action? That is, is it possible that the “doing” that activates the Physical stance gives rise to the Physical stance as a preferred, more accessible cognitive pathway? In other words, could the act of sustained use of the TPN create the conditions for its own re-creation? Jack et al.’s results suggest that the DMN is inhibited during the activation of the TPN. By extrapolation, such practices could condition people to unconsciously apply mechanical reasoning to situations where social or moral reasoning would be better fit for
the purpose. In the extreme, could a singular overemphasis on the Physical stance unintentionally create a tendency for people to habitually objectify people (i.e., utilize the TPN) rather than empathize with them (i.e., utilize the DMN)?

To be sure, these conjectures are provocative. However, is it possible that laboratory science is enabling us to see weak signals of the dynamic interplay between our cognitive actions and our state of being? Do these conjectures explain anything of the patterns we see, such as an observed overrepresentation of engineers in terrorist cells (Gambetta and Hertog 2007), and decreased interest and capacity for moral reasoning observed in engineering students as they progress through their curricula relative to their non-engineering peers (Cech 2014; Rasoal, Danielsson, and Jungert 2012)?

Theme 2: Implications of inhabiting and managing neurological stances

The Jack et al. (2013) article underscores the possibility that what we call our state of being is coupled to activation of one or more neurological networks. This raises the opportunity of building the ability to sense and consciously inhabit a particular state (or neurological “stance”, as identified by Jack et al.), presuming that our state conditions our actions. This correlation between one’s state and actions is the basis of Lakoff’s “frames.” He asserted,

“One of the major results in the cognitive and brain sciences is that we think in terms of typically unconscious structures called ‘frames’: These structures are realized in neural circuits in the brain. All of our knowledge makes use of frames, and every word is defined through the frames it neurally activates. All thinking and talking involves ‘framing.’ And since frames come in systems, a single word activates not only its defining frame, but also much of the system its defining frame is in. Moreover, many frame-circuits have direct connections to the emotional regions of the brain. Emotions are an inescapable part of normal thought... In short, one cannot avoid framing. The only question is, whose frames are being activated—and hence strengthened—in the brains of the public.” (pp. 71-72, Lakoff 2010)

Our ability to consciously inhabit the Physical or Phenomenal stance may enable us to make conscious choices about which reasoning to draw upon, if simultaneous reasoning about physical and social relationships are indeed mutually exclusive. Jack et al. (2013) referred to the Intentional stance as having access to an emotionless version of the Phenomenal, citing a study where people were being objectified and manipulated from within the Intentional stance; whether the Intentional stance offers simultaneous access to physical reasoning and moral reasoning involving principles (versus emotions) is not clear.

As we speculate on possible implications of inhabiting the Physical more than the Phenomenal stance, we note the similarity and differences of the tasks participants completed in the Jack et al. (2013) study and those that engineering students typically engage in (see Appendix I). As with any experimental findings, it is tempting to generalize results to situations that bear no resemblance to the carefully controlled conditions of the laboratory setting in which the findings occurred. However, the dynamic that sustained practice of engaging an isolated neurological stance strengthens the involved neurological pathways is well-established; simply put, creating this robust neurological structure is the purpose of learning. It is the possibility that developing a robust Physical stance for engineering simultaneously undermines the neurological development needed for social and moral reasoning that gives us pause. We are also alert as we consider the potential risk of developing a singularly-robust cognitive strength, captured in the aphorism, “If one only has a hammer, everything looks like a nail.”

These reflections have led us to ask the following questions:

- How are we ensuring the balanced cognitive development necessary for the social and moral reasoning required of our profession?
- Have we out-sourced this responsibility to colleagues in the liberal arts? If so, is the result as intended?
Is it our responsibility to provide engineering students with the means for self-awareness and balance?

Can integrating Phenomenal activities with Physical activities serve holistic developmental aims?

Can we envision integrative alternatives to present incarnations of engineering curricula?

As an example, The Engineering Management Institute advocates meditation to strengthen mindfulness—a capacity shown to bear a number of other attributes desirable for effective engineering, such as a strengthened ability to sustain positive, healthy relationships (Singleton et al. 2014).

Beyond the neurological stances identified in Jack et al. (2013) article, it is reasonable to conjecture that there are a multiplicity of states of being, and by inference, a multiplicity of neurologically-activated states. Owens and Tanner (2017) raised the possibility of designing learning environments to facilitate neurological states that are more conducive to learning (i.e., synaptic formation and reinforcing). As mentioned above, a state of "fight or flight" or fear, because it causes the release of cortisol, chemically inhibits our ability to build the neurological connections that are the basis of "knowing." On the flip side, Owens and Tanner proposed that during states of motivation, dopamine is released, which "boosts" the ability for the synapses to make new connections (p. 6). What would engineering education look like if we designed courses to more equitably activate the Physical and Phenomenal stances? Could, for example, teaching core engineering courses like thermodynamics in ways that integrate moral considerations not only improve social and moral reasoning but also provide a more complex neural network to improve students' recall of the material?

Although we have found the ideas proposed by Jack et al. (2013) to be intriguing, we add a note of caution lest we mistakenly generalize the results from these highly-controlled laboratory situations to that of all situations. Jack et al. similarly issued caution to those unfamiliar with the nuances of brain studies (Jack et al. 2017). Further, we note that the neuroscience studies we have referenced here, although differing in their particulars, share an objectivist epistemology; none account for the emergent nature of consciousness, where the "mind" is modeled as a holistic co-arising of sensory information from the body and recollection of past experience (Siegel 2010). Through the frame of dynamic complexity, would the fMRI patterns of Jack et al. (2013) occur to mean something different? This is a much larger conversation that is not addressed in our paper, yet we point to it in the spirit of considering the limits of objectivist models.

Summary

In this paper, we have offered a number of reflections about possible connections between fMRI findings presented by Jack et al. (2013), the traditional process of developing engineering competency, and systemic patterns in engineering education. To be certain, our efforts to find points of convergence between neuroscientific research and well-recognized challenges in engineering education are speculative.

We also note that neuroscience is in its infancy, and there is much to learn about the intricacies of the brain. And there is even more to be done before neuroscience findings can be confidently linked to a highly complex activity like engineering practice if we are to use the statistical definition of confidence. However, we offer these speculations as potential weak signals in a system of dynamic complexity; are these findings pointing to a pattern that is yet to be confidently described in the same way that climate simulations in 1972 (Meadows et al. 1972) were? We invite others to enter this inquiry with us.

Acknowledgments

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Chanel Beebe, Wilella Burgess, and Anthony Jack, whose input can be found at Murmurations. We encourage readers to particularly consider the reflections of the neuroscientists Anthony Jack with Jared Freedman included in the journal’s prepublication page notes; they extend the ideas of this paper.

Linda Vanasupa, Nicola Sochacka, Ruth Streveler, 2018

References


Appendix

Descriptions of ecologically valid tasks designed to engage rich mechanical ("Physical") or social ("Phenomenal") state representations. These descriptions are taken directly from Jack et al. 2013 and included here so the reader can understand the nature of the tasks used in the study relative to tasks performed in engineering courses. Images are reprinted from Jack et al. 2013 with permission from Elsevier.

<table>
<thead>
<tr>
<th>Phenomenal</th>
<th>Physical</th>
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<tbody>
<tr>
<td>&quot;The social videos depicted conversations between two individuals who often misunderstood each other. The questions concerned one actor's belief about the emotional state of the other actor.&quot; (p. 387)</td>
<td>&quot;The mechanical videos were clips excerpted from the Video Encyclopedia of Physics (Education Group and Associates, 1995). The questions were counterfactuals that tested understanding of the illustrated physical principle.&quot; (p. 387)</td>
</tr>
</tbody>
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**Does he think that she is angry?**

| - | - |

**Would water flow if there was a large hole in the tube?**

| - | - |

"The social texts were adapted from a prior study (Saxe and Powell, 2006) and described scenarios in which at least one protagonist had a false belief. The questions tested understanding of this false belief." (p. 387)

Sue sneaks into the kitchen, gets on a chair, and puts her little hand into the candy jar to grab a heaping handful of treats. As she walks out of the kitchen, she smirks at the thought of disobeying her mother, who told her not to have any more sweets. But as she brings the candy to her mouth a sinking feeling of guilt comes over her. She knows the candy is being saved for a party tomorrow. Conflicted, Sue finally decides to put the candy back and not eat any.

Does Sue's mother know that Sue has tried to sneak some candy?

| - | - |

Will the flare land in front of the snowmobile?

| - | - |

"The mechanical texts described puzzles similar to and adapted from examples found in popular scientific puzzle books. The questions asked participants to predict what would happen next." (p. 387)

A snowmobile is cruising over plains of white, hard packed snow. The driver steers the snowmobile in a straight line while at the same time pointing a flare gun straight into the air. The driver pulls the trigger, firing a bright flare into the air. Then, the driver immediately slams on his brakes. The flare flies through the air and then lands in the snow.

| - | - |

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