Introduction to Motifs in Physics

These notes[1] are part of a series concerning "Motifs in Physics" in which we highlight recurrent concepts, techniques, and ways of understanding in physics.

The Recurrent Ideas in Physics

In *Bioglogical Physics: A Search for Principles*, William Bialek distinguishes physics from biology by asserting that physics, although quite diverse in subject matter, is unified by a commonality of approach. That is, the mathematical and deductive structure of physics in which physical predictions are derived from principles exists as surely in condensed matter physics as it does in cosmology, and thus all physicists (or, at least all theorists) have a common set of practices and general methods for understanding the world even if what they are attempting to understand is unique to their sub-discipline. Out of this common set of practices arise ideas and approaches to understanding nature which repeatedly appear throughout physics. In this set of notes, we outline and discuss eight recurrent ideas which we term "motifs in physics". The goal is to show through many disparate examples that the sub-disciplines of physics although extensive and multifarious are unified by the larger scale ideas they uncover in their study of the physical world.

A comment about the title of this work: Why do we use the slightly more technical term "motif" rather than the more easily accessible term "theme"? The choice boils down to precision and humility. By its literary usage, the "theme" in a work concerns the central idea or message of the writing. However, we humans, striving everyday to build new and better understandings of our physical world, cannot be so presumptuous as to believe that we currently know "the central ideas" behind physics. A basic knowledge of science history discourages such speculation: Go back a little more than a century, and any such themes scientists would have reasonably put forward would seem incredibly limited today.

But a "motif" in a work, as simply a recurrent idea or image in the piece, is less sweeping. It does not presume we can ever know the purpose of the creator, but it does suggest we can intuit his or her constant preoccupations. For example, physicists at the end of the 19th century would have been proven wrong in a few decades if they had claimed that the theme of physics concerned finding the deterministic dynamics of all systems, but they would still be correct if they labeled such determinism as a motif in physics. Thus as a hedge, we term these recurrent elements "motifs in physics."

Inspirations

This work is inspired by a blog post ("Five Under Appreciated Ideas in Undergraduate Physics") by Philip Tanedo. Also, in my attempt to qualitatively discuss important and complex ideas in physics, this work seeks to match the spirit of Feynman's *Six Easy Pieces*, and *Six Not So Easy Pieces*.

Preview of The Motifs

The eight themes we will discuss in the subsequent notes are as follows.

- **Evolution and Time:** All physical theories are, in a way, concerned with how physical systems evolve (i.e., change) in time. And in all of these theories, time appears in more or less the same way with no clear explanation of what precisely it is. This both suggests that time is pivotal to physics and that we do not understand time very well.
- **Linearity and Solubility:** Many of the laws of physics can be approximated as linear equations. This allows us to solve them exactly and treat non-linear corrections as perturbations. Related Ideas concern

[1] Inspired by a blog post by Philip Tanedo

the ubiquity of complex exponentials in defining the dynamics of system, the relevance of superposition, and the utility of perturbation theory.

- **Indeterminacy and New Phenomena:** Making systems probabilistic introduces new interactions which are not present when the system is deterministic
- **Importance of Geometry:** Euclidean geometry was the first mathematical field to make the study of the natural world deductively rigorous. Since then, geometry has become an important mathematical and conceptual tool for developing physical theories.
- **Symmetry and Simplicity:** Symmetries in a physical system simplify our study of the system by allowing us to ignore parts of the system which do not change.
- **Duality and Description:** There are often two related and equivalent ways to understand or describe a physical system and each way complements the other. These two ways comprise what is known as a "duality".
- **Scale and Effective Theory:** All physical theories exist on a certain length scale and each theory is connected to a single theory at a larger length scale but many other possible theories at smaller length scales. The larger length scale theory is called an "effective theory" of the smaller length scale theory.
- **Large Numbers and Emergent Phenomena:** In other words, many-particle systems often have qualitatively different properties (termed "emergent properties) and thus often require different quantitative models from the properties and models of single-particle systems.