Systems Thinking for Thermodynamics

Thermodynamics is a branch of science that is particularly relevant to our upcoming, March and April, Systems Thinking Ontario discussions. On March 15th, Rose K. will lead a discussion of *The Circular Economies* and, in April, David M. will lead us in discussion of *Non-equilibrium Thermodynamics*. Central to Thermodynamics are fundamental concepts like, "*Heat*", "*Temperature*", "*Work*" and "*Energy*" and how these are generated, consumed or transformed by *any physical system*. It was the science of Thermodynamics that motivated creative new mathematical approaches used to construct an intricate and precise bridge of understanding between very small-scale systems (like molecules, atoms and their constituent parts) and very large-scale systems (like galaxies, quasars and black holes). It would be hard to overstate the importance of Thermodynamics in understanding any physical system. Pretty much *every* physical science – if you delve deep enough or, push it far enough - will look to the science of Thermodynamics for explanation and understanding.

Origins of a new Science

Thermodynamics finds its origin in debates concerning the possibility of a perfect vacuum and regarding the true nature of *heat*. Aristotle, striving to comprehend the order of Nature in 350 BCE wrote in his, *Physics*:

> *When we have determined the nature of motion, our next task will be to attack in the same way the terms which are involved in it. Now motion is supposed to belong to the class of things which are continuous… Besides these, place, void, and time are thought to be necessary conditions of motion…*
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> *The void is thought to be place with nothing in it. The reason for this is that people take what exists to be body, and hold that while every body is in place, void is place in which there is no body, so that where there is no body, there must be void…*
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> *Let us explain again that there is no void existing separately, as some maintain…*

Aristotle's conclusion, that there can be no void – no place containing absolutely *nothing* - was later restated as "*Nature abhors a vacuum*". Generations of experimentation brought us eventually to the work of Galileo Galilei and Evangelista Torricelli and, building on their efforts, Blaise Pascal's "*New Experiments with the Vacuum*" (1647), which developed our understanding of *Pressure* and demonstrated the possibility of a vacuum. A short time later, Robert Boyle formulated the first physical law to be expressed in the form of an equation describing the dependence of two variable quantities – Boyle's Law: [Pressure] x [Volume] = a constant. Applying the knowledge of his time, Isaac Newton tried to explain this relationship, but failed. Then; in 1738, Daniel Bernoulli theorized that gases consist of great numbers of molecules moving in all directions, that their impact on a surface causes the gas pressure that we feel, and that what we experience as heat is simply the kinetic energy of their motion.

Atoms and Molecules, *Statistically Speaking*

In the later part of the 19th century, Rudolf Clausius published foundational papers in the science of Thermodynamics wherein he was the first person to introduce the concept of Entropy. He concludes his landmark 1865 paper with the following summary of the first and second laws of thermodynamics:

- The energy of the universe is constant.
- The entropy of the universe tends to a maximum.

After reading Clausius' papers, James Clerk Maxwell formulated the first-ever statistical law in physics quantifying the velocity of molecules. In his article of 1873 entitled, "*Molecules*", Maxwell states: "*we are told that an 'atom' is a material point, invested and surrounded by 'potential forces' and that when 'flying molecules' strike against a solid body in constant succession it causes what is called pressure of air and other gases.*" With his classic book, "*Theory of Heat"* (1871) Maxwell joined the chorus of scientists building on the idea that heat has something to do with matter in motion. The Preface to Maxwell's, "*Theory of Heat"* begins:

> *THE AIM of this book is to exhibit the scientific connexion of the various steps by which our knowledge of the phenomena of heat has been extended. The first of these steps is the invention of the thermometer, by which the registration and comparison of temperatures is rendered possible. The second step is the measurement of quantities of heat, or Calorimetry. The whole science of heat is founded on Thermometry and Calorimetry, and when these operations are understood we may proceed to the third step, which is the investigation of those relations between the thermal and the mechanical properties of substances which form the subject of Thermodynamics. The whole of this part of the subject depends on the consideration of the Intrinsic Energy of a system of bodies, as depending on the temperature and physical state, as well as the form, motion, and relative position of these bodies. Of this energy, however, only a part is available for the purpose of producing mechanical work, and though the energy itself is indestructible, the available part is liable to diminution by the action of certain natural processes, such as conduction and radiation of heat, friction, and viscosity. These processes, by which energy is rendered unavailable as a source of work, are classed together under the name of the Dissipation of Energy…*

Subsequent contributions of Ludwig Boltzmann and then Albert Einstein, in 1905, finally left no doubt of the reality of atoms and molecules. The ensuing, *Kinetic Theory* describes a gas as a large number of submicroscopic particles (atoms or molecules), all of which are in constant rapid motion that has randomness arising from their many collisions with each other and with the walls of the container. Kinetic theory explains macroscopic properties of gases, such as pressure, temperature, viscosity, thermal conductivity, and volume, by considering their molecular composition and motion. Statistical Thermodynamics models these large systems of atoms and molecules – to relate the microscopic properties of individual atoms and molecules to the macroscopic, bulk properties of materials that can be observed on the human scale, thereby explaining Classical Thermodynamics as a natural result of Statistics, Classical Mechanics, and, eventually, Quantum Mechanical theories of today.

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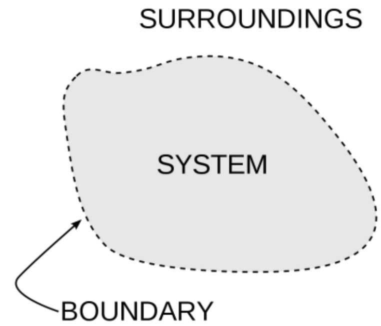

An important concept in thermodynamics is the, *thermodynamic system*, which is a precisely defined region of the universe under study. Everything in the universe *except* the system is called, "*the surroundings*". A system is separated from the remainder of the universe by a boundary. Exchanges of work, heat, or matter between the system and the surroundings take place across this boundary. We can conceive of the boundary surrounding a single atom resonating energy, as did Max Planck in 1900; or, as a body of steam or air in a steam engine, such as Sadi Carnot defined in 1824 – the definition of the Thermodynamic system is selected as most suits the nature of the inquiry being undertaken.

As time passes in an isolated system, internal differences of pressures, densities, and temperatures tend to even out. A system in which all equalizing processes have gone to completion is said to be in a state of thermodynamic equilibrium. Once in thermodynamic equilibrium, a system's properties are, by definition, unchanging in time. Systems in equilibrium are much simpler and easier to understand than are systems which are not in equilibrium. When a system is at equilibrium under a given set of conditions, it is said to be in a definite *thermodynamic state*. And; to transform from one state to another, the system undergoes a *thermodynamic process*.

Earth Systems and Living Systems

Our world seems to offer infinite energy and resources; however, other than the constant influx of solar energy, and gravitational oscillations of the moon, the energies and resources available to us are only those we find here already, on planet Earth. It is often remarked that fossil fuels – the dissembled hydro-carbons of ancient flora and fauna - are stored sunlight. And; we are depleting those stores with no way of operating our modern, industrial civilizations directly on renewable sources. And; advanced technologies for achieving a clean, "Green" energy system rely on *extremely rare* elements such as Lithium, Platinum, Tellurium, Neodymium – which we presently plow under at landfill sites around the world.

So, at the March 2017 session of Systems Thinking Ontario, when we talk about the Circular Economies, there is a profound level at which we are really talking about *patterns of thermodynamic processes* that steer our Earth system – where we live – from it's *present state* to its *future state*. As we set about powering-up the Circular Economy, we're faced with an abundance of opportunities for creative product, service and systems design. And; it may do us well to appreciate that Maxwell's words of 1871, might just as well describe people, social systems and industrial processes: "*The whole of this part of the subject depends on the consideration of the Intrinsic Energy of a system of bodies, … the form, motion, and relative position of these bodies. Of this energy, however, only a part is available for the purpose of producing mechanical work, and though the energy itself is indestructible, the available part is liable to diminution by the action of certain natural processes.*"

David M's discussion, in April, will address *Non-Equilibrium Thermodynamics,* and will expand our appreciation for the dazzling variety of "*engines*" driving our planet's physical, ecological and biological systems. Maybe David will even answer the riddle of how it is that, *Life* itself– which seems to contradict the second law of thermodynamics – nevertheless, arises.