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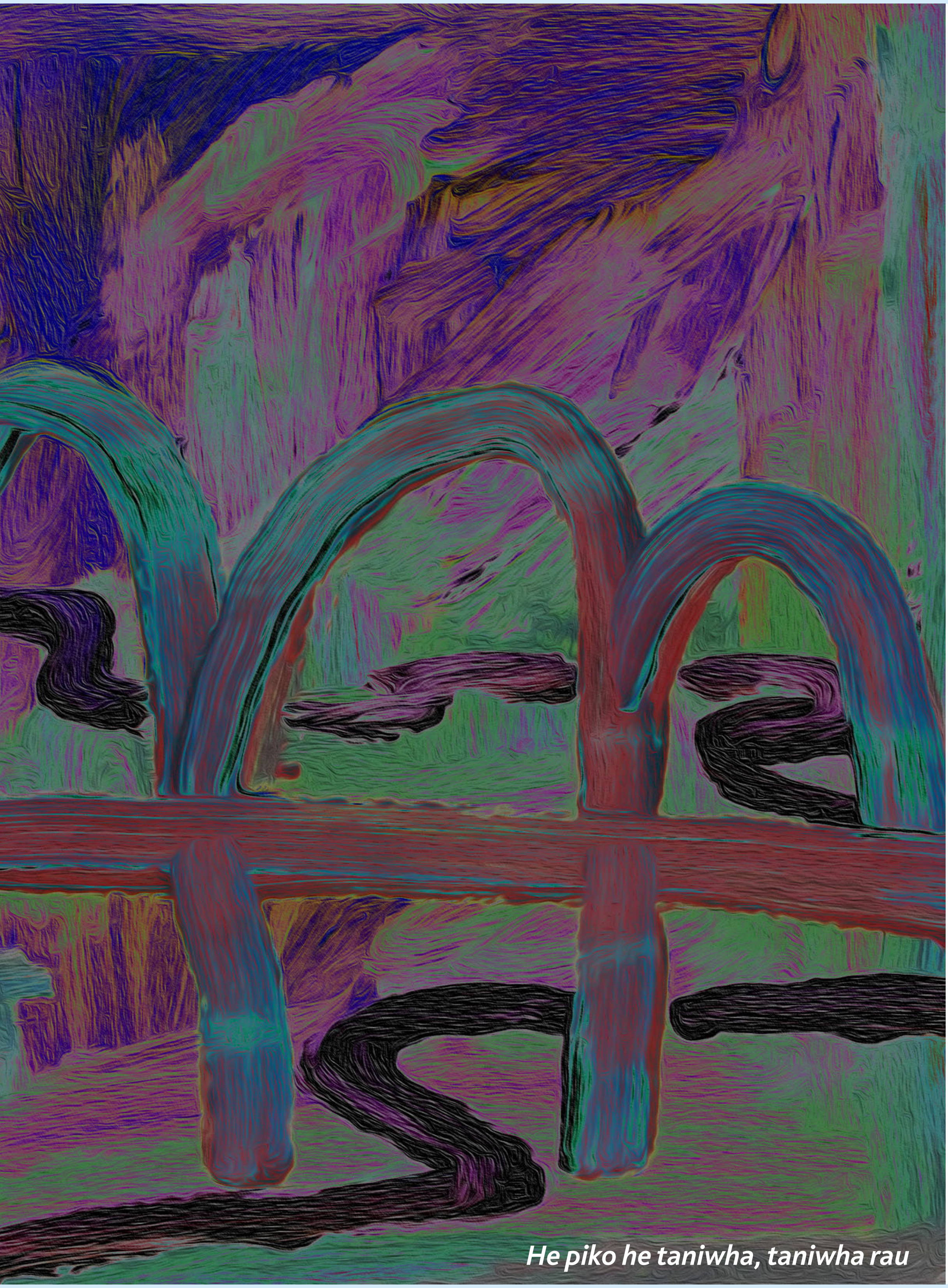


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# Waikato Journal of Education
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# Waikato Journal of Education

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# Forging the jewels of the curriculum: Educational practice inspired by a thermodynamic model of threshold concepts

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## Abstract

*In this article, a thermodynamic view of learning is taken. Internalisation of a threshold concept, the so-called act of "passing through the portal", is viewed as a phase change. It is postulated that threshold concepts are associated with learning that both involves a large entropy change and that has competing possible learning outcomes. Through analogy with enthalpy of matter, it is predicted that certain learning activities will aid students, especially in the case of reaching true understanding of threshold concepts, much as certain physical processes aid the formation of diamond in preference to graphite.*

## Introduction

Threshold Concept Theory (TCT) is now one decade, five biennial symposia, several books, and many papers old (Meyer & Land, 2003, 2006; Scott, Peter & Harlow, 2012; Flanagan, 2014). TCT has found support in a wide range of disciplines (Atherton, Hadfield, & Meyers, 2008). It holds that certain few ideas are sharply differentiated from others, less troublesome, less connected, less ontologically-altering (transformational) ideas. Threshold concepts (TCs) are sometimes called the "jewels in the curriculum" of a discipline, to emphasise their relative importance to teaching and practice, a term attributed to Meyer but used by many others (J. H. F. Meyer, personal communication, 2013). It has been suggested that internalisation of these ideas alone makes the skilful practitioner and underpins the expert (Cousin, 2006; Meyer & Land, 2006). Considerable thought has gone into ways of identifying TCs (Davies, 2006; Rountree & Rountree, 2009; Scott & Harlow, 2012). A notable success of the theory to date has been as a tool for teachers to address the "stuffed curriculum" (Land, Cousin, Meyer, & Davies, 2005; Cousin, 2006).

A key aspect of TCT is the identification of a so-called "liminal state" transited during the process of coming to understand a TC. A student typically experiences a period of time during which they seem to possess all the relevant facts but are frustrated in applying them in a meaningful way. A successful learner eventually overcomes this condition of confusion and arrives at understanding. A learner so coming to grasp or internalise a threshold concept is variously described as "passing through a portal", reaching a "transformed way of understanding", achieving "a rite of passage", reaching "a changed state", "opening a gateway", or having a "light-bulb moment" (Atherton et al., 2008; Davies &

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Mangan, 2005; Meyer & Land, 2006; Kiley, 2009; Yorke-Barber, Atkinson, Possin, & Woodall, 2008). These descriptions bring to mind the idea of a *phase change*, akin to the boiling of a hot or superheated liquid, the crystallisation of solute in a supersaturated solution, or the onset of schooling behaviour in groups of fish.

A concept map attempts to visually portray the connections between ideas (Jaffer et al., 2012; Novak & Gowin, 1984). Threshold concepts are expected to appear as more-connected nodes in such maps (Park & Light, 2010). If the connectedness of ideas is order within the collection of ideas, the understanding of an idea may be associated with the thermodynamic concept of entropy. Entropy is best understood as the "disorderedness" of things, a property of the state of a system that reduces as the system becomes more regularly arranged or more critically connected. Learning can then be recognised as a phase change, and so will be associated with a decrease in entropy. This view is not new, see for example, Macqueen and Marshak (1975), or Stephen, Boncoddo, Magnuson and Dixon (2009). It was noted by Von Neumann (1955) in the context of his extension of entropy to quantum mechanics.

Passing through the portal corresponds with a phase change in the ontological organisation in the mind of the learner. It is the conjecture of this author that the transition to deep and proper understanding of a TC—passing through the portal—is associated with greater ordering and interconnectedness of ideas, and hence that learning a TC involves a *greater change in entropy*, in comparison *both* with the learning of non-threshold ideas, and with the shallow, memorisation-style of acquiring a threshold concept that is described as "mimicry" or "shallow learning".

## The thermodynamics of phase change

An important problem in thermodynamics is to determine whether a given reaction or physical change will proceed, whether it is "thermodynamically favourable". Gibb's Free Energy is introduced as a quantity that allows prediction of the circumstances for a given reaction to occur. Consider the following equation for change in the Gibb's Free Energy of a given sample of substance for a postulated change:

$$\Delta G = \Delta H - T\Delta S \qquad (1)$$

where $H$ is enthalpy, $T$ is temperature, and $S$ is entropy. When the change in $G$ for a postulated reaction or change in state, written $\Delta G$, is less than zero—that is energy will be left over after the change has occurred, and the system is left in a lower-energy state—the reaction is likely to proceed. Derived from the idea of conservation of energy, this is effectively saying that the reaction will more likely occur if the end state is lower in energy than the starting state. Conversely if $\Delta G$ is greater than zero the postulated change is not likely to happen. Enthalpy may be further written as

$$H = U + PV \qquad (2)$$

where $U$ is the internal energy of a sample of substance, $P$ is pressure and $V$ is volume. Thermodynamics is most commonly applied to discussions of whether a given chemical reaction or physical change in state will occur, and this expression for enthalpy allows Gibb's energy to be expressed in terms of a finite number of tangible properties, namely heat, pressure, volume, temperature and entropy.

To see how the idea of Gibb's free energy works, consider a vessel filled with liquid. As heat energy is removed from the vessel, the liquid cools, and a point is reached where the liquid starts to solidify. In this transition—referred to as fusion—the entropy $S$ of the molecules decreases, so $\Delta S$ is negative. The magnitude of the right-hand term in the first equation above decreases, and since $T$ and $S$ are always greater than zero the minus sign implies that this right-hand term represents a positive change in $G$, actually a decreased negative contribution. The change to solid happened because the left-hand term, enthalpy, decreased by a greater amount than the right-hand term increased in the transition. This required a certain value for the temperature *T*, such that the enthalpy decrease exceeded the product of temperature *T* and entropy decrease. Without going into complicated mathematics, the density and heat capacity of the material changed also as it solidified, and without a change in temperature the energy yielded from the ordering of molecules was assumed in the solidification, reflected in a decrease of enthalpy.

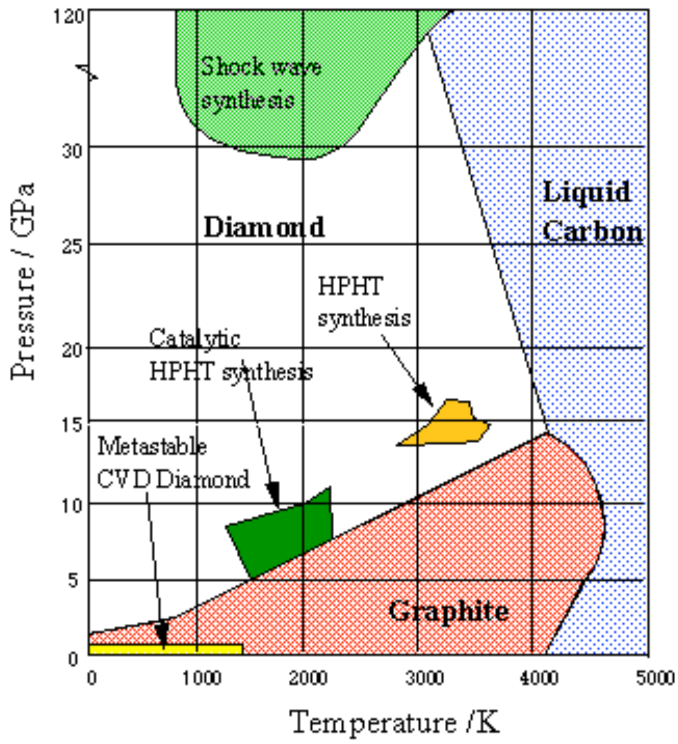


**Figure 1. The phase diagram for diamond and graphite, depicting the pressure-temperature regions that correspond to the liquid and the two solid states of the element carbon. Note that the solid form known as diamond sits above the solid form known as graphite on the pressure scale. Inset regions identify where various man-made processes lie.** From Bundy (1980)

Now consider the case of pure carbon, capable of assuming various solid forms, including graphite and diamond (Fegley, 2013). The various forms of carbon, including liquid, graphite, and diamond, are called "phases" of carbon, since the transition from one to another involves a phase change. When liquid carbon cools it unusually has a "choice" of two solid forms that it can take. Gibb's free energy helps us understand how it makes the "choice" between the two solid forms. The understanding of the phase changes is aided by consideration of a "phase diagram" such as that in Figure 1. Note that the diagram has essentially three regions labelled "Liquid Carbon", "Diamond", and "Graphite". At high-enough temperature, carbon becomes a liquid, as indicated by the liquid-carbon region of the diagram extending all the way from top to bottom at the right. It is common to visualise this as the state deep in the core of the primeval earth—the scales in the figure represent huge temperatures and pressures. The two solid phases of carbon occupy the upper and lower parts of the left-hand side of the diagram. At low-enough temperature, room temperature for example that is at the very left-hand edge of the figure, there is not enough energy to break any covalent bonds between carbon atoms, and solid carbon remains "frozen" in whatever phase it took as it cooled. The formation of diamond from liquid carbon is not as common as the transition to graphite, because it does not usually happen at extraordinary pressure, so graphite is common and diamond rare.

Ignoring the small patches in the figure that represent positions momentarily achieved in various artificial methods of synthesising industrial diamonds, it is clear that if the liquid carbon is cooled at high pressure it will solidify as diamond, but if it is cooled at lower pressure the result is graphite. Why this difference? The difference lies in the fact that diamond is denser than graphite, so there is a larger change in volume, $\Delta V$, and a larger change in heat capacity, and enthalpy, but also a larger change in entropy. Given a large enough value of pressure, $P$, the change in volume $V$ in the transition to diamond gives a large enough change in enthalpy that the temperature $T$ for that transition to be favourable is higher, even given the greater change in entropy $S$, than the corresponding one for graphite, and diamond is preferentially formed as the sample cools. Finally returned to low temperature and pressure, graphite remains as graphite, and diamond as diamond. Mathematically, the Gibb's energy for fusion to diamond

$$\Delta G_{Diamond} = \Delta H_{Diamond} - T\Delta S_{Diamond} \qquad (3)$$

becomes <0 at a higher temperature $T$ than the energy for fusion to graphite

$$\Delta G_{Graphite} = \Delta H_{Graphite} - T\Delta S_{Graphite} \qquad (4)$$

does, but only provided pressure is high enough. The control of both pressure and temperature—two degrees of freedom—permits control of the solid form that results.

## Summary of thermodynamics

Thermodynamics is a notoriously esoteric piece of physics. Nevertheless, two important aspects of the above discussion can be stated succinctly. In nature, there are certain changes, called phase changes, that represent a sudden and drastic alteration, such as the precipitation of a solid from a solution, or the sudden conversion from fish swimming randomly, to fish aligning in schools. When a system is trying to coalesce or "come together", it may be the case that there are two (or more) possible outcomes—phases—that can occur. In this situation, there will be two (or more) driving forces encouraging the transition, and the interplay between the two will influence which of the possible outcomes actually comes out. As described in the introduction, it will be taken in this article that learning a significant concept corresponds to a phase change in the learner's mind. The contribution of this article lies in extending the model to threshold concepts.

## The thermodynamic model of a threshold concept

By definition, a TC is troublesome to learn. The phase change of passing through the learning portal to true understanding in the case of a TC is an especially difficult transition. This implies that $\Delta S_{TC}$ is especially large.

True and profound understanding is not the only possible outcome when a learner seeks to grasp a TC. Many an undergraduate student passes a course without coming to a true understanding of all the TCs, simply by learning how to solve the problems that are used supposedly to test the understanding—without the understanding (Mazur, 1997). An example taken from electronics concerns Thévenin's theorem. This is often tested through the student's ability to reduce a network of components to a simpler equivalent. It is not difficult to skip the understanding of the idea and train yourself to solve the numerical problems through rote execution of heuristic rules. As in the case of solidifying carbon, there are two possible outcomes—true understanding and merely the ability to pass a test—the desirable one of which has a much higher entropy change. To make the desirable transition (learning outcome) appealing, the analogy with diamond suggests a great deal of "pressure" manipulation will be required. What does this mean in the pedagogical domain?

## Cool learning

At this point, it is only possible to speculate based on "accidental" observation. Three such observations are presented below. There is no hard evidence in the literature suggesting how one might alter one's teaching methods to specifically enhance the learning of TCs.[i] The aim of this article is to promote discussion that may lead to experiments that prove more conclusively that different degrees of freedom in teaching have different impacts on the learning of TCs. The following examples describe "surprising" instances of learning, some of which may be familiar to the reader. TC-optimised teaching would aim to produce what might be called "cool learning".

## Exam concentration

Is your mind uncommonly sharp and ready when you sit an exam? Have you had the experience of learning something in solving an unseen-problem-question in an exam? The literature suggests that an exam—the traditional assessment task—should be every bit as much a learning experience as a class with an expert. There is to be found, in the mind of a well-prepared student, the right mixture of confidence, apprehension, preparation, focus, and concern that makes for high enthalpy with low temperature. The student is cool and ready, calm but charged like a spring wound up.

I speculate that this slowly applied mental strain coupled with confidence and factual preparation makes the "diamond" outcome more likely.

## Peer pressure

Imagine you have 10 graduate students and you tell each of them that you want to see the start of that important chapter by the end of the week and turn them loose. Experienced supervisors will know that the outcome will be panic, some rubbish, and likely very little good work. In contrast, if you put the same 10 graduate students at 10 desks in a large circle in the middle of a quiet gymnasium, then tell each of them that you want to see the start of that important chapter by the end of the week and finally that they are going to sit down at these desks and get to work, the outcome will be different (Johnson, personal communication, 2013). You may get 10 good efforts, but certainly more than in the turned-loose case. Perhaps each of them thinks that they have to write something or nine of their peers are going to think they do not know what they are doing. The right mixture of pressure, motivation, and circumstances makes for high enthalpy with low temperature, so they collect their thoughts and perform.

## Sleep on the problem

How often have you heard someone say, "I just woke up with the answer"? Coming to grips with the idea of entropy and understanding, I woke up realising that diamond and graphite made a good

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[i] At the time of writing, this is seen as the major unsolved problem facing Threshold Concept Theory. While it has enabled concrete and valuable changes in the design of courses through balancing the curriculum, it has yet to provide equivalent insight into teaching methods.

analogy.[ii] After juggling the concepts of thermodynamics for days, I had to turn my attention to other matters, and when the pressure of semester tasks disappeared, I returned to thermodynamics and TCs and the way forward was clear. Such events are commonly reported.

Some unconscious part of the mind remains active to process ideas, notably in REM sleep. This may well be able to provide the right mixture of preparation, relaxation, and remembered need: Cool learning.

## On the existence of threshold concepts

Some authors question the validity of TCT and the existence of threshold concepts (O'Donnell, 2009, 2010). The prediction through thermodynamic argument that multiple factors can influence transition to essentially different learning outcomes in the case of concepts with greater learning entropy lends much credence to the theory. That some concepts will have the distinct attribute of more than one kind of learning outcome, more than simply remembering or not remembering, is consistent with Meyer's assertion that concepts must either be, or not be, threshold, with no grey area between (Scott & Harlow, 2012).

## Conclusion

Learning involves a reduction of entropy. Learning a threshold concept is put forward as a phase change associated with an especially large reaction in mental entropy. In this article, it is postulated that the outcome of profound understanding of a TC competes with the outcome of acquiring only a shallow memorisation of facts associated with the TC. The former is what we recognise as "passing through the portal". If such competition exists, different techniques can be expected to favour one outcome or the other.

Meyer and Land (2006) suggest that pre-liminal variation is the key to understanding how and why students might effectively negotiate liminal space. Here we suggest that the variation is equally as likely to arise from their mental state and a trade off between mental "temperature" and "pressure". The desire is now to identify ways of increasing mental pressure without increasing mental temperature—cool learning—by finding the pedagogical analogues for pressure, temperature and enthalpy.

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[ii] The author wishes to stress that entropy is literally involved in learning—this is fact not analogy. Learning a TC is postulated to be a case where entropy in the physical material of the brain is reduced by a larger margin than in the case of learning an idea that is not a TC or ineffectively coming to grips with a TC. The forging of diamond as opposed to graphite is an analogy, an example in chemical thermodynamics of the same mechanism as is postulated to govern the learning outcome that follows address to a TC. The author is not putting forward the idea of TCs involving a large change in entropy as an analogy, but as fact—albeit as yet unproven. We may be forging the "jewels of the curriculum'" more literally than we think.

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