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EXPLOITING LANGUAGE IN TEACHING OF ENTROPY

Fredrik Jeppsson
Jesper Haglund
Helge Strömdahl

Abstract. *The words disorder, information, freedom and spreading are used as metaphors and analogies in science teaching to capture the scientific qualitative sense of entropy. In addition, the identification of entropy with the everyday conception of heat has been proposed. While physical sciences are regarded as exact disciplines, in which terms have precise definitions, the words being used in the qualitative interpretation of entropy have many senses. This may provide an obstacle to achieving a scientific understanding of entropy. In this study, the metaphors for entropy and seeing entropy as heat were analysed by use of the different entries for the words in a dictionary. The present paper is a contribution to highlighting the importance of making any metaphors and analogies and their benefits and limitations explicit.*
Key words: *entropy, metaphor, science education, semantics, thermodynamics.*

Fredrik Jeppsson, Jesper Haglund, Helge Strömdahl
Linköping University, Norrköping, Sweden

Introduction

Entropy, among other concepts in thermodynamics, is considered to be an abstract concept that is difficult for novices to grasp. Sears (1944, p. 447) claims that: "There is no concept in the whole field of physics which is more difficult to understand than is the concept of entropy, nor is there one which is more fundamental." He adds: "It has been said regarding some of the equations of thermodynamics, 'Experience indicates that it is much less difficult to use [certain] formulae than to understand them'. The same may be said of the entropy concept; it is much less difficult to use it than to understand it." As a result, after an introductory course in thermodynamics, the lasting impression may be that entropy is *S*, a letter, whose value may be calculated according to the rules of quantity algebra. In an early study on conceptions in thermodynamics among Scottish upper secondary school students, Johnstone, MacDonald and Webb (1977, p. 249) state that "one is left with the impression from the test results and from casual conversations with pupils and students that they have little or no conception of entropy."

It is an objective of science teaching that the students' knowledge and abilities should go beyond mere calculations and incorporate a conceptual understanding, for example of the entropy concept. One way to introduce abstract scientific concepts is to use metaphors and analogies. In the case of entropy, the disorder metaphor, often corresponding to the messy room analogy, has historically been used extensively in thermodynamics teaching. However, due to several drawbacks of the metaphor 'entropy is disorder', Lambert (2002) concludes that it is a "cracked crutch" for learning. Partly based on Lambert's argumentation, several American science textbooks have removed the disorder metaphor from their accounts of entropy in later editions.

One common reaction among teachers to the misconceptions

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that have been found to be induced among students in empirical studies of their conceptual understanding is to give them a correct definition of a new term, by the use of a formal scientific language. For instance, Lambert (2002, p. 187) claims: "Entropy is not disorder. Entropy is not a measure of disorder or chaos. Entropy is not a driving force. Energy's diffusion, dissipation, or dispersion in a final state compared to an initial state is the driving force in chemistry. Entropy is the index of that dispersal within a system and between the system and its surroundings." However, we claim that exposing students to definitions like this is not sufficient when scientific concepts are introduced, but that we have to make full use of the language of the students. If the disorder metaphor is removed, the question remains of how the students can build a conceptual understanding of entropy. Apart from disorder, several other metaphors for entropy are available in the science education literature, including seeing entropy as information, freedom and, spreading. In addition, Falk, Herrmann and Schmid (1983) propose that entropy should be thought of as the everyday conception of heat.

Williams (1999) claims that many words used when teaching science have many different meanings, both within science and in non-scientific domains; examples are given from dictionaries, spoken language and science textbooks. Within the field of linguistics, different senses of a word refer to stable interpretations, typically found as entries in a dictionary. By contrast, meanings of a word refer to the subjective interpretation in a given context. Although specific senses of a word may have been agreed upon within a scientific community, the word typically has many other and vaguer senses in colloquial language. When a student meets a scientific field, the use of known words in new ways provides a challenge to learning. In a previous study about the senses of entropy (Haglund, Jeppsson, & Strömdahl, 2010), we found evidence to support and reinforce Williams's position. Five distinct senses of entropy were identified: the macroscopic thermodynamic sense; the microscopic statistical mechanical sense; the information theory sense; the disorder sense; and the homogeneity sense. The fact that there are many alternative senses of entropy may be one source of confusion when trying to understand its scientific meaning.

Another source of confusion is related to the use of metaphors and analogies when teaching the scientific interpretation of terms, such as entropy. The word in the source domain of the metaphor, e.g. 'disorder' in the case of 'entropy is disorder', also has different senses, which contributes to the ambiguity in the interpretation of the metaphor.

The purpose of the present study was to analyse how four common metaphors, seeing entropy as disorder, information, freedom and spreading, respectively, and the identification of entropy as the everyday understanding of heat can be interpreted from a student perspective.

Metaphors in Science Education

Metaphor was regarded as one of the main tools of rhetoric in ancient Greece, characterised by the following form: A is B, e.g. 'Achilles is a lion', where A is compared with B. The intention is figurative and not literal in that Achilles is not identical with a large feline carnivore, but perceived as strong and brave. Typically, a new or abstract target domain is compared with a more familiar, concrete base or source domain. As opposed to the more explicit analogies, metaphors are typically implicit and focus on language use.

Gentner's Structure Mapping Theory (1983) of metaphors and analogies has been influential within science education research. In the analogy 'the hydrogen atom (target) is like our solar system (base)', the focus should be on relationships, e.g. the electron revolves around the atomic nucleus, just as the planets revolve around the sun, and not on attributes such as the assumption that the atomic nucleus is yellow and warm, like the sun. In our analysis of metaphors, we argue that, in addition to structural relationships, attributes of the word in the source domain influence the interpretation of the target. This contention is supported by Gick and Holyoak (1983), who found that students often focus on attributes rather than the intended relational structures when interpreting analogies presented by a teacher.

Commonly used metaphors may shift from a figurative to a literal interpretation, thus forming into a 'dead metaphor'. As an example, the biological interpretation of a cell developed by metaphor from the private space of a monk, but has taken on a sense in its own right. Overall, metaphors pick out and amplify certain characteristics, but at the same time put less emphasis on others. There is no complete match between the source and target domains and when unintended characteristics of the source domain are transferred, the metaphor breaks down. One approach to dealing with this situation is to present several metaphors to students, so that misleading features of each metaphor can be controlled.

Lakoff and Johnson (1980) introduced the term 'conceptual metaphor' in the field of cognitive linguistics, based on the assumption that metaphor is an ubiquitous feature of language. For example, many statements can be based on the conceptual metaphor 'argument is war', such as "He attacked *every weak point* in my argument." Within science education, Brookes (2006) has identified conceptual metaphors in the teaching of thermodynamics. Particularly state functions, such as energy (or entropy), are difficult to handle. They cannot be spoken about in a direct way, but only metaphorically, primarily as a substance or a location.

Another type of metaphor, an extension of the traditional metaphor, is 'grammatical metaphor', a concept introduced by Halliday (1985). One grammatical form is used in place of another, seemingly more natural, form. In science language, nominalisation is common; here processes normally expressed by verb phrases are presented in the form of nouns. For example, 'pH measurements were taken' may replace 'pH was measured'. Another example of 'grammatical metaphor' is the process variable 'heat', which is frequently mentioned in terms of a substance-like quantity, i.e. as a noun.

Methodology of Research

Four metaphors for entropy, used in science education as deliberate instructive tools for learning, are analysed herein; namely, entropy as disorder, information, freedom and spreading. In addition, the proposal to regard entropy as the everyday conception of heat is analysed. In connection to each construal, we apply different senses of the source domain words from an online dictionary (http://dictionary.reference.com/), and discuss possible interpretations. In the analysis of the metaphors, we follow the approach of Gentner (1983) in primarily trying to identify relational comparisons, corresponding to analogies. Only entries in the dictionary where such comparisons can be made are included in the results section. In some cases, the relational comparisons are complemented by attributes, such as the negative connotation of 'entropy is disorder'.

Results of Research

Entropy is Disorder

As mentioned earlier, the metaphor 'entropy is disorder' has been used extensively in teaching and has taken on a distinct sense of entropy in its own right, as identified in Haglund et al. (2010). Through the process of conventionalisation, 'entropy is disorder' has become a dead metaphor that is also used in non-science settings. Due to strong criticism, however, the metaphor has become less popular in science teaching. The following senses of the noun 'disorder' are listed in the dictionary (http://dictionary.reference.com/):

1. Lack of order or regular arrangement; confusion: *Your room is in utter disorder.*
2. An irregularity: *a disorder in legal proceedings.*
3. Breach of order; disorderly conduct; public disturbance.
4. A disturbance in physical or mental health or functions; malady or dysfunction: *a mild stomach disorder.*

Leff (2007), Lambert (2002) and Styer (2000) claim that spatial configuration is emphasised in the metaphor 'entropy is disorder', in line with sense 1. Here, the source domain represents a system model involving two levels, in which the system at one level comprises a set of elements at a lower level, in different degrees of disorder relative to each other. This relational structure is transferred by analogy to the thermal domain. The typical example is the messy room analogy, as presented by Ekstig (2002, p. 90) in a textbook for teacher education in Sweden:

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> The entropy is a measure of the disorder in a system. If I empty a box of Lego pieces on the floor, there is disorder among the Lego pieces. They are randomly scattered over the floor. The entropy of the Lego pieces is higher when they are scattered than when they are arranged in the box.

The intended target of the metaphor is the statistical mechanics sense of entropy, where one macrostate of a system is linked to a large set of corresponding microstates. The configuration of the Lego pieces is supposed to correspond to a microstate of the thermodynamic system. However, there are obstacles to mapping the two domains. While the source domain refers to a snap-shot of one configuration in time, the target domain involves fluctuation between the microstates corresponding to a single macrostate. Brosseau and Viard (1992) point out the weakness of the disorder metaphor in practical problem solving, i.e. the failure to take into account the energy distribution and the overemphasising of spatial configuration. Similarly, Sözbilir and Bennett (2007) found that the disorder metaphor is not useful in problem solving situations among chemistry undergraduate students.

The 'messy room' analogy requires a system with two levels. Therefore, it is not suitable for introductory thermodynamics teaching that takes a classical, macroscopic approach, where there is no apparent connection between the source and target domains. There is no match between a macroscopic description of entropy, based on characteristics of a heat engine, and the spatial configuration emphasised by disorder.

An alternative to the messy room analogy is presented by Atkins (2003, pp. 122-123):

> The analogy I like to use… is that of sneezing in a busy street or in a quiet library. A sneeze is like a disorderly input of energy, very much like energy transferred as heat. It should be easy to accept that the bigger the sneeze, the greater the disorder introduced in the street or in the library. That is the fundamental reason why the 'energy supplied as heat' appears in the numerator of Clausius's expression, for the greater the energy supplied as heat, the greater the increase in disorder and therefore the greater the increase in entropy. The presence of the temperature in the denominator fits with this analogy too, with its implication that for a given supply of heat, the entropy increases more if the temperature is low than if it is high. A cool object, in which there is little thermal motion, corresponds to a quiet library. A sudden sneeze will introduce a lot of disturbance, corresponding to a big rise in entropy. A hot object, in which there is a lot of thermal motion already present, corresponds to a busy street. Now a sneeze of the same size as in the library has relatively little effect, and the increase in entropy is small.

With an explicit educational aim, Atkins guides the reader through this analogy, pointing out the structure mapping between the source and target domains. The sound volume or level of activity in the surrounding environment corresponds to the temperature of the system receiving heat and the 'size' of the sneeze is mapped to the amount of heat transferred. Atkins focuses mainly on the macroscopic perspective, but he also shows how the analogy is linked to the metaphor 'entropy is disorder', typically aimed at a statistical mechanics interpretation. This particular analogy also has the advantages that, as opposed to the messy room analogy, the sneeze is a dynamic process and not limited to visual configuration. As all analogies and uses of everyday language, however, also this example suffers from vagueness, e.g. in the introduction of an undefined 'size'.

Apart from the relationships mapped, misleading attributes of 'disorder' may be inherited in the resulting interpretation of 'entropy'. For instance, irregularity, health problems and disorderly conduct in senses 2, 3 and 4 can give negative associations to unnatural or abnormal processes.

Entropy is Information

The connection between entropy and information was pointed out by Shannon (2001), when he adopted the term 'entropy' with a new sense in information theory. Eight senses of the source, the noun 'information' are listed in the dictionary (http://dictionary.reference.com/); we consider the following to be the most relevant for our analysis:

1. Knowledge communicated or received concerning a particular fact or circumstance; news: *information concerning a crime*.
2. Knowledge gained through study, communication, research, instruction, etc.; factual data: *His wealth of general information is amazing*.
3. The act or fact of informing.…
7. (In information theory) an indication of the number of possible choices of messages, expressible as the value of some monotonic function of the number of choices, usually the logarithm to the base 2. …

Within the field of information theory (sense 7 above), entropy is interpreted literally, i.e. not metaphorically, as a measure of the amount of information. Originally, it was adopted metaphorically in information theory, due to the similar mathematical formalism as in statistical mechanics, but it has since become a dead metaphor. However, the domains of information theory and statistical mechanics are different, particularly as the former relates to items of information and the latter to physical quantities, such as energy and temperature. Therefore, from the perspective of statistical mechanics, 'entropy is information' is still interpreted metaphorically. Entropy can be seen as the lack of information pertaining to the unique microstate, given only knowledge of the macrostate. Alternatively, from inside the system, entropy represents information relating to the particular microstate (Brissaud, 2005; Jaynes, 1957). Overall, analogies between information theory and statistical mechanics can be used in both directions, providing additional nuances to the interpretation of entropy.

Sense 7 mainly invokes a neutral, objective interpretation, related to elements in communication or data processing. In relation to knowledge, senses 1 and 2 have more positive, subjective connotations, suggesting that data has to be selected and processed in order to be called information. Information is regarded as valuable and useful, thus potentially giving rise to anthropomorphic interpretations of entropy.

Entropy is Freedom

Styer (2000) proposes the use of the metaphor 'entropy is freedom', the freedom to choose between several microstates. There are 17 entries for the noun 'freedom' listed in the dictionary (http://dictionary.reference.com/); of these, we consider the following four to be the most relevant for our analysis:

1. The state of being free or at liberty rather than in confinement or under physical restraint: *He won his freedom after a retrial.*
2. Exemption from external control, interference, regulation, etc.
…
8. Ease or facility of movement or action: *to enjoy the freedom of living in the country.*
…
17. Philosophy. The power to exercise choice and make decisions without constraint from within or without; autonomy; self-determination.

It is difficult to pin-point the intended source domain of the metaphor 'entropy is freedom'. However, in general, freedom suggests liberty to 'move about' at random without restrictions or external influence. When transferred to the target domain, this can be interpreted as an explanation of the postulate of equal *a priori* probability, that all possible microstates of an isolated system are equally likely. Freedom also allows a dynamic interpretation, focusing on the next possible microstates, which according to Brissaud (2005) complements the more static metaphor 'entropy is information'.

A characteristic of all senses of freedom is that they relate to human endeavour, rather than to the domain of natural laws. Although senses 1 and 8 may be regarded literally as being related to inanimate phenomena, this is not the most likely interpretation for a novice. There is an underlying implication that they involve a human being, able to act in a purposeful way. 'Freedom' does not lead the thoughts towards causal scientific reasoning. Rather than looking for laws that determine the behaviour of nature, the learner is led to believe that nature has the opportunity to do whatever it likes to do; it is imbued

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with free will. This may create an obstacle to grasping the mechanisms of spontaneous processes, where the random fluctuation between possible microscopic states is bound to lead to the most probable macroscopic state.

Styer (2000) points out that the senses of freedom are emotionally positive, in contrast to disorder. He argues that 'freedom' and 'disorder' in combination may offer two complementary emotional perspectives.

One additional challenge to the freedom metaphor is that the concept 'degrees of freedom' is already established in a specific sense within thermodynamics, referring to for example translational, rotational and vibrational modes of motion, which may cause confusion.

Entropy is Spreading

Leff (2007, p. 1744) argues that "it is appropriate to view entropy's symbol *S* as shorthand for *spreading*" and that 'the spreading metaphor' is powerful in the introduction of entropy in thermodynamics teaching. There are 41 senses of the word 'spread' according to the dictionary (http://dictionary.reference.com/). Seven of these senses may be relevant for our analysis:

– Verb (used with object)
1. 1. To draw, stretch, or open out, esp. over a flat surface, as something rolled or folded (often fol. by out).
…
3. 3. To distribute over a greater or a relatively great area of spaceor time (often fol. by out): to spread out the papers on the table.
…
9. To extend or distribute over a region, place, period of time, among a group, etc.
10. To send out, scatter, or shed in various directions, as sound, light, etc.
11. To scatter abroad; diffuse or disseminate, as knowledge, news, disease, etc.: to spread the word of the gospel.
…

The spreading metaphor may be used to convey a microscopic understanding of entropy, where microstates correspond to material objects (senses 1, 3 and 9), events in time (sense 3) or other entities, such as sound, information or disease (senses 10 and 11). The emotional neutrality of spreading is appropriate for describing natural phenomena.

By using the 'spreading metaphor', Leff (2007) wants to capture the sense of dynamics and temporal fluctuations over microstates at equilibrium. We argue that fluctuation at equilibrium is difficult to convey in this way, due to fact that in colloquial language spreading is typically interpreted as a radial expansion in space. In addition, we interpret spreading in time as occasions, distributed as widely as possible, rather than a uniform Newtonian time arrow, clocking up new microscopic configurations. In thermodynamics, spreading has come to be applied on the coverage of all accessible microstates in phase space, but this specific interpretation of spreading has to be made explicit in education.

Spreading is proposed as an interpretive tool for thermodynamic processes and equilibrium states. However, the fact that spreading, from the infinitive 'to spread', is a verb makes it difficult to convey entropy as a state function. Even though entropy is central for understanding the second law of thermodynamics and the dynamics of spontaneous processes, it does not represent the process itself, but is an index determining the state at a given point in time. As discussed in the study by Brookes (2006), the use of conceptual and grammatical metaphors in spoken and written language within science is common. However, we consider that the metaphor 'entropy is spreading' uses grammatical metaphor in an unusual way, using a verb to represent a state function. This is the opposite approach to nominalisation, where a process is spoken about as a noun. In this respect, by using the noun 'dispersal', which is closely related to spreading, for example proposed by Lambert (2002), these problems would be avoided. Another way to modify this approach in order to avoid the grammatical mismatch can be to explain 'increase of entropy' as connected to 'energy and/or particle spreading', which are related processes.

Entropy is Heat

The Physics group at the University of Karlsruhe have developed an alternative approach to teaching physics (Falk, et al., 1983; Herrmann, 2000). Within this framework, entropy is seen as the everyday conception of heat. There are 25 senses of the word 'heat' provided by the dictionary (http://dictionary.reference.com/), of which we consider the following to be most relevant for our analysis:

- Noun
1. The state of a body perceived as having or generating a relatively high degree of warmth.
2. The condition or quality of being hot: *the heat of an oven.*
3. The degree of hotness; temperature: *moderate heat.*
4. The sensation of warmth or hotness: *unpleasant heat.*

   . . .

6. Added or external energy that causes a rise in temperature, expansion, evaporation, or other physical change.
7. Physics. A nonmechanical energy transfer with reference to a temperature difference between a system and its surroundings or between two parts of the same system. *Symbol:* Q

   ...

– verb (used without object)

23. To become hot or warm (often fol. by *up*).
24. To become excited emotionally.

In the Karlsruhe Physics Course, entropy is regarded as a 'substance-like quantity', corresponding to the everyday conception of heat (Herrmann, 2000). In the statement 'entropy is heat', two words within the same domain, i.e. the thermodynamic domain, are being compared. In other words, this is not a typical example of a metaphor, which involves a comparison between two different domains. Instead, 'heat' can be regarded as an explanation of what the more abstract word 'entropy' means, in everyday language.

As seen in the excerpts from the dictionary, heat has many, different senses. One interpretation of heat is the 'degree of hotness; temperature', i.e. the intensive physical quantity of temperature, which should not be identified with entropy. Within the Karlsruhe framework, Job and Landau (2003) propose that one way to avoid this unintended interpretation is to identify entropy with 'quantity of heat'. However, this still leaves room for alternative interpretations.

In the view of Karlsruhe Physics, substance-like quantities may be conserved, but not necessarily so, as seen in the cases of entropy and amount of substance. Analogies are made between different subfields of physics, where energy is seen as a unifying concept.

The Karlsruhe approach is appealing since it allows the use of the everyday understanding of heat and provides a mathematical structure shared across different subfields of physics, thus enabling the use of analogies. However, one limitation to the identification of entropy with the everyday understanding of heat is that it focuses on the macroscopic perspective of entropy and does not contribute to the understanding of the microscopic statistical sense. In fact, some taught aspects of entropy may have to be 'unlearned', if the students would later take a course on statistical mechanics. In addition, the everyday conception of heat is not in line with entropy for all thermal phenomena. For example, during the process of free expansion of an ideal gas in an isolated system, the temperature and internal energy remain unchanged, but the entropy increases, due to the increased number of possible spatial configurations. This is counterintuitive from the perspective of the everyday conception of heat. From a practical point of view, the identification of entropy with heat may lead a person that looks for a 'good heat source' in everyday terms to settle for an object of high entropy and end up with an object that has big volume, but relatively low temperature; obviously a poor heat source.

Another challenge is the tension between entropy as a substance-like, yet not conserved, quantity. Christensen, Meltzer and Ogilvie (2009) have found that the idea that entropy is conserved is one of the most common misunderstandings among students. This misunderstanding may be reinforced by the Karlsruhe approach.

Reif (1999) argues against a macroscopic approach to the introduction of thermodynamics, partly because it is difficult for students to visualise the concepts. However, Fuchs (2007) has demonstrated how the Karlsruhe approach enables students to use their existing conceptions of fluid substances in the macroscopic interpretation of entropy. To see entropy as a substance-like quantity is attractive in engineering thermodynamics, where flows of entropy and energy are dealt with from a macroscopic perspective.

Discussion

Williams (1999) has shown that many words in science have many senses. We show that, in addition, words commonly used as sources in metaphors for entropy also have many senses. While it may be perfectly clear to a teacher which one of the senses is intended in a given metaphor, this is not necessarily so for the students. This semantic ambiguity adds further to the challenge of learning abstract scientific concepts. Therefore, the structures of the analogies corresponding to a metaphor have to be presented in detail and the limitations and points at which the metaphor breaks down have to be communicated explicitly.

Lambert (2002) suggests that entropy should not be taught by using the metaphor ‘entropy is disorder’, and suggests that correct literal explanations should be given. However, as Brookes (2006) points out, it is difficult to talk about a state function, such as entropy, in a direct, literal way in natural language. The use of metaphors is one possible way to handle this problem. We contend that metaphor is one of many educational tools that should be considered as long as it is well designed and its limitations are recognised and communicated to the students. Disorder is one possible starting point, and can be applied by the use of a dynamic and rich analogy, like the sneezing analogy proposed by Atkins.

Another alternative to presenting analogies and metaphors is to invite students to come up with their own self-generated analogies in order to explore a phenomenon. In this way, the risk of students misinterpreting the source domain and how it is linked to the studied phenomenon is reduced. In a current investigation of self-generated analogies for thermodynamic processes, we have found the students’ analogies and their analyses of where they break down useful tools for identifying and discussing their conceptions of central terms, such as ‘entropy’ and ‘reversible processes’.

As found in the present analysis, however, presentation of shortcomings of metaphors when they are introduced is rarely found in science education literature. In our view, this lack expresses an unproblematic perspective on metaphor. For instance, stating boldly that entropy is disorder or heat, words that in themselves are ambiguous and problematic, or identifying it with the verb spreading may lead the thoughts in wrong directions and without tools for further reflection.

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Fredrik Jeppsson	PhD student at the Swedish National Graduate School in Science, Technology and Mathematics Education Research, Linköping University, Sweden. E-mail: fredrik.jeppsson@liu.se Website: http://www.isv.liu.se/fontd
Jesper Haglund	PhD student at the Swedish National Graduate School in Science, Technology and Mathematics Education Research, Linköping University, Sweden. E-mail: jesper.haglund@liu.se Website: http://www.isv.liu.se/fontd
Helge Strömdahl	Dr, Professor Emeritus at the Swedish National Graduate School in Science, Technology and Mathematics Education Research, Linköping University, Sweden. E-mail: helge.stromhdahl@liu.se Website: http://www.isv.liu.se/fontd