IRRESISTIBILITY OF IRREVERSIBILITY

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Reversible changes are an important ingredient of the school physics. If they run in the opposite direction everything gets back to the initial state and it is as if nothing has happened. Movement is the prototype of all other changes. This analogy is perpetuated through language.

Classical mechanics deals with rigid bodies with no internal structure. It explains reversible changes of movement by forces. Movement itself does not need any explanation. This is acceptable for celestial events but contrary to everyday expectations. At this point physics teaching departs from common sense. It tacitly suggests that changes in general do not need explanations. But of course they do. Also flow of water through pipes is explained by pressure differences.

Real world is inhabited with irreversible changes. Children are familiar with them. It is quite difficult to convince them about reversible idealizations. And if we do that we build a very effective barrier towards chemistry and life sciences in which irreversibility is accepted as part of their trade.

In school science irreversibility should be dealt with from the start on. It is not a minor discrepancy from the reversible world of Eden where everything goes on reversibly for ever but something which is our destiny. The curse or the blessing that we have (opportunity) to work is direct consequence that things get down by themselves and we have to put them up again.

For this we need matter m and energy W. To make our home more comfortable than its surroundings we have to provide it with openings, pipes and wires through which "clean" substances and energy flows are entering but also those through which we shall get rid of "dirty" wastes. This applies also for factories, organisms and the whole planet. Wastes. are results of irreversible changes of matter and energy called consumption and dissipation. These processes go on in spite of conservation laws: m = const. W = const.

Matter, energy and other conservative quantities can tell only which states are available to the system from the present one. They do not distinguish future from the past and so they do not help to understand irreversibility. This has to be introduced to school science through another route.

In the project Eden in Slovenia we are trying to find those conceptual frames which can make school science more meaningful for the students. This means that school science should be more compatible with their way of thinking and also that it will be easier for them to see the purpose and usefulness of learning it. We believe that an important possibility to achieve this is through better coordination of all sciences. This can be learned through common inservice training of all science teachers.

We are looking for the ideas and processes which are characteristics for all sciences. Matter, energy, internal structure of systems and irreversibility of processes (measured by entropy production) are conceptual schemes which might not only enhance understanding of science but also enable better understanding of ecology and *economy of natural resources. Our aim can be condensed in a slogan: **E**nergy & **E**ntropy for **E**cology & **E**conomy.*

We have found a number of promising physics courses developed in different countries which are compatible with our aims. People who have developed them were willing to cooperate with us. They also participate at this conference.

Kinetic and potential energy

Science is a study of changes. We can not understand them just by recognition that "panta rhei": everything flows. Descriptions and explanations of events have two facets. They include what is *changing* and what stays constant. In the language constants are described by *nouns* and time variables by *verbs.* "The ball rolls," means that the shape of the body is constant (ball) and that the distance and angle are changing.

Energy is a quantity which explains which states are available to the body if we know its present state. If the body is isolated from the surroundings only those states are available which has the same energy. For a body moving in space far from all other celestial bodies $W_k = mv^2/2 = const$ means that the body moves with constant velocity.

When there are two bodies interacting the energy of one in the presence of other can be divided into kinetic energy and potential energy which depends on the relations between the two bodies. From $W_k + W_P$ = const. one gets for a falling ball that the smaller its distance from the ground h, the bigger will be its velocity v.

Elastic and internal energy

For the ball just hitting the floor another term, depending on the change of the shape s should be added We which is called elastic energy. The states which are available to the ball are now described by: $W_k + W_P + W_e$ = const. Only those states defined by triplets (h, v, s) which are compatible with W = const are available to the ball. Availability relates both to the future and to the past states of the ball.

The ball which is not perfectly elastic will warm up a little bit whenever it hits the ground. A new energy term W_i should be added to total energy. It is called internal energy and is defined by the temperature T. It is still true that the ball can reach only those states (h, v, s, T) which are compatible with the restriction $W_k + W_P + W_e + W_i$ = const but what is more: only those states for which W_i is equal or bigger than now are available to the ball in the future: $\mathrm{W_{if}} \geq \mathrm{W_{in}}$. The states for which internal energy is smaller than now can belong only to the past: $\mathrm{W}_{ip} \leq \mathrm{W_{in}}$. So internal energy is not only just another energy but a special one by which one can distinguish the future from the past. Transformations of other energy "forms" into internal energy are possible, but internal energy can not be transformed into other forms. This is why we speak about dissipation of energy and at the same time still believe in its conservation.

Kinetic energy is ascribed to the body because it moves, potential energy is energy of a body in the field of another body. Internal energy is something special. It reveals that the body has some sort of internal structure, that it is made of smaller parts. It does not say however whether internal energy should be ascribed to the movements of its parts or to the relations (fields) among them or both. This lack of information connected with internal energy is at least for some authors definitional property of internal energy (for instance Franco Wanderling's position in a workshop on this conference). This is why internal energy is associated with entropy.

Elastic energy has somewhat dubious status. It is energy associated to the relations among the internal parts of the body. This is why some teachers classify it as internal energy. But on the other side it is not associated with uncertainty and entropy. So it might be better to classify it as potential energy.

From force dialect to energy dialect

Potential energy of a body depends on some of its properties like mass m or electric charge e and on the properties of the other body and its relation(s) to the observed body (distance r for instance).

For the point like bodies gravitational potential energy is $W_{pg} = m(\kappa m_0 / r)$, electric potential energy is $W_{pe} = e(e_0 / 4\pi\nu\varepsilon_0 r^2)$. The expressions in the brackets include both: the property of the other body (m_o *or* e_o) and its relation to the observed body (r). This combination of the two is called *potential* φ. Gravitational and electric potentials are: $\varphi_g = \kappa m_0 / r$ and $\varphi_e = e_0 / 4\pi\nu\varepsilon_0 r$.

Negative gradients (slopes) of the potentials are *fields.* Gravitational and electric field strength are: $g = \kappa m_0 / r^2$ and $E = e_0 / 4\pi\nu\varepsilon_0 r^2$. Multiplying field strength by the coupling property of the observed body gives *force F.* Gravitational and electric force are: $F_g = \kappa m m_0 / r^2$ and $F_e = e e_0 / 4\pi\nu\varepsilon_0 r^2$. Gradient of potential energy gives the magnitude of the force.

These relations offer the possibility for a visual symbolism which enables translation of the more common "force dialect" into "energy dialect" (expression used by Franco Dupne). Gravitational potentials (*gh*)can be related to the sea level *(r =* r_o + h, where r_o means the radius of the "water" globe and h is the height above the sea level). Differences of gravitational potential can then be seen as steps, thresholds, slopes, hills and valleys.

In the next step one can generalize this picture to electric and chemical potential, temperature differences and so on. These differences (of intensive quantities) are responsible for the spontaneous changes. Let us call them driving differences. Many changes can be interpreted as movement of some continuous staff - flow or current.

Changes and currents

Changes can be understood as changes in the amount of some substance like (extensive) quantity (mass, electric charge, amount of substance), which flows from one to another body driven by potential differences. The product of driving difference and the change of this substance-like quantity in a spatial region is the change of energy.

The material on the way resists the flow of extensive quantity. To overcome this resistance R it is necessary that driving differences push all the time. If they are constant the flow is constant as well. Resistance of any sort can be compared with friction because it is accompanied by heating.

This description is in accordance with common sense: constant movement needs constant push. This can be easily generalized: constant driving difference is needed for constant current (flux) through the boundary of the observed system or body: $\Delta\xi = R(dX / dt) = RI_x$. If this quantity is conservative then constant currents produce constant rate of change inside the body. One should resist temptation to call driving differences "forces". Mechanical force is translated into the "flow dialect" as a current - momentum current namely - and not as one of the driving differences. So mechanical force (momentum current) in a resistive medium is not driving anything. On the contrary it should be driven. The driving difference in this case is difference in the velocities of the observed body and the resistive medium around it.

If we decide for "irreversibility from the start" it is not Newton's Second law but rather Ohm's law (and its analogs in other fields of science) that is taken as a basis for teaching physics. It would be difficult to be otherwise. Not Newton but Ohm has taken irreversibility in consideration.

Extensive quantity X can be stored in a body which then serves as a container with the capacity C. If X is pushed into container with to driving difference $\Delta\xi$ the following equation describes the relation among the three quantities: $X = C\Delta\xi$.

Discharging the container through resistance is described by (differential) equation: $X(t) = (RC)dX/dt$ with the solution $X(t) = X_0 \exp(t/RC)$.

Energy dissipation and entropy creation

Energy is needed to push something through resistive medium. It is again in accordance with common sense that energy spent (dissipated) per second is proportional to the driving difference $\Delta\xi$ and to the current I_x pushed through resistance. It is possible to say that current I_x of extensive quantity X, driven by $\Delta\xi$, carries energy current $I_w = P = \Delta\xi I_x$.

If energy current $I_w = \Delta\xi I_x$ is dissipated in the resistance the production rate of entropy is $\Sigma_S = \Delta\xi I_x / T$. Energy never travels alone. Currents I_x and their driving differences Dx are specific for different branches of physics. Energy and entropy however are universal. They make possible to predict the development of all phenomena. Energy alone is enough to predict events in heavens and in an idealized garden of Eden without resistance. In the real world of irreversible struggles and death entropy is always present. It distinguishes good from bad, improvement from deterioration.

Dissipation of energy is measured by the rate of entropy creation: $\Sigma_S = I_w / T = \Delta\xi I_x / T$. Entropy which is often introduced just as an extensive quantity specific in thermal physics becomes the second universal quantity which is necessary for description, explanation and prediction of irreversible phenomena in all branches of science. The first one was energy, but energy alone is not sufficient to describe irreversible changes.

Recent history of energy and entropy teaching

One of the major events connected with teaching irreversibility and entropy in schools was 6th Danube seminar *Disorder in the school* in 1983. The opening address had the title Entropy in the school? (Marx G (Ed.) 1983). Question mark in the title indicates that seminar opened debate whether this topics should be taught at school or not and so there was less emphasis on how to teach Second Law if we decide to do so at all. There were several other conferences addressing this question after that. At least *Energy Matters* (Leeds 1985) organised by Driver R and Millar R and *Taormina conference on Thermodynamics* (Taormina, 1991) and *Thinking Physics for Teaching* (Rome, 1994) both initiated by Vicentini M should be mentioned.

Should we do it

One of the arguments pro was that dissipation and transformation of energy should be taught first and that conservation comes later (Black and Solomon in Marx

1983, p. 54) because this is nearer to the world of pupils' everyday experience. On the other side "there are good general arguments within engineering thermodynamics for teaching a Running Down principle in its own right" (ibid.).

In this arguments there was already the recommendation that Second Law can be presented in the school as Running Down principle which has been introduced already by Carnot. It has been later elaborated by Clausius which expanded the equation for Carnot cycle from:

$$\frac{Q_1}{T_1} - \frac{Q_2}{T_2} = 0$$

to a longer form:

$$\frac{Q_1 - Q_2}{T_1} - Q_2\left(\frac{1}{T_2} - \frac{1}{T_1}\right) = 0$$

which can be interpreted, that two different changes are happening simultaneously:

- **heat** (Q_1-Q_2) taken in at high temperature T_1 changes **into work** and
- **heat** Q_2 taken in at high temperature T_1 changes **into heat** Q_2 given away at lower temperature T_2 (Radnai, in Marx 1983, pp 31-32).

Clausius way of teaching has been recommended also by another participant of the seminar (Thomsen P, in Marx 1983, pp 375-387) which contrary to Black and Solomon did not believe that it would be a good idea to change introductory teaching of energy in order to teach Second Law. He recommended to teach storage and conservation of energy first and disagreed "entirely" that it is easier to make students understand the second law than the first.

Duit looked into empirical studies (Duit R, in Marx 1983, pp 87-97) and concluded that "an idea of energy conservation which is applicable to processes in mechanics is not formed during cognitive development" and that "comprehending the first law of thermodynamics is not at all an easy task for students".

About learning the second law he concluded, that we know almost nothing. Nevertheless he expressed the opinion that the reason for the minor role of the Second Law in school physics was caused "mainly by prejudices of people with an uneasy feeling about entropy' concept." He has cautiously added that Second Law might be easier to understand than the first law because it is more in accordance with everyday experience.

Sexl (Sexl R U, in Marx 1983, pp 101-110) recognised that entropy is more mysterious than energy. The reasons for this is nonconservation of entropy and trivial applications of it in school physics. He thought that school physics might get along without entropy, in chemistry and biology however it is absolutely necessary. "School physics does not need entropy - the pupils do."

The most decisive was P. Atkins who said that "teachers have an intellectual duty to explain the role of entropy to others. We have to show not only that it accounts for little things, ..., but that it also accounts for big things of life, such as consciousness and illusion of purpose." (Atkins P in Marx G (ed.) 1983, pp 134 - 150).

About the difficulty of new topics he said: "The great advantages of entropy and the basis of the Second Law are that one is trivial and the other is obvious."

Nevertheless he has envisaged some difficulties in teaching. He has classified them and given some hints how to tackle them.

How should we teach it

Sexl proposed to introduce entropy in two steps:

- finding a convincing and simple way for the introduction of the concept,
- finding interesting and motivating examples for the application of the concept.

As about teaching he proposes the introduction through information theory. Then he connects informational entropy with TD entropy by considering expansion of gas in a vacuum. The two terms in the expression for entropy of ideal gas are interpreted as "lack of information about the exact position" (Nk ln V) and "lack of information about exact momentum" (3/2 Nk ln T). So it is possible to speak about "positional" and "momentum" entropy or "where" and "how fast' entropy. His colleague (Pflug A, in Marx 1983, pp 323-341) has spoken about "desk type disorder" or "cold" disorder and "disco type disorder" or "hot" disorder. Desk type disorder is disorder in the coordinate space, and disco type is disorder in the momentum space. The set of all possibilities is mapped into the phase space consisting of all possible pairs of position and momentum values. The phase space is divided into cells with the volume h^{3N} ,where N is number of particles.

As about teaching Pflug thinks that teachers have difficulties in understanding Second Law because they have been trained in Newtonian mechanics before meeting thermodynamics. Children consider it simpler and more natural so we should therefore learn TD from our children.

Falk (Falk G, in Marx 1983, pp 243-259) agreed with Sexl that it is necessary to teach entropy in schools, but disagreed with him completely in how to introduce it to pupils. "Entropy is considered to be one of the most important but least understandable concepts in physics."

Phylogeny and ontogeny of entropy

Falk's opinion was that entropy by itself is not difficult, it has been made difficult due to historical contingencies. He proposes to follow the historical tradition that heat was substance-like quantity in the sense that it can be stored in a localizable space region and that it can flow from one to another region. Black J (1803) has used the term in this way and it is used in the same way in common language.

Everybody also understands that friction *creates* heat and that heat is *released* from the food and in burning fuels. These sentences had the same meaning in everyday language in 18th century as they have nowadays. They are all scientifically correct if the word heat is replaced by the word entropy. These words which are commonly used in biology and chemistry and halfofficially also in physics have absolutely no sense if heat is interpreted as energy. They are however good description of the entropy changes. In friction entropy is created. In food and fuels there is some "desk type" entropy already present, much more is however created in the irreversible processes of digestion and burning.

Conservation is not definitional characteristics of substance-like quantities although it is often associated with them. The fact that entropy is only half-conserved quantity expresses the irreversibility and does not exclude entropy from substance-like quantities.

For Carnot heat had double meaning and he also used two words for them. One was directed towards the present concept of entropy, the other could have been developed into energy. In the middle of 19th century the conservation of energy was discovered. The work of Mayer and Joule has interrupted the development of the entropy concept included in the term heat and emphasised its energy component. The crucial turn, which still influence our teaching today, has been made when the term heat has been firmly associated with energy only. Because energy is conserved there was no place left for entropy inside the term heat. Clausius resume the work of Carnot and reconciled different views about heat in the last quarter of 19th century. Heat is neither (transport of) energy nor entropy alone. It is both. But not very often in the contemporary schools.

Let us double the fun also at school

By saying that heat is energy we are rejecting all commonsense knowledge of entropy associated with the common word heat. (It is worth to mention that the development was exactly opposite in teaching electricity. Electricity in common language has been interpreted as electric charge in physics. Its energy component has been left out. So it is difficult for children to understand how electricity can drive motors if it is conserved.) Falk stressed his opinion that entropy becomes an easily understandable concept if one accepts the view that heat from common language means (primarily) entropy. He wrote that this is useful not only for qualitative description but can be the basis also for quantitative understanding.

Besides the possibility to use the word heat either as a name for the transfer of energy or for the transfer of entropy it is possible to use it as a connotation for combination of both events. Heat interaction which "results in net exchange of both energy and entropy, requires that the interacting systems be almost at the same temperature" (Beretta G P, Gyftopoulos E P in Giaquinta et al (eds.) 1992 p. 339).

These two authors require that heat should be defined by the condition that it is entirely distinguishable from work - no part of a heat interaction be mistakable as a work interaction. From their definition it is obvious that they deal only with the reversible heat exchange. They conclude: "Work and heat are ingenious concepts. For given end states of a system, they allow the quantitative distinction between *entropy generated by irreversibility* and *entropy exchanged via interaction* with other systems (italics JF). This distinction is useful because it provides practical tool for reduction of entropy generation by irreversibility. The identification of the opportunity for reduction of irreversibility would be missed if heat were defined "as just any interaction that is not work, i. e. any *nonwork interaction."* (ibid.; italics JF).

For other authors interaction heat has two possible realisations: reversible and irreversible one (Falk, Ruppel 1976, pp 261 - 270). In the case of irreversible heat interaction (called "nonwork" by Beretta and Gyftopoulos) an additional descriptive variable is necessary for quantitative description of the combined process called "heat" namely the newly created entropy (Ferbar J in Bernardini C et al (eds.) 1995, pp 249 - 260).

It seems that giving double meaning to the word heat might gap the bridge between present way of teaching TD with entropy introduced *at the end* of thermodynamics and the new propositions which require introduction of irreversible changes and entropy from the start. *Concept formation through gradual differentiation* as practiced by Herrmann and Ogborn and recommended by R Duit (personal communication during GIREP conference) might prove to be a better didactic approach than start with clear-cut definitions which are only accidentally connected with students' previous ideas. Gradual differentiation was also the historical way how momentum has been differentiated from energy in mechanics (Herrmann, 1995), how temperature has been differentiated from entropy and entropy from energy and how in schools electric charge is differentiated from energy. On the other side Ausubel has shown that gradual obliteration of conceptual differences is the most important way of forgetting meaningfully learned material.

Falk was very sceptical about the usefulness of probabilistic approach (as recommended by Sexl, for instance). He said that this approach was an intellectual delicacy for professionals which leads to substance-like character of entropy only through a long detour.

What is new in the new decade

The idea of teaching entropy in the schools has been accepted by the professional community more than a decade ago. It is therefore reasonable to ask if the teachers are nowadays better off to perform this task than at the time when pros have won against cons at Balaton.

1. Constructivism

This is an attempt to build an educational practice - not a theory - which is taking into account the student's previous knowledge, experience and ideas. Students' ideas are often shared by many people of the same culture. Some of them are even universal. They are also difficult to change. Both these characteristics - universality and resistance to change - imply that common sense science which is shared and perpetuated by using common language is at the basis of all science including also school science.

It is therefore prudent to study conceptual structure built into common sense knowledge and to map carefully the semantic maps of words in everyday language (Duit 1993) and to compare them with the conceptual maps in science. It is often easier to rename a concept which is already established under a common sense word than to build a new concept. A typical example for this is the concept of entropy which starts in common sense language as heat (Job 1972, Herrmann 1992, 1995, Job) or the concepts of free enthalpy G and free energy F, which have much in common with the everyday meaning of energy (Ogborn in Driver et al (Eds.) 1985).

This is a radically new approach in comparison with the traditional view that a clear definition of the terms should come at the start (Stmad 1994) with little regard about the conceptual structure of the student.

2. New courses

At least two new courses for lower secondary schools have been developed and published since:

Herrmann F 1995 *Der Karlsruher Physikkurs* (KPK)

Boohan R, Ogborn J 1996 *Energy and change* (E&C)

They have been both tested with pupils and for both of them a formal evaluation is going on. In the meantime the courses can be included in inservice teacher training and discussed with them. A consensus should be reached what changes are acceptable for pupils, teachers and community as a whole.

3. New symbolic systems

Contrary to the science courses in 60s and 70s when students were expected to learn by experience and create their own notes using their own language and creating their own symbols the new science courses have developed common symbolic systems.

This is of crucial importance. Experience rely heavily on sensation and perception. Training of sensation means training for better *differentiation,* to be able to observe the differences which were imperceptible for an untrained observer.

Learning through symbols is training for *generalization.* Symbols like words and drawings are signs for *classes* of objects, events and relations. Classification is based on what different things have in common. Generalizations are made in mind. They are over and above perceptions.

It is therefore appropriate to teach predominantly hands on science in primary schools and children in their early teens when their reasoning relies on perceptions and concrete operations of the material world. Thinking at this age is concentrated on single cases.

In the lower secondary schools it is however necessary to teach hands-on and heads-in science. Reasoning is abstract and this means that it deals with classes. This is why symbols are of crucial importance. The most important however are symbols for qualitative reasoning which differentiate between equality and non-equality and symbols for semiquantitative reasoning which differentiate between more and less and between growth and diminution.

Quantitative reasoning comes later in upper secondary school.

Drawings:

In E & C events are represented by the initial and final states. Pictures are not realistic. Each of the picture symbols corresponds to a term in the calculation of entropy changes or free enthalpy changes. Many perceptually different events can be interpreted as molecular crowding, mixing, making patterns. Time development is represented by one type of arrows, the direction of spontaneous changes by another type of arrows relating the pictures into an ordered pair as time increases or entropy increases.

In KPK systems are represented by rectangles with names inscribed into them. The flows of extensive quantities (energy carriers) are represented by lines with arrows showing directions of currents. Energy currents are represented by guide boards among systems showing the direction of energy flow.

Language:

In E & C a language has been developed which fits realistically to the changes of a body moving in the gravitational potential field. **The driving differences** (of gravitational potentials) are represented by the differences in heights and fields are represented by slopes of hills. The same vocabulary is then transferred to thermal, electrical and chemical hills representing driving differences and gradients of potentials.

Spontaneous events are going "downhill". For an uphill event to happen there should be another downhill process in the same system or in the surroundings which is coupled with the observed uphill event. Potential differences can be sometimes transported from place to place. A battery is sleeping electric potential difference which can be carried around in the pocket. But electric potential hills can be also transferred through wires. Downhill processes are destroying potential hills which are driving them. New potential hills can be built by downhill currents if their energy is not completely dissipated. "It takes a difference to make a difference," is a simple rule to be remembered. These are examples for using simple language to describe qualitatively what can be done quantitatively either by reference to increasing entropy or decreasing free enthalpy. In KPK there are substance-like quantities for which spatial density and currents can be defined. They fill spatial regions in a similar way as sand or water. Although they are weightless they are similar enough to substances that children can think about them as a new type of substance. This is not at all difficult to them. Many of them imagine air as a substance with negative weight long before any school teaching. So it is almost trivial for them to imagine impoderabiliae (Strnad, at this conference).

Some of substance-like quantities can be even created (entropy) and/or annihilated (amount of specific substance) like porridge in fairy tales. Children can use the same language for storing and transferring these quantities in bodies as it is used for storing and transferring sand and water. The same equations are used for describing these processes. The materialized model enable children to use all their joyful experience from the sandpit and water tub to many new situations.

In KPK one can find differences *driving* currents of energy carriers, and currents. dragging with them other currents and creating new *driving differences.* Devices specially designed for creating new driving differences are pumps. There are water pumps but also pumps for electric charge, entropy pumps and chemical pumps.

4. Connections among science subjects

Energy and entropy considerations have equal importance in physics, chemistry and biology. Physical chemistry is traditionally interdisciplinary subject taught at university level. It was introduced into upper secondary chemistry courses two decades ago (Nuffield) but only recently there are attempts to include this topic also to the lower level. Cooperation of chemists and physicists in writing teaching materials seems to be necessary condition for success (Herrmann, Job, Morawietz in Germany, Boohan, Ogborn in England). It seems that the work of P. Atkins had profound influence on teaching this subject in different countries (Ben Zvi, Silberstein in Israel, Kornhauser-Glaliar in Slovenia, Boohan, Ogborn in England).

It is more difficult to find examples for application of entropy and energy law in biology courses. Katsuki's work on environmental education for science students is interesting in this respect (Katsuki A in Marx (Ed) 1995).

Although vast majority of processes studied in science are irreversible it is possible to find topics in physics where this question can be avoided: mechanics of rigid and elastic bodies, waves, geometrical optics. It is much more difficult to dodge this issue in chemistry because most of chemical reaction are irreversible. This is probably the reason why entropy has been introduced into school chemistry first.

In biology irreversibility of processes is so obvious that it seems that nobody feel the need to explain it. This might explain why there is so little done here.

Interdisciplinary teaching of thermodynamics is needed. Examples of irreversible processes in physics might be the easiest to explain. But then there is a danger that internal energy would be mainly reduced to "thermal energy" connected with the movement of the particles. "Chemical" energy was often dealt with as something separate. In a similar way in physics we deal usually with "disco type" entropy connected with the distribution of energy among the movements of the particles. Entropy connected with the distribution of particles in space ("desk type" of disorder) is usually left out from physics as something which really belongs to chemistry.

In biology energy is often dealt with only qualitatively. Organisms get energy with food. They need it for their vital function and to perform useful work which is often associated with the movement of the body and its organs. Heat which is interpreted as energy "liberated" from the food and "escaping" into the surroundings does not seem to have any useful purpose. So plants and animals should better avoid this "waste" of energy.

While conservation of energy can be used to explain undamped oscillations in physics it does not seem to have much value in biological processes where energy is "spent" for driving vital functions. Spending energy is associated with spending food. Food was there before eating and then it is gone. So there is little sense to speak about conservation of food and similarly about conservation of energy.

Teaching about dissipation or degradation of energy by spreading it among many particles is necessary condition for the concept of energy to become a meaningful concept in irreversible processes. It is possible to say that pendulum does not stop because total energy is being conserved. It is not possible to say that a car has been stopped by breaks because total energy is being conserved.

5. Microscopic or macroscopic

After the decision to teach irreversibility and entropy another dilemma has been resolved not by discussion but through teaching practice. This is the dilemma how to teach these concept: from microscopic statistical point of view or from macroscopic phenomenology. It seems that entropy can be early introduced as a substance-like quantity by reference to the common meaning of heat and by analogy to other extensive quantities. This description is particularly successful for reversible changes when entropy is conserved.

Irreversible changes can be introduced first with sets of macroscopic bodies: cubes, marbles, beans. Spontaneous changes towards increased disorder (mess) and dissipation of energy can be shown with them directly with Cinderella mixing experiments and pulling down Pisa type towers.

For transfer to microscopic level it is only necessary to replace macroscopic building blocks by atoms. Representing atoms with marbles or tennis balls is enough for this purpose. The concept of entropy however is the same in macroscopic model and in microscopic reality. There are however large quantitative differences in entropy changes among macroscopic model and atomic reality.

Intensive quantities and driving differences can also be represented by microscopic pictures. These pictures are convenient for qualitative understanding of entropy changes especially for representing positional entropy. Changes of density, concentration and patterns can be represented by initial and final state. These pictures are less appropriate for representing momentum (thermal) entropy (p^z cc T, Sexl in Marx 1983, p. 109). Temperature differences are represented by shading, which can be connected with momentum differences only by stipulation.

For irreversible changes it seems that "downhill" analogy transferred from gravitational potential to electrical, chemical and thermal potential is quite convincing at a higher level. It seems that chemists prefer to speak about "decay" and "collapse in chaos" (Atkins P, in Marx 1983, pp 134 - 150) instead of "moving downhill". Decay implies falling apart, losing structure, mixing up which is easier to understand.

More preparation is needed for understanding "downhill" or "running down" analogy. Before its introduction it is necessary to teach concepts of current, driving difference, resistance and their interdependence. The concept of resistance is probably enough to introduce creation of entropy in qualitative terms.

For quantitative understanding currents of extensive quantities should be related to energy currents and these to the rate of entropy production.

6. New experiments and equipment

Because there is little tradition in teaching irreversibility and entropy there is a need for new experiments and equipment. In many cases however old experiments can be reinterpreted (Rubik cube; Drinking duck, Richmond P E in Marx 1983, pp 215 - 227). For statistical representation it is possible to use either sets of objects (Sokalski K, in Marx 1983, pp 342 - 354)or computer models (Nuffield Advanced Physics, 1972).

The following types of experiments are missing:

- Sets of object which will enable to show changes of entropy in the coordinate space connected with crowding, dispersing, mixing and patterning of similar objects.
- Experiments which will show changes of entropy in momentum space: movement of rigid bodies, sets of interconnected rigid bodies, "golden eggs and silver cans" with different internal structure, laminar and turbulent fluid flow.
- Experiments for clear distinction between cases when entropy of the body has changed because entropy has been exchanged with the surroundings or because it has been created.
- Exchange of entropy can be produced by exchange of energy or exchange of matter.
- Entropy can be created by irreversible exchange of energy by heat or by irreversible exchange of different types of work. Experimental examples of all these processes should be prepared.
- Special care should be devoted to experiments in which configurational (cold) entropy has been "released" to momentum space (hot) entropy. This transition is namely connected with the change of entropy "perception".
- We need also experiments to show how changes of entropy can be perceived with different senses (Norwich 1993).

7. New examples of irreversible changes

Many good examples of changes has been already prepared for semiquantitative use of entropy (Boohan R, Ogborn J, 1996) in the processes which are both relevant and interesting.

More simple examples should be discovered or invented for illustrating single types of entropy changes.

Special care should be devoted to find more simple examples from biology.

More work is needed about teaching entropy of light and changes of entropy when light interacts with matter (Fuchs 1996).

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