Lessons from the 20\textsuperscript{th} century for 21\textsuperscript{st} century science education

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Abstract

Effective teaching starts with getting the basics right. There has to be a good working atmosphere in the classroom, there should be well structured lessons, there should be a reasonable textbook even in the age of internet, a knowledgeable teacher, and a credible assessment/examination system. Once these basics are fulfilled, then we can make further gains through use of sophisticated teaching methods and use of ICT. The most effective methods are the ones stimulating intellectual engagement (Hake, 1998) and active learning and many of these methods have been developed particularly for large enrollment university classes in the USA (40–300 students/class) but they can be easily adapted to large secondary school classes and my colleagues and I have done so successfully.

The paper starts with a brief excursion to art and science. Then follows a list of characteristics of effective conventional teaching from the education productivity studies and meta-analyses by Walberg (1991). This is followed by lessons learned from studies of conceptual understanding (Duschl et al., 2007) and the implications for teaching. Then I give examples of how conventional teaching could be enriched with intellectual engagement (Hake, 1998) in order to take into account what we learned about conceptual understanding. Two of these intellectual engagement methods (embedded assessment and concept cartoons) are worked out a bit more. I conclude with some comments about metacognition. Together Walberg’s research on effective conventional teaching, Duschl’s comments on learning for understanding, and the intellectual engagement methods constitute lessons from the 20\textsuperscript{th} century for teaching in the 21\textsuperscript{st} century. The skills involved in learning for understanding are actually a nice operationalization of the 21\textsuperscript{st} century skills advocated nowadays.

1. A brief excursion to art and science

Art and science are often seen as opposites, emotion versus ratio, heart versus mind, impulsiveness versus thoughtfulness, beauty versus functionality. In fact they are closely related as we can see in both ancient and modern art, ancient and modern technology, and in the beauty of nature itself as well as in the beauty of theories. And as for emotion versus ratio, scientists are emotional people as the history of science makes abundantly clear, and artists can be quite rational as can be seen in the work of architects, the “architecture” of novels, and the composition of paintings.

Let’s just look at a few examples of art and science. The first is a painting from the Flamish painter Peter Paul Rubens (1577–1640). It is a beautiful painting but there is something wrong with it. The rainbow is in the plane of the painting (it must be, we never see rainbows from the side). However, in the painting the light comes from the left. With real rainbows the sun is always exactly opposite to the rainbow. So the Sun should have been at the painter’s back and not on the side. Ruskin commented (quoted in Minnaert, 1954, p.170) \textit{Rubens is not to be blamed for ignorance of optics, but for never having so much as looked at}
a rainbow carefully. Of course painters have artistic freedom and can paint the world whichever way they like.

Figure 1. Peter Paul Rubens’ rainbow (left) and Henri Matisse golfdish (right).

Henri Matisse (1869-1954) painted more abstract but nevertheless painted the optics more realistically. Light rays from the fish and refracted through the air above the water to our eyes would suggest another (higher) location of the fish than light rays from the fish perpendicular to the side of the glass (almost no refraction). Some artist achieve surprising effects by playing with the laws of perspective. The Dutch graphic artist Escher is well known for this and he has many followers like Rob Gonsalves (Figure 2 (left)). Back to the rainbow, using the old overhead projector and a plastic tank one can make a beautiful rainbow-like spectrum (Figure 2 (right)) but please note, it is not a rainbow as this spectrum can be projected on a screen while a real rainbow is virtual and cannot be projected on a screen. There is a lot more that can be said about art and science, but I will get on to the main topic of the paper. In the 20th century we learned many lessons about science education which are applicable in the 21st century and which we should not forget.

Figure 2. Tree house of Rob Gonsalves (left) and spectrum produced by a cone of light from an overhead projector being refracted into and out off the water (right).

2. Lessons about effective teaching which are trivial, but often not followed

Effective teaching starts with getting the basics right, at the classroom level, at school level, and at educational system level. There has to be a good working atmosphere in the
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At the classroom level there are some trivial rules for teaching. In 1991 Walberg summarized the following “lessons” from the many research synthesis studies and meta-analyses he had conducted in the 1970s and 1980s:

Successful teacher practice the following steps:

a) Clear objectives which are clear for both the teacher and the students.
b) Daily or per lesson review, homework check, and if necessary, re-teaching; these checks can be random, not every student needs to be checked every lesson, furthermore there are fast methods to check for understanding (later in this paper);
c) Rapid presentation of new content and skills in small steps;
d) Guided student practice with close teacher monitoring; students practice with questions, problems, or other activities while the teacher goes around to find out what is understood and what is not and to give corrective feedback;
e) Corrective feedback and instructional reinforcement;
f) Independent practice in seatwork and homework;
g) Weekly and monthly review.

And for teaching physics I would like to add to Walberg’s list:
h) Use visualizations and different representations.
i) Use exciting demo’s and other means to motivate and introduce variation.

The typical teaching Walberg referred to is conventional or traditional teaching which is the most widespread in both lower and higher income countries including the U.S.A. and Western Europe. In conventional teaching a major part of the lesson is done in plenary with the teacher introducing new concepts, conducting demonstrations, and guiding and discussing student seatwork. In higher education most of the lesson might be lecture. In high school part of the time may be for students answering textbook problems (seatwork) or teacher guided lab activities. Following Gage and Needles, Walberg (1991, p44) writes: “it is important to retain well implemented conventional teaching as a major option for improving education. It works moderately well in attaining conventional criteria of academic progress, and it does not require extraordinary teacher preparation, materials, and facilities. Although other methods have shown larger effects on specific criteria they are designed to accomplish, they lack conventional teaching’s long history. Many such innovations have come and gone, and conventional teaching remains the pervasive method in schools in low- and high-income countries”.

Conventional teaching may be more or less interactive. The teacher has a very active role (teacher-centered), most students may be rather passive. Using rules such as a) through g) conventional teaching can be made quite effective in preparing students for traditional exams consisting of standard problems. However, for reaching deeper understanding of the
3. Motivation

Science has many opportunities for making lessons exciting and creating interest within the boundaries of conventional teacher-centered teaching as well as in student-centered settings. The key to creating motivation is variation: variation of teaching methods, variation in seatwork tasks of students, variation in grouping using a spread of plenary, small group work, and individual activities in the classroom. Furthermore, the science teacher can make use of the many the everyday phenomena to illustrate science concepts. There are spectacular demonstrations with surprising outcomes. For example see Liem’s (1987) Invitations to Science Inquiry with 400+ demonstrations which can be done with very simple materials. See also my description of over 60 short physics demonstrations and visualisations which can be carried out without any special equipment in any classroom and it is relatively easy to expand this collection with new ideas (Berg, 2015). There are many interesting stories to be told about scientists (google on internet). There is interesting science in the many products we use such as computers and telephones and cars and satellites. Many simple ways to make science more interesting to our students in secondary school are not used sufficiently. The time invested in these activities is easily gained back through increased interest and motivation of students. Now we will turn to more sophisticated lessons of the 20th century which concern conceptual understanding of students.

4. Lessons from concept learning studies in the 1980s/1990s

From all research about learning in the sciences there is a general consensus (Duschl et al., 2007) that:

a) The brain is not a blank slate but it is filled with preconceptions which may have developed from very early life experiences or were even hard-wired in the brain (Thijs & Berg, 1995).

b) Some of the preconceptions match with science, others do not.

c) Therefore much learning involves reconstruction of prior ideas.

d) This can only succeed in an active process of minds-on learning activities.

So the question is what do we need to add to conventional teaching/learning in order to get this conscious, minds-on concept construction process going? The answer is to use intellectual engagement methods. This can be done in simple steps and in small steps. Nevertheless it will take a very conscious effort of teachers to learn to apply these simple methods. If applied properly, students will also:

e) acquire and exercise the important “learning-to-learn” skills which are part of the much advocated 21st century skills.

The statements of Duschl (2007) and Walberg (1991) above are results of the science education research of the past 40 years and could be called lessons from the 20th century for the 21st century. How can physics teachers apply these lessons under the normal classroom conditions they face in Indonesia and elsewhere?

5. Intellectual engagement methods

In many countries university engineering students take a series of 2 or 3 Physics courses and these are usually taken in large classes with hundreds of students per section.
The typical teaching method is lecture. Most of the lecture contents can also be found in the excellent textbooks such as Young and Freedman (2012), Knight (2014), and Cutnell & Johnson (2015). Often these courses are the bottle neck in the engineering curriculum, the place where students strand or are delayed because they do not pass. Examination used to consist of traditional problem solving of textbook problems. Studies of conceptual understanding of students and particularly studies with the Force Concept Inventory (Halloun & Hestenes, 1985; Hestenes & Swackhammer, 1992) showed that even students with acceptable results on traditional tests, have poor conceptual understanding. Since the mid 1980s there have been lots of studies with so called interactive engagement methods in which students are challenged with conceptual tasks during the lectures. Hake (1998) analysed the FCI results of many such courses in the USA with over 6000 students and found that intellectual engagement methods did have positive effects on the conceptual understanding of the students. As with all teaching methods, the effects are greater as the teacher gains more experience. So do not give up if the first time results are still disappointing. Interactive engagement was also studied in University of Surabaya engineering classes (Cahyadi, 2007) with positive results for conceptual understanding. Most of these methods are very applicable in Asian junior and senior secondary school classes. My teacher education students and I have used them in secondary schools in Indonesia, the Philippines, and the Netherlands. Some simple examples are the following:

1) Include some simple but challenging conceptual questions and let students discuss these in class with their neighbours (groups of 2 or 3 students). Students enjoy the discussions with their classmates and also enjoy the intellectual challenge of the questions. Appropriate discussion questions for Biology, Chemistry, and Physics can be found all over the internet and in good textbooks such as Hewitt’s (2013) Conceptual Physics and his Conceptual Integrated Science (Bio, Chem, Phys), the Tutorials of McDermott and Shaffer(2002), or ranking problems from O’Kuma et al (2000). It could be just one question and a few minutes discussion; it could also be several questions and a bit longer. A15-minute discussion in small groups can be very useful for students and the teacher will learn much about student problems with conceptual understanding.

2) Predict-(Explain)-Observe-Explain (POE) demonstrations, popularly called POEs. I use the term PEOE to emphasize that students also need an explanation to back up their prediction so that it is not just a guess. Liem’s Invitations to Science Inquiry (1987) contains more than 400 Physics and Chemistry demonstrations for secondary education with simple materials which can easily be changed to fit the PEOE format. A free pdf is still floating around the internet. I was told that there is an Indonesian version, but I have not been able to find it yet. Many other examples can be googled using “POE” or “predict-observe-explain”. Nowadays many have been recorded as YouTube films. Sokoloff & Thornton (2004) developed special interactive lecture demonstrations for large enrolment classes.

3) Students individually answer a conceptual multiple-choice question about a key concept and vote for an answer using coloured cards, white boards, or their telephones with Socrative or Plickers. The teacher immediately knows the result and can see which misconceptions are popular. If there are few mistakes, the lesson continues with the next topic. If there are many mistakes the teacher can either add additional explanation, or let students discuss (peer teaching, Mazur, 1997). See also section 8 below.

4) The teacher can take small and simple experiments to class using very common materials. For example, Fred Goldberg (Goldberg et al., 2012) forced by budget cutting at his university has transformed his inquiry labs for a maximum of 30 students/class
into classes with simple real and virtual lab activities with up to 100 students per class. Other teachers have developed similar materials. Such small 10-minute experiments with simple equipment would do well in secondary school classes to illustrate the connection between phenomena and concepts.

5) 21st century technology invented flipping-the-classroom. Teachers either record their classroom explanations to be viewed at home by their students, or they refer to existing explanations such as those of the Kahn Academy (https://www.khanacademy.org/) or Hewitt or other YouTube. Then classroom time is used for guided practice with the concepts. The point is to transfer part of the theory study to homework and use more class-time for guided practice. Of course one can also use textbook theory assignments as homework instead of viewing YouTube and then spend more class-time on concept discussion (see 1) and guided practice. We tried this in the Netherlands with a group of 15 teachers and they were surprised about the diligence of their students.

6) Knight (2002, chapter 4) lists more ways to stimulate intellectual engagement, particularly in large enrolment classes (>50 students) which of course can be used in smaller classes as well.

6. Time???

The most common reaction of teachers and lecturers is that there is no time for such activities because the curriculum is overflowing. Answer 1 is that there are textbooks. Not all curriculum concepts need to be explained in class, students can study the textbook and one of the main educational objectives is that student learn how to learn from textbooks. Answer 2 is that there is no point in “covering all material” without students understanding it. As Nobel prize winner Viktor Weisskopf said: it is better to uncover a little than to cover a lot (Figure 3). Answer 3 is that Hakes’s extensive studies showed that students in intellectual engagement classes achieved a better conceptual understanding and did equally well in traditional problem solving as compared with students in traditional courses.

Figure 3. Viktor Weisskopf (Nobel Prize winner): It is better to uncover a little than to cover a lot (drawing by Gerry van Klinken).

Please note also that your students’ conception of teaching is one where the teacher lectures and the student is passive and listens. Students will adapt to different teaching, they are young and flexible, but keep them clearly focussed on learning objectives and point out to them what they are learning (concepts, reasoning, …). Students in upper level secondary
and lower level university sometimes take the attitude that they are used to a certain way of (passive) learning and that it is too late for them in life to change. As Cahyadi (2007) wrote about her students in Surabaya: “students still possess a traditional paradigm of teaching-learning”.

7. **Embedded formative assessment and feedback**

If we learned anything from the many misconception studies, it is that continuous interaction is needed between students and teachers to track conceptual progress and provide continuous feedback. Furthermore, studies on formative evaluation have demonstrated the power of constructive feedback on student work (Black & Wiliam, 1998; Hattie & Timperley, 2007). How can one implement this without spending a lot of time on checking student work?

In many topics in physics it is possible to identify some main misconceptions and misunderstandings of many students in real-time during the lesson and attempt remediation immediately. Embedded in the teaching method the students are given short conceptual questions in a graphical format such as force diagrams, graphs, optics ray diagrams, sketches, etc. The questions are given one by one at a common pace. These are learning tasks, but from the results the teacher can immediately see what students understand and what not (Mazur, 1997; Berg, 2003; Keeley, 2008). With each question the teacher goes around and can check answers of ten students easily within 30 seconds due to the graphical format (force diagrams, sketches, etc.). (S)he can even squeeze in a brief interview regarding an unusual answer. As for many conceptual questions student answers tend to vary, peer teaching already starts while the teacher goes around. In their explanations to each other students will be *reasoning with concepts*, an important 21st century skill. Then, in plenary, the teacher can proceed according to the main conceptual problems he or she encountered while going around the classroom. Please note that this “embedded assessment” is also a form of interactive engagement.

A simple mathematics example comes from a diagnostic test in the Philippines among 567 students of age 13/14 and 15/16 (years 2 and 4 of secondary education). Figure 4 shows a simple subtraction problem that students in 6th grade elementary should be able to do. The wrong answer is surprising as here subtraction leads to a bigger rather than a smaller number. This is a conceptual problem, the student carries out an operation without estimating an approximate outcome. Looking a bit closer we see that the technical problem is that the student does not use the regrouping: 1–7 is difficult, so then the student does 7–1 instead of regrouping 11–7. The same for 2–6. Once you see that as a teacher, you know what to do. The trouble was that these students had progressed from elementary school to years 2 and 4 of secondary education and had never been corrected. Very sad. Problems like this can be prevented by regularly checking student work during class time (no need to take home piles of student note books).

![Figure 4. Answer of a secondary student to an elementary school subtraction problem.](image)
Figure 5(a) shows a rock on an inclined slope and asks the students to draw the forces. Figure 5(c) is a typical student answer with frequently made mistakes such as drawing gravity at a right angle to the slope, drawing a normal force straight up and friction in the direction of possible motion rather than opposing motion. Figure 5(d) shows a Dutch student’s (age 16) answer with a car in which exactly these errors are made. The red arrows are corrections by the teacher. A 10–20 minute exercise with force diagrams (Court, 1998) can expose a lot of student problems and assist them to develop their ideas about force. The exercise may need to be repeated a few weeks later to consolidate the results.

Fun and physics can be combined in the following exercise. Students are asked to draw an optics ray diagram to explain the photograph. While walking around, the teacher can clearly see whether students understand refraction and can apply it to an everyday situation. Subsequently the teacher can add more explanation or exercise if needed. A booklet with many ideas for concept checks and fast feedback is available as pdf from the author (Berg, 2008).

I developed and used methods for embedded assessment and feedback in the Philippines (Berg, 2003). It is interesting to do for the teacher and the students. The students get quick feedback on their own learning and the teachers learn much about the ideas and misconceptions of students and learn how to react effectively. At present we are applying these methods with a group of Dutch physics and chemistry teachers and in the process they learn much about teaching for understanding.

Figure 6. (a) The slide is shown in a screen or worksheet, the students are asked to sketch a ray diagram which explains what we see, and (b) from student solutions the teacher can infer whether students understand refraction or which errors are being made and need to be corrected.
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8. Reasoning with concepts and evidence

Research has shown that there is very little reasoning in the classroom while reasoning is one of the most important 20th and 21st century skills to be learned and practised (Naylor et al., 2007). Keogh and Naylor (1999) developed concept cartoons to stimulate reasoning in the classroom. In a cartoon (Figures 7(a) and 7(b)) students are shown different opinions about an everyday phenomenon. The opinions are typical for children and they make sense to them. The scientifically most acceptable opinion is presented neutrally as one of these. Then students are asked who is right and why. The cartoons turn out to be quite successful in getting students from age 9–18 to reason using their own experiences as evidence (Naylor et al., 2007; Naylor & Keogh, 2012). The cartoons can be used in three different ways: 1) to diagnose preconceptions, 2) to stimulate reasoning with evidence, and 3) to start investigations. I myself ask the students to think of ways how the phenomenon in the cartoon could be investigated. Students from grade 4 (age 9 or 10) and up are very quick in thinking of ideas and in a very spontaneous way start to investigate. The teacher then has to follow the process critically. There are concept cartoons on physics, chemistry, biology, and mathematics (www.millgatehouse.co.uk). Free cartoons can be found using google with “concept cartoons”. It is also easy to make cartoons yourself, perhaps involving one of your students who can draw well. A higher level of cartoons for senior secondary are Paul Hewitt’s Next Time Questions which appear every month in The Physics Teacher and can be downloaded for free from http://www.arborsci.com/next-time-questions.

9. Metacognition and higher order thinking skills

A teacher can try to correct all the little misconceptions encountered in the classroom, but it is learning itself that needs to be changed. Students have to become much more aware of how they can learn effectively and how they can consciously control their own learning. That is metacognition. That was the insight of an Australian group at Monash University in Melbourne in the 1980s, another 20th century lesson for the 21st century. With a group of teachers from different subjects they tried to make the students much more aware of their own learning (metacognition) and to develop Higher Order Thinking Skills (HOTS). Metacognition sounds sophisticated and it is, however, in the Monash project Ian and Judie Mitchell developed very practical ways to exercise metacognition such as giving instructions for a lab activity in random order to force students to think about what to do rather than following recipes. Or making concept maps or Venn diagrams, or distinguishing details and main points in texts, etc. (in Baird & Northfield, 1995). Zohar (2014) recently reviewed...
metacognition studies in science education and made a strong plea for more attention to metacognition and learning how to learn.

In short, there are simple 20th century lessons about the basics of teaching as Walberg (1991) taught us. Applying those, our students will improve much. There are also more sophisticated lessons about conceptual understanding and yet relatively simple to use intellectual engagement methods. Try to use them and teaching and learning will become more interesting.

References


