The Institution of Engineers in Scotland

The discipline of critical thinking

Working with complex uncertainty

A Strategy report

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Contents

1. Introduction

This report discusses ideas as to how the thinking modes and principles used by those who achieve success in situations of complex uncertainty can be identified and adopted.

A *critical thinker* is defined as a person who is constantly looking for and adopting principles that will lead towards successful outcomes. The principles that guide actions is *ethos*.

The contexts described in Section 2 illustrate some of the pitfalls in the solution of complex problems and some of the positive strategies that can avoid them. In Section 3, I draw together some of the principles and strategies involved and Section 4 discusses how people might learn to be critical thinkers.

Ethos is the core issue. Critical thinkers need to be students, in the sense 'one who studies', of the thinking modes/ principles that guide their actions. They need to collect guiding principles, and discipline their minds to use them - to avoid, for example, blind acceptance of what their intuition prompts them to do. Most people can adopt such a discipline but it best practised in the company of others and one should learn to adopt it from an early age. Therefore, it should become a discipline in another sense, i.e. a 'branch of learning' in education, as discussed in Section 4.

2. Contexts

The design of the Panama Canal[1]

Ferdinand de Lesseps (1805-1894), a French diplomat, gained international fame as the main promoter of the Suez Canal completed in 1869. In 1879 he arranged a congress in Paris at which an agreement was made for a French project to build a canal at the Isthmus of Panama. An important feature of the proposal was that it would, like the Suez Canal, be a sea level waterway i.e. there would be no locks. de Lesseps, on the basis of his success with the Suez Canal, got this principle accepted against the advice of engineers.

The construction started in 1882 but failed in 1889 due to a number of factors especially that the sea level passage proved to be impractical. de Lesseps made the serious error of assuming what worked in one situation would also work in another apparently similar situation. For Suez the maximum land elevation at a cut was 28m; for Panama it was 100m. Suez has a desert climate with little rain; at Panama there was a critical need to control swollen rivers during the rainy season.

Options for how the canal was to be built were considered but they were not properly evaluated by experts. An American team successfully completed the canal in 1914 by fitting locks to lift the vessels to a large artificial lake that controlled the flow of the rivers and provided water for the locks.

Constructing a canal to join the Atlantic and Pacific Oceans was a *non-determinate* problem[1] in that there was no 'exact' solution. The Americans achieved a solution but it may not have been the optimum. Building the canal further south using the existing Lake Nicaragua might have been more appropriate.

Note that the overall strategy for identifying a solution was to consider a number of possibilities. This is the *top-down* approach where one starts by postulating solutions and tests them against requirements.

Note also the consequences of not doing careful testing of solutions, of not listening to the experts. By not having his proposal fully tested, de Lesseps triggered a financial disaster and ruined his previously very high reputation. He barely escaped going to jail. He suffered from *hubris* - excessive confidence in his ability - a state of mind to be avoided by critical thinkers. Reliance on the efficacy of a previous successful solution has been studied by psychologists who call it the Einstellung Effect[2].

Preventing scurvy[3]

During long voyages in the sailing ship era, crew members suffered from scurvy, a disease with a range of debilitating symptoms commonly resulting in death. The problem was to find a way to avoid it.

In the 16th century, when it was observed that eating fresh food seemed to be good for avoiding scurvy, the only available strategy to address this problem was a top-down approach. We now know that scurvy is caused by shortage of ascorbic acid - vitamin C.

Dietary experiments included regular issues of lemon juice, lime juice, malt and wort but the success of these tests was varied. Lime juice was easier to procure than lemon juice but had less Vitamin C. Boiling the juice to concentrate it for easier stowage, removed the Vitamin C. During his first circumnavigation, Captain Cook issued malt and wort and had no crew deaths to scurvy although these substances are not rich in vitamin C. The likely reason for Cook's success in preventing scurvy was that he arranged fresh food for his crew when they went ashore.

It is interesting to note that James Lind, a ship's surgeon is credited with having conducted, in 1747, the first use of clinical trials (a critical thinking strategy) in seeking to identify the cause of scurvy.

We see in this experience, some of the pitfalls in the top-down approach:

- It can be dangerous to assume that a small change (e.g. (boiling the juice) will not affect the outcomes.

- Beware of a *post-hoc* argument where if B follows A then A is deemed to be the cause of B. Captain Cook's issued malt and wort (A) and scurvy declined (B); but B did not follow from A or was at least not the main reason for A. This is an example of a false correlation - a common situation in testing against data.

This was a fundamentally different type of problem from that facing the developers of the Panama Canal. It was *determinate* because it has at least one solution that fully meets the requirements i.e. ensure adequate intake of vitamin C.

The use of a top-down strategy was a minefield of unexpected consequences. By identifying the root cause as vitamin C deficiency and finding the needed level of intake, a determinate solution was identified. This allowed a bottom-up strategy for solving the problem i.e. the answer could be synthesised from rules. For most complex problems there is no root cause and solutions cannot be synthesised. This example shows the huge advantage of using science to find a root cause if it exists.

Identification of the role of vitamin C (in 1932) arrived too late because, with steam power, voyages had become short enough to avoid scurvy without taking dietary precautions - a solution that was not available in the sailing ship era.

The Glasgow water supply scheme[4]

In the mid-19th century, it was realised that the quality of drinking water for the city of Glasgow was a major issue for health. Glasgow Corporation hired John Bateman, from Yorkshire, to design a water supply system. Bateman was the foremost water engineer in the UK at that time with a reputation for leading successful water supply projects. He, and his colleagues, considered a number of possibilities and decided that using water from Loch Katrine, 38 miles from Glasgow was the best option. A 26-mile-long aqueduct was built providing water by gravity to a service reservoir. The structures for the aqueduct, built to a high specification, are still in very good condition.

By the 21st century, the quality of the water needed to be brought up to new international standards so a treatment works was designed and built close to the service reservoir. In reference 5 the following statement is made:

> 'Over 100 technical staff from 25 different disciplines considered 6000 possible options and 17 potential development areas were looked at in great detail. In total some 196 potential schemes were evaluated with respect to environmental impact, cost and risk.'

From this information we can identify some important principles.

First, the appointment of John Bateman was a wise decision. The success of a project is critically dependent on the ability of the leader of the team. In 1810, the Swedish authorities appointed Thomas Telford, the renowned Scottish civil engineer, as the engineer for the Göta Canal that links the west east coasts of the country. On a visit to that canal, I noted that the contribution of Telford was barely mentioned in the publicity about it. Telford's appointment in 1810 was controversial in Sweden. 'Why was it necessary to go abroad for expertise?' 'Were there no Swedish engineers who had the necessary competence?' I expect that when John Bateman was appointed as engineer for the Glasgow Water Supply, similar questions were asked. A quite different attitude is appropriate. Rather than being criticised for not supporting local talent, the action of the Swedish Government and of Glasgow Corporation in putting aside their national prejudices and appointing the top gun should be celebrated as critical thinking.

Second, designing the Loch Katrine water supply system for the long term was a good strategy. Keeping down the cost of the works was important but not if that compromised the long-term performance.

Third, having 25 disciplines working on the design of the new treatment work is evidence of a clear intention that all relevant issues should be competently addressed. Also, the design team considered a very wide range of possibilities for the new works: where it should be sited, what treatment technologies should be used, etc. It is interesting to note that the siting of the works was criticised at the time. It is likely that those who suggested that it was wrongly placed lacked important information but it is also possible that despite trying very hard to identify the most appropriate solution, a better site could have been chosen. When working with complex uncertainty, even if you adopt critical thinking to the limits of its potential, there is no guarantee that you will eliminate faults. What is guaranteed is that the risk of unsatisfactory outcomes will be reduced.

Manufacturing, The Deming philosophy

There is a story, probably true, that in the 1980s a delegation of American engineers went to Japan to find out the reasons for the success of the latter's manufacturing industry. The Japanese hosts explained how rather than have production targets, everyone in the organisation adopted a constant and unremitting drive towards improving the processes that were used to create products and provide services. The visiting party asked about how such a mode of operation arose. Was this part of the Japanese culture? The reply was that it was an American, W Edwards Deming, who had introduced these ideas to Japanese manufacturers. Deming (1900-1993)[5] had promoted his ideas in USA with little success but the Japanese were amenable to adopting them.

Manufacturing is one of the most competitive activities in society. It is very difficult to succeed without careful attention to strategies for doing well. Manufacturing firms use a range of methodologies e.g. Lean, 5S, Six Sigma, Total Quality Management, that lead back to the work of Deming. He is the 'father' of the concept of continuous process improvement.

His principle that one should not set production targets is counter-intuitive. How can you produce more widgets unless you have an objective for doing that? Deming was opposed to *numerical* targets. He is quoted as saying "Give a manager a numerical target he will make it, even if he has to destroy the company in the process." In meeting the target, a manager may, for example, compromise the quality of the product leading to customer dissatisfaction and a drop in sales. Deming's point was that improvement in production rate should be based on a *method* of achieving it rather than on exhortation to work harder.

Drive out fear

Deming set out 14 points for good management of manufacturing processes. Point 8 is: 'Drive out fear, so that everyone may work effectively for the company'. My interpretation of what that means is shown in Table 1.

Table 1 Drive in fear, drive out fear

Action by employee	**Action by manager**	
	Drive out fear	**Drive in fear**
Make a non-wilful mistake	Treat as a learning opportunity.	Threaten employee with punishment.
Point out faults in the organisation	Welcome suggestions and use them if appropriate; reward those who make suggestions that are adopted.	Ignore such advice; treat the employee as a whistle-blower; seek to have them dismissed.

A 'drive in fear' style of management is common. It is a high-risk strategy because (a) the employee is likely to hide mistakes and (b) working with ideas from all persons directly involved in a project is likely to give better results. Some managers seem to believe that their appointment confers special status in relation to wisdom and that because of this, their ideas must be superior to those from people at lower levels in the organisation. This is absurd.

Working in safety-critical contexts tends to result in acceptance that a 'drive out fear' ethos is essential. If getting it wrong can be disastrous, then it becomes recognised that every strategy for reducing risk must be used. For example, it was discovered that in some air disasters, crew had information that the captain needed but was not communicated by colleagues because of the rigid command structure in the cockpit. Crew are now trained to share information; captains are expected to consult with their crew members and to welcome information from them. It is called

‘Crew resource management’. Such ethos should be pervasive in organisations. It is whistleblowing turned on its head. Rather than being vilified for pointing out faults, people are praised for putting forward ideas that might help to improve performance.

It is important that people learn, from the earliest practical age, that a ‘drive in fear’ style of management is inappropriate. Those who have experience of working under a drive in fear manager will tend to adopt that style when they become managers. Regrettably, in some cases, the abused become the abusers.

Use of the ‘drive out fear’ principle is also described as a ‘just culture’.

Collaboration

A key issue in Deming’s philosophy is collaboration. It seems obvious that everyone in an organisation should be focused on the goals of the organisation but this is often not the case. If management creates a ‘them and us’ ethos, the employees will focus on their own goals.

Some people believe that competition/the market will solve all problems whereas other believe that co-operation is the answer. It seems clear that both competition and cooperation are necessary in society and a fundamental objective of any management system must be to get the right balance between the two. The Deming approach leans strongly on the co-operation side.

The Deming philosophy defines how attitudes should be shaped for success; it can be applied beyond manufacturing.

Critical thinking in Parliament

Parliamentary procedure

The Government develops policy and the Opposition seeks to find faults with what the Government proposes. Karl Popper, the 20th century philosopher, put forward the principle that when scientists test a theory, they should try to prove that it is wrong: to show that it is false. If they fail to so do, they can have some confidence that the theory is correct but can never be certain of that. Solving a non-determinate problem may not be quite the same as assessing a scientific theory but the basic principle that one should seek to prove that a solution is unsatisfactory is relevant. In law, the accused is considered to be innocent until proved guilty; when solving complex problems, a proposed solution should be assumed to be unsatisfactory until its efficacy has been properly assessed.

That members of the Opposition should challenge government proposals is therefore a worthwhile principle but the Government tends to ignore proposals by the Opposition and the Opposition tends to disagree with the Government. The situation is confrontational. For successful problem solving, a collaborative approach is needed where both sides seek to find the most appropriate solution, each of them being *prepared to change their minds* in the face of better arguments. But in politics changing your mind is viewed as a sign of weakness. Especially due to pressure from the media, politicians are very reluctant to change course.

Parliamentary/government decision-making tends to weakly address solution testing. Use of evidence-based policy is often talked about but it does not appear to be a major feature of government decision making. This situation is negative to a main aspiration of Parliament - that it should take actions that are in the best interests of the people.

The role of government ministers

When speaking about decisions made within their sphere of influence, government ministers tend to talk in the first-person singular. They, understandably, enjoy making their own decisions. That they do make independent decisions represents a serious fault in parliamentary decision-making. They should not be allowed to over-rule well thought out proposals developed by a team of experts. If they have an alternative proposal, they should say to the team “Here is another solution, please test that against what has been proposed.” When the proposals are put to Parliament, the justification for them should be made available to the public. When talking about decisions, ministers should speak in the first-person plural.

Energy policy and critical thinking
The EU Renewable Energy Directive[6] is aimed at reducing emissions from the firing of fossil fuels. The 2018 directive requires that member states will fulfil a binding renewable energy target for 2030 of at least 32% of total energy use. This violates the principle (see page 4) that one should not set a numerical target for an objective in a multi-objective context, unless it is based on a plan that takes account of all relevant issues. Countries should develop a feasible plan based on the resources available to them. Successful implementation of the plan then becomes the target

Making significant reductions in CO_2 emissions may be one the most complex problems ever attempted to be solved on a global basis. Use of critical thinking will be an essential component of the strategy being used.

Summary for Section 2

The contexts discussed in in this section exemplify features of complex problems such as:

- They are intrinsically difficult
- A range of competing objectives may need to be considered
- Solutions need to be tested using formal processes.
- They involve risk
- A range of disciplines may need to be involved.

A range of problem types is also evident: The Panama Canal and the Glasgow Water Supply Project had to be *designed*. i.e. what was to be built had to be specified. Then the process of how it was to be built had to be defined. This was *planning*. Investigation is about identifying the state of an existing or of a past entity. The scurvy problem was *diagnosis* - a special type of investigation. Design and planning normally involve investigations.

Table 2 lists generic contexts for complex problems (there may be others). Although 'design' normally relates to physical objects and 'planning' normally relates to processes, these words are used interchangeably.
'Design' and 'Plan' are about structuring the future. 'Investigate' is about the present or the past.

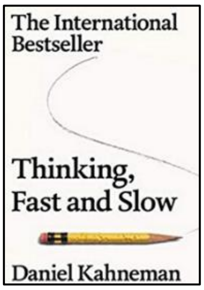
Table 2 Contexts for complex problems

Context (What is to be done)	**Design/plan** (Decide how it is to be done)	**Implement** (Do it)
Create a physical object	Design - create models of the object	Make the object
Work with a new process	Define the plan for the process	Administer the process
Investigate - gather information about the condition of an existing or past entity, diagnose	Plan the investigation	Carry out the investigation, issue a report

From the contexts discussed in this section, one can infer some of the principles that may be used in critical thinking. I investigate some of these principles in Section 3.

3. Principles for Critical Thinking

The psychology of critical thinking



In his 2012 book, *Thinking fast and Slow*[7], Daniel Kahneman, the psychologist and economist, puts forward the idea that we make decisions in two modes: a fast mode where we use intuition and heuristics (i.e. simple rules) and a slow mode where we make judgments based on evidence i.e. we use logical thinking. He makes an analogy with computer operating systems. It is as if our brains have two operating systems: System 1 for the fast decisions and System 2 for slow, logical decisions. He does not claim that this is how the brain works, it is just a simple analogy.

Kahneman and his colleagues identify a range of heuristics that prompt us to make quick decisions. For example, when we use the *availability heuristic,* we make judgements that are based on the most recently accessed information. What we hear in the news strongly shapes how we interpret situations. One could read Kahneman's book to identify and seek to avoid the heuristics that we use in System 1 decision-making but there is a safer method. One can bypass these heuristics by using the overarching one: 'In critical thinking, do not jump to conclusions: always test solutions' i.e. 'Use System 2'

Chapter 7 of *Thinking fast and slow* is titled: *A machine for jumping to conclusions* but the human brain is also a machine for using critical thinking in situations of complex uncertainty. This is a defining characteristic of our species. No other animal can come close to the ability of humans to design, to plan, to investigate - and no computer algorithm can come close to replicating the full scope of such cognitive activity.

People often relate problem solving to puzzles where there is a unique answer but where the process of identifying the solution is not known to the participants. In complex problem solving, the situation is reversed. There is normally no solution that meets the requirements precisely but the overall, top-down strategy for identifying the solution is fixed. One has to guess solutions and apply some level of testing of their validity. The crucial issue is how much resource should be allocated to the testing work. Natural instinct is to take the easy option to do no testing by relying on intuition.

Rather than use a binary 'operating system' analogy (i.e. the two 'operating system' model mentioned above), it is also useful to think of a spectrum of decision making - Figure 1. At the tacit end of the spectrum, one jumps to a conclusion. In the explicit zone one allocates an appropriate amount of resource to seek to ensure satisfactory outcomes. As the complexity increases, a project team needs to work to a plan.

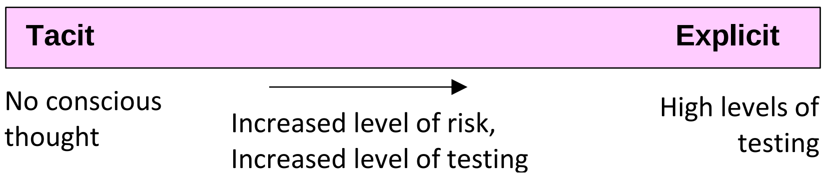


Figure 1 A spectrum for decision-making

For many situations in day-to-day life, the tacit approach is appropriate but when, for example, the decisions will affect other people or the environment, then, if solutions can be tested, they must be tested.

Intuition is an essential component of thought. It prompts ideas about existing and new concepts but it should not be blindly trusted when making important decisions. It is not easy to counter one's instincts but when confronted with a complex problem, the natural reaction - the ethos - should be to test solutions rather than to jump to conclusions.

The solution testing process

In *To Engineer*[8], I used the term 'Engineered design process' to denote the basic process in decision-making for top-down problem solving, but that name suggests that it is only applicable to design. Here I use the term 'Solution testing process' to better represent what it is for, and its wider scope of application - although more that testing is involved.

In the solution testing process, certain actions are dominant:

1. Information about the context is gathered.
2. A set of requirements is established against which solutions will be tested
3. Information about options sufficient for the assessment is gathered. It is best to compare a range of options.
4. The options are compared against the requirements and a decision made as to the one to be used.
5. The chosen option is then fully developed.
6. Review and revise cycles are pervasive in the process.

While the process is described with different words and phrases, e.g. as in Figure 2, there is very little difference in what is intended. It seems that it is *the* fundamental process for testing solutions - because the needed actions follow logically from the intention to test. However, the testing is unlikely to be a linear process or be confined to the design/plan stage - Table2. For example, in manufacturing, prototypes are often designed, made and tested followed by re-design. Review and revise can be pervasive through the *life* of a product.

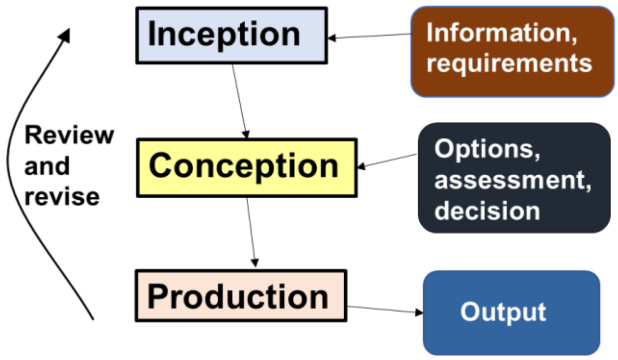


Figure 2 The solution testing process

Ethos

There is a crucial need to be explicit about the ethos that needs to be adopted by critical thinkers[8,9]. The mainly tacit heuristics used in fast decision-making must be replaced by a different set. I denote these alternative heuristics as 'guiding principles' or 'principles' and together they comprise the 'ethos'.

Other words/phrases that relate to this concept are: 'culture', 'habits of mind' (see reference 9), 'attitude', 'mindset'. 'Ethos' has other meanings: for example, it represents a mode of persuasion in rhetoric but I find it to be the most useful existing word in this context.

Here are some guiding principles that may be applicable in most contexts:

- Test solutions

  Allocate an appropriate amount of resource to testing of solutions.
  Use the solution testing process - before making a decision.
  Monitor performance - after decisions have been implemented so as to identify and correct faults.
  Do not assume that what worked in one situation will necessarily be applicable in another similar context.

Assess risk.
Seek to ensure that all relevant issues are taken into account (the holistic approach).

- Be reflective
  Ask questions, find answers and make appropriate responses.
  Have an open mind: challenge personal prejudices and conventional wisdom, avoid dogma, be open to your opinions being challenged and be prepared to change your mind.
  Think for yourself but not by yourself.
- Treat failure as a learning opportunity
  If you make a mistake - own up and move on.
  Drive out fear- see page 4.
- Focus on the project goals
  Put the achievement of the project goals ahead of personal considerations such as prestige, pride and avoid conflicts of interest.
- Adopt an ethical stance.
  Integrity beyond question.
- Work to a plan that is appropriate to the context.

Everyone can improve their ability in critical thinking by submitting to the needed discipline of identifying and using appropriate guiding principles. Actions to achieve this can include:

- Train your mind to avoid jumping to conclusions.
- Be a student of ethos i.e. be constantly on the lookout for guiding principles that may be used to improve outcomes.
- Observe how people who are good at solving problems operate. Seek to be explicit about what guides their actions and copy them.
- Write down the principles and use them.
- Do not assume that the principles will all be relevant in every context. Look for context specific principles.

One can adopt an explicit ethos to guide one's own actions but in a leadership role it is important to seek to ensure that the ethos under which you intend to operate is understood and adopted by the members of your team. Ethos tends to flow down a management hierarchy. One cannot expect to influence the ethos of those above you in an organisation and direction from above may limit your ability to adopt your preferred ethos - but this should not prevent you trying.

Getting others to adopt an ethos is not just a matter of putting a list of principles on the wall e.g. as is often done for mission statements. It is necessary that those involved 'live' with the ideas. Strategies for making this happen need to be devised and used.

4. Education for critical thinking

In *To Engineer*[8] I state that:

"There would be significant benefits to society if:

- all learners were introduced to the principles of critical thinking principles and
- education initiated a lifelong development of ability to solve complex problems."

One of the objectives of education is to learn to operate in job roles - Figure 3. I can think of no more important job skill than the use of critical thinking.

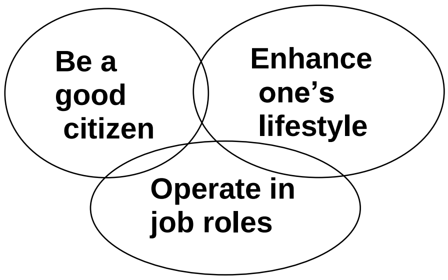


Figure 3 Some Objectives in education

Critical thinking and STEM

The Scottish Government's 2017 report[10] states:

> "STEM related education and training seeks not only to develop expertise and capability in each individual field, but also to develop the ability to work across disciplines and generate new knowledge, ideas and products through inter-disciplinary learning."

This important statement infers that STEM should address critical thinking.

To 'generate new knowledge, ideas and products through inter-disciplinary learning' is a very worthwhile goal but it should be a pervasive feature in education, not exclusive to STEM. STEM education needs to be strengthened to have a stronger focus on critical thinking and this focus needs to be extended across education.

Modes of learning

In *taught learning* students acquire knowledge and skills that are mainly pre-defined. The contexts are dominantly determinate where the outcomes can meet the requirements precisely. At the outset these outcomes are known by the examiners. Rote learning is in this category.

In *project-based learning* students develop ability to solve complex problems that are mainly non-determinate, where top-down is the only feasible strategy. The context may focus on a subject or on a general problem that involves a range of subjects/disciplines. The project outcomes are not known by anyone at the outset. This makes project-based learning radically different from taught learning.

One can think of taught learning and project based learning as ends of a spectrum of real life learning experiences. Traditional education tends to be close to the taught end of the spectrum and a better balance is needed.

One connotation for the term *problem-based learning* is that of acquiring specialised knowledge via solving of problems that require such knowledge. This has been used, for example, in the education of medical doctors and is sometimes criticised for resulting in lower level of knowledge uptake than is desirable. For example, it would be very difficult for a medical student to acquire a good overall knowledge of the bones, muscles and nerves of a body only via problem solving. In some learning contexts, rote learning is needed. Learning for critical thinking' is not strongly directed towards acquisition of specialised knowledge. It is focused on a different educational objective.

I use the term *Project Learning* as a separate subject that is dedicated to learning to be a critical thinker.

In Table 3 issues in relation to learning modes are summarised.

Table 3 Issues for learning modes

Issue	Taught learning	Project-based learning
Support role	Teach, instruct	Mentor, advise, instruct
Knowledge of outcomes	At the outset, teachers know the expected outcomes.	At the outset, neither mentors nor learners know what the outcomes will be.
Attitude of learners	"Show me how to do it and I will do it."	"Tell me what is to be achieved and I will try to find a way to do it."

While opportunities can be taken in taught learning to develop critical thinking, the essential activity for developing such skill is project work.

Critical thinking in primary education

A primary school project

Jean, the head teacher of Scottish Primary School A needed to brief architects about the layout of a new building for her school. She asked Aileen, head teacher of Primary School B, to advise her. School B has a semi open plan layout. Aileen set up this request as a project for her senior pupils and gave Jean two reports, one from herself and the other from her pupils.

This was a very suitable project because asking the pupils to report on the suitability of an environment with which they were familiar was a very good exercise for developing critical thinking in a design context. Also, the clear purpose of the project is likely to have been good for motivation.

Primary school teachers often take advantage of flexibility in the curriculum to use project work in learning.

Primary school teachers should seek to help learners to be critical thinkers when they work on projects - see information about Primary Engineer on page 14. Research is needed to identify typical ages at which different aspects of critical thinking may start to be used.

Critical thinking in secondary education

As part of a Primary Engineer postgraduate module for teachers, Lynne Mylet, a Technology teacher in a secondary school in Glasgow carried out a study of the effectiveness of engineering project work[11]. She wrote

> "Prior to this project, students were unlikely to question or analyse the work that they had been given and simply followed instructions, normally from a worksheet or from the board. Now they can think for themselves and problem solve more readily than before. This is an area which will greatly improve their employability in the future and I will keep trying to foster this skill in my students in future years."

This encapsulates the arguments that I make in this paper for a more explicit approach to critical thinking in education. A further dimension needs to be added to the way that learners think (e.g. to think for themselves) and to the way that teachers think (e.g. seek to foster such skill). It also demonstrates the importance of the work being done by Primary Engineer[13].

The subject oriented structure of secondary school curricula makes it difficult, but not impossible, to introduce projects that address a range of subjects. Because the curriculum is established nationally it is not easy to introduce a Project Learning subject.

Learning for critical thinking should be treated as a discipline where:

- Opportunities are taken in all projects to develop critical thinking.
- Teachers use opportunities to promote critical thinking in their subjects. For example: history teachers can use methodologies for historical analysis to develop ability in carrying out

investigations; science teachers can demonstrate how information from scientific theories are used in decision making; English teachers can promote the principles of technical writing that are used in project work.

Critical thinking in university education

In university education there is tension between what is 'academic' and what is 'vocational' as exemplified by the development of engineering education in the UK.

Engineering education in the UK

The first appointment to a chair of engineering in the UK, in 1840, was at the University of Glasgow. The conventional wisdom at UK universities at that time was that the practice of engineering did not have sufficient rigour for study at university. It was not till 1872 that the then professor of engineering at Glasgow, William Rankine, was able to establish a degree in engineering science on the basis that it was not to be concerned with engineering practice.

In mid-20th century, I studied for the degree of Engineering Science in Civil Engineering at Glasgow University that was based on the 19th century curriculum. Application of the science was not absent. Our introduction to engineering design was via an example of how to specify the connection between plates connected by a bolt. The minimum diameter of the bolt could be established from the shear stress in the bolt and the minimum plate thickness could be identified from the bearing stress. That is, we were shown how to synthesise the sizes for the connection. Later we learned how to calculate the minimum area of steel in a reinforced concrete beam. We were given a formula that included the depth of the cross-section as a variable. We asked "What is the formula for the depth of the beam?" The shocking answer was "There is no formula. You have to guess a value and find out if it is adequate". Thus, in the third year of the course, we were introduced to the top-down approach to problem solving and the uncertainty inherent in engineering design.

That this was revealed to us more than half way into the course was not the fault of those who taught us. It resulted from the UK-wide decision in the 19th century not to address the practice of engineering in engineering degrees. The practical issues that we did address were only related to the design of components and not to systems. Although this was a narrow spectrum within the scope of engineering design, it was important. It was mainly concerned with safety - a critical issue in the design, for example, of a structure. Also working with safety criteria helped us to develop a mindset for testing solutions. We were not introduced to a holistic approach to solution testing but it was a good start in that direction.

The course, as established by William Rankine, was a 'sandwich' course: there were four six-month academic sessions interleaved with three six-month sessions working in practice. This was a worthwhile arrangement but experience in practice is a lottery. Working on innovative projects under the direction of highly competent practitioners is probably the best way to learn about the practice of engineering but that cannot be guaranteed. Education should seek to instil the use of a range of fundamental principles that may not be well addressed in practice.

In 1980, the Finniston Report[12] advised that the deep focus on science in UK engineering education should be abandoned. This has resulted in the adoption of, for example, a more holistic view of design and the inclusion of project-based learning. But a good balance between engineering science and other important professional engineering issues and between the basic principles and their application, has been slow to develop. The achievement by professional engineers, of successful outcomes in situations of complex uncertainty, far from representing a low level of intellectual achievement, requires mental activity at the highest order. In the 19th century, the people who managed the UK universities failed to understand this. This failure still casts a long dark shadow over engineering education in the UK.

University curricula

The subject oriented nature of tertiary education limits the potential for learning to solve problems across subjects and disciplines but, from an administrative point of view, the introduction of Project Learning modules is not difficult to achieve. Project Learning subjects are included in some curricula, for example:

- Degrees in engineering where the project contexts are mainly in engineering design.
- Degrees in architecture where the title of the subject is normally 'Design Studio' and is normally 50% of the curriculum. The context is architectural design.
- The University of Aalborg in Denmark was set up in 1974 on the basis that a significant proportion of the curricula is Project Learning. Contexts are wide-ranging.

Project Learning modules can be introduced as part of a course, can be faculty wide or institution wide. Making such modules available across the curricula allows students from a range of disciplines to be involved. This can be very worthwhile because complex problems often require a multidisciplinary approach.

Teachers can take opportunities to help leaners to be critical thinkers via taught learning and project work. For example, here is a brief account of my experience in seeking to do that:

Learning for structural analysis

One of the subjects that I taught was *Structural Analysis* - the use of mathematical models to predict the behaviour of structures under load. In the past, the main difficulty was in doing the calculations and therefore in learning, the main question was: "How do I do the calculations?" Using computers, the calculations became the easy part of the process and a wider range of types of model could be used. Important questions for learning became "Will the model satisfy the requirements" i.e. model validation, and "Are the results from the computer correct?" i.e. results verification.

In the examination that I set for this subject, I provided a description of an analysis model and computer results for it. The students were required to validate the model and verify the results. I gave them a checklist of questions for these processes. To help with study for the examination, I made available typical responses for the previous examination paper where the model was a bit different from that in the current paper.

About half of the class tended to give responses as for the previous year - that did not apply to the new context. These students had not grasped the fundamental principles of validation and verification. I had failed to appreciate that, what was obvious to me, was not obvious to that group of students. They expected to be asked to get correct answers by doing calculations. I had asked them to operate in a non-determinate context where they were expected to make judgements about the suitability of assumptions. Looking back, I should have been more explicit about the difference between these contexts.

I am pleased to say that some of my students got the message. Well, at least one of them. Mohamad Ali Mian made this comment on a book[13] that I wrote:

> 'The book took my thoughts back to the 1980's when I was a student in your company, making discussions and your emphasis on structural behaviour, modelling and back of envelope assessment. These thought processes continued and matured in my mind: the mindset I use in all my pursuits of engineering endure.'

Support for learning for critical thinking

Primary Engineer A teacher who had an idea about learning for problem solving and made it happen

In 2005, secondary school teacher Susan Scurlock was disappointed that the future performance in education of a good proportion of her pupils was going to be compromised by lack of commitment to learning. She asked herself “What could I do to change this situation?” She decided that involvement in engineering projects was the best way to capture the imagination of learners. She obtained seed corn funding, quit her post and launched Primary Engineer[14]. Under her leadership, this organisation, with a staff of 20, now provides a range of services to help teachers and learners in primary and secondary schools to be involved in engineering projects. The activities include:

- Teacher training modules for projects established by Primary Engineer.
- Annual competitions:
  - The Leaders Award competition where pupils respond to the question “If you were an engineer, what would you do?”
  - STATWARS where pupils use data to design Films and TV Series and to identify things they can change to positively impact Climate Change.
- A postgraduate module for teachers that is focused on methods for supporting the development of critical thinking.
- Support for Project work via the Institutions of Primary, Secondary and Tertiary Engineers where a network of teachers, learners and people from industry collaborate to develop a culture for solving real world problems.

Primary Engineer is now a major resource for teachers who seek to promote critical thinking. It represents a very good example of the type of support that is needed.

Needed actions

I do not suggest a radical change to the way that subjects are taught. What I do propose is that learning for critical thinking should be introduced as a discipline - in the sense of a branch of learning. This prompts the need for the following actions:

1. *Ethos of education* The principle that critical thinking should be viewed as a discipline needs to be accepted.
2. *Leadership* Those who are responsible for programme planning in education should adopt the above principle and take action to make it happen.
3. *Resources*   A range of resources is needed to support learning for critical thinking. For example, the contribution to this of Primary Engineer is summarised above. Online information is needed including: guidance for teachers and learners; experience sharing e.g. project briefs, examples of project outcomes, etc.
4. *Training* Teachers need to be trained to act as mentors in project-based learning and to take advantage of any opportunity to help learners to adopt a critical thinking ethos.

Summary for Section 3

The need for critical thinking is pervasive in society. I take it as irrefutable that such learning should be given more attention in education. A critical thinking discipline needs to be introduced in education.

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