Thinking like an engineer: using engineering habits of mind to redesign engineering education for global competitiveness

Lucas, B.
Director
Centre for Real-World Learning
University of Winchester
Winchester, UK

Hanson, J.[1]
Researcher
Centre for Real-World Learning
University of Winchester
Winchester, UK

Conference Topic: The attractiveness of Engineering; Curriculum development; Active learning

INTRODUCTION

If we want to ensure that young engineers are ready to meet the challenges of the future and can operate in a global environment, we need to know how successful engineers think and act when faced with challenging problems. Once we have identified these distinctive engineering 'habits of mind' (EHoM) we can then suggest how the education and training system might be re-designed to ensure the cultivation of these EHoM in school, college and university. Funded by the Royal Academy of Engineering, our research found that there was considerable agreement about the six habits of mind that engineers use most frequently when engaged in the core activity of 'making' things or 'making things work better'. As a result of these findings, we suggest that active teaching approaches, such as PBL or CDIO, although helpful, can in themselves only take the learner so far. However, if the curriculum overtly articulates EHoM as an outcome of learning and if teachers provide students with opportunities to develop and practice them at all levels of the education system, more successful engineering learning will occur.

1 ATTRACTING YOUNG PEOPLE INTO ENGINEERING

1.1 The need for more engineers

The worldwide shortage of engineers is traditionally described as a classic supply and demand problem, as most recently identified in the UK by the Perkins Review of Engineering Skills [1]. However, we suggest that at least part of the reason that we do not have enough engineers is because we do not know enough about how great engineers actually think. Furthermore, we do not make enough use of what we do know to actually teach engineering in schools, colleges and universities in ways that cultivate the kinds of engineering minds we need. In fact, we argue that the opposite is more common. This is why, in response to an approach from the Royal Academy of Engineering, the Centre for Real-World Learning (CRL) suggested that research into the apparent supply-demand issue might be approached by asking two fundamental questions: (*1) How do engineers think and act?* and (*2) How best can the education system develop learners who think and act like engineers?*

Our first challenge was whether we could we reach consensus on how engineers think, considering the huge breadth of the engineering sector. Our second question is dependent on a successful result with the first. Can we re-design the education system in terms of its pedagogy so that it is more likely

[1] Corresponding Author: J. Hanson, janet.hanson@winchester.ac.uk and www.winchester.ac.uk/realworldlearning

to produce more people who think and act like engineers? In this paper we explore the idea that a better understanding of engineering habits of mind (EHoM), could lead to more precise specification of the learning cultures and learning methods which might best cultivate the desired EHoM. Then the pedagogies used by teachers in schools, colleges and universities might change to produce more and better engineers and we no longer have to talk of 'shortages'.

1.2 Why the minds of engineers matter

Despite the urgent need for more engineers, we found that, in the UK, with a few exceptions, engineering does not appear on the timetables of pupils of primary or lower secondary school age. After age 14, engineering starts to become more visible as, for example, in some academies, university technical colleges and studio schools. Post 16, further education colleges provide a wide range of engineering qualifications and at university there is a rich tradition of higher level study, and yet society still needs more engineers. Our response to this challenge is to suggest that it is reframed by exploring it through a new lens stimulated by the 'habits of mind' approach. In approaching the research in this way, we posed questions such as: What do engineers do? How do they think? How do they approach problems? How is what they do similar to but different from how a scientist or a mathematician sees the world? What does an engineer have in common with an artist or a designer or a technologist or a politician or a team sports player? What, in short, goes on in the mind of an engineer when he or she is in full flow doing engineering?

We discovered that engineers do think and act in certain distinctive ways and we refer to these specific ways of thinking and acting as 'habits of mind'. In this paper we explore the EHoM which have emerged through an iterative process of study and conversations with practising engineers and educators. We do not present our EHoM simply as a different way of describing or packaging the engineering curriculum, nor aim to develop a new set of competencies or standards. At the very least we think that how people think and act as they learn is likely to give us greater insight into their mind than what they know – their knowledge - or what they can do – their skills. We suggest that, without a good understanding of EHoM on which to ground choices about teaching and learning methods, we should not be surprised that too few young adults choose to study engineering.

2 RESEARCH APPROACH

We adopted a mixed methods approach for our research which aligned well with the Royal Academy of Engineering's wish to incorporate multiple perspectives and explore real-world approaches to learning. We reviewed the literature relating to habits of mind in engineering, mathematics and science and searched for case studies in which innovative pedagogies had been used to develop habits of mind at all levels of education. While there is an extensive literature relating to engineering pedagogy in higher education in the UK, there is relatively little at lower education levels, in contrast with USA, where we found some exciting examples of engineering education with young children. As non-engineers, we also sought to increase our insight into engineering by reviewing definitions and creating word clouds from these. We also mapped terms from specifications such as UK-SPEC and EUR-ACE; looked at websites offering young people insight into engineering careers and learned much from jokes about engineers. From these sources we developed our initial list of potential EHoM and carried out semi-structured telephone interviews with twelve engineering educators. These individuals were selected from a list of 28 names provided by the Royal Academy of Engineering and included engineers involved in education at all levels. The interviews were recorded and transcribed. In order to reach a wider audience, we developed a questionnaire that was circulated by the Royal Academy of Engineering and completed online. Anonymised quotes have been used from the interviews and survey to illustrate points throughout this paper. In order to validate our findings and gain further insight into EHoM and effective pedagogies, we established an expert group of practising engineers and engineer educators whom we brought together on two occasions for seminars at the Royal Academy of Engineering. A total of 23 individuals participated in the first session and 12 in the second. In the first session we discussed our EHoM model and invited participants to share examples of effective pedagogies. In the second session we invited participants to discuss our draft report and help us formulate recommendations based on our findings. The final stage of our research involved matching learning and teaching methods recognised as effective in a wide range of disciplines to our validated EHoM, allied to conceptual development by the research team of a broader pedagogical framework within which these might fit.

3 HABITS OF MIND

3.1 Background to Habits of Mind

Habits of mind (HoM) is an expression used by psychologists such as Resnick [2] to describe aspects of intelligence. It has been adopted in the USA by educationalists Costa and Kallick who suggested how the role of teachers might change if they were deliberately trying to encourage the kinds of HoM mentioned by Resnick. They came up with sixteen HoM which, taken together, describe what smart people do as they go about their lives successfully dealing with whatever unexpected problems are thrown at them [3]. In the UK, Guy Claxton created an approach to teaching and learning called 'Building Learning Power' (BLP) [4] which has seventeen HoM. More recently at CRL we have drawn from these three traditions to create and validate an extended model of practical learning which blends habits and frames of mind [5]. We have also researched the development of creative habits of mind [6] which became a proof of concept for focusing on a discipline such as engineering and seeking to identify its characteristic HoM.

3.2 Engineering Habits of Mind

Drawing on our broader experience of HoM, we investigated the extent to which they are used in engineering pedagogy and also within the teaching of its associated disciplines of mathematics and science. In the USA, engineering is now included as a specific subject within the school curriculum at primary and secondary levels in many states and educators have drawn on the HoM tradition to consider which HoM might be at the core of engineering. In particular, a major review of engineering education within K-12 primary and secondary education has called for curriculum development to be underpinned by the promotion of six EHoM [7]. These six are 'systems-thinking', 'creativity', 'optimism', 'collaboration', 'communication' and 'attention to ethical considerations'. Thinking in Australia also supports the idea that engineers need to be lifelong learners and that current educational approaches need to change [8].

3.3 Mathematical and Scientific Habits of Mind

Interest in habits of mind in mathematics and science has also emerged, fuelled by concern about public perceptions of these subjects and their role in society. In discussing the contribution of these subjects to solving important real world problems, scientists, mathematicians and educationalists identified a mismatch between what scientists and mathematicians actually do and what gets taught in school. One way of resolving this was suggested by Cuoco et al. [9] who distinguished between real-world mathematics and what happens in schools and then explicitly refocused on the teaching of mathematics as the cultivation of mathematical habits of mind (MHoM), or the ways in which mathematicians think about problems, rather than on the mathematical content which is taught. They identified a generic set of MHoM together with more specific subsets for geometry and algebra. They imagine mathematicians as 'pattern-sniffers', 'experimenters', 'tinkerers', 'visualizers' and 'conjecturers'.

There has been parallel thinking about scientific habits of mind (SHoM). Çalik and Coll [10] evaluated various approaches to the selection and definition of key SHoM. Their selection proved to be reliable and useful as a predictive tool in various contexts and included habits of mind such as 'open-mindedness', 'scepticism', 'objectivity' and 'curiosity'. Leager [11] stresses how teachers can overtly develop SHoM in the classroom by modelling the attributes of curiosity, openness and scepticism.

3.4 CRL's Engineering Habits of Mind

From this review we developed our own EHoM to evaluate with practising engineers and engineer educators. We retained six overall, but adopted only one of the American terms outright, systems-thinking. We rejected the other five, although important, as being more generic and substituted other EHoM by drawing on the more detailed descriptions of the American terms and on the mathematics and science HoM which appeared to us to overlap with the EHoM. Our six EHoM are described in *Fig 1*. Of course, in addition to our specific EHoM, there are other powerful learning dispositions such

Fig. 1. Centre for Real-World Learning Engineering Habits of Mind	
Systems-thinking	Seeing whole, systems and parts, and how they connect, pattern-sniffing, recognising interdependencies, synthesising
Problem-finding	Clarifying needs, checking existing solutions, investigating contexts, verifying
Visualising	Move from abstract to concrete, manipulating materials, mental rehearsal of physical space and of practical design solutions
Improving	Relentlessly trying to make things better by experimenting, designing, sketching, guessing, conjecturing, thought-experimenting, prototyping
Creative problem-solving	Applying techniques from other traditions, generating ideas and solutions with others, generous but rigorous critiquing, seeing engineering as a 'team sport'
Adapting	Testing, analysing, reflecting, re-thinking, changing (physically and mentally).

as curiosity, optimism, resourcefulness, resilience and reflection, which engineers, like all professionals, need for lifelong learning.

4 OUR RESPONDENTS' VIEWS ON EHOM

When asked the question 'What do engineers do?' our respondents repeatedly stressed that the desire to 'make things that work' or make things 'work better' was the driving force behind what made them become engineers:

Great engineers constantly challenge the 'norm' and are always looking for improvements and innovation in everything they do. They are never fully satisfied with a product or outcome and will try and modify and improve what they have designed or produced to make it better. ***(Respondent 2:34)***

We also found considerable consensus among all respondents that our six EHoM were appropriate descriptors for the characteristic ways in which engineers think and act when faced with challenging problems relating to making and improving things. However, despite an overall agreement on the importance of all six, there were some differences of opinion on the relative importance of each at different education levels.

Systems thinking was universally supported as an important EHoM but was felt to be particularly difficult to cultivate, perhaps being of most importance the more advanced the level of engineering became:

*The idea that everything you do sort of builds to making you into a rounded, capable person who can link all the knowledge together is the one that perhaps we could work on. (****Respondent 8:57****).*

Problem-finding was also regarded as a sophisticated EHoM and more likely to be exercised by experienced engineers or by learners after they had successfully built up a repertoire of approaches to problem solving based on given problems:

I want them to solve the problems that I presented and then build up a sort of database on that experience that will help them find problems later on. ***(Respondent 3:70)***

Some respondents wondered whether 'finding' was the best term, suggesting 'formulating' or 'framing' as alternatives. But the majority agreed that separating out problem-finding from problem-solving was important.

Visualising was regarded as an important EHOM for all education sectors to cultivate, since it enabled an engineer to take an abstract idea and communicate a practical solution in a more concrete form:

To be able to take something abstract and then make it into a practical solution, you have to have that sort of visualisation to be able to do that. ***(Respondent 4:38)***

Improving, or a relentless drive to improve products, was regarded as a core characteristic of an engineer. It was the result of constant tinkering and experimenting to find better solutions:

They [engineers] *are never fully satisfied with a product or outcome and will try and modify and improve what they have designed or produced to make it better.* ***(Respondent 2:34-36)***
However, this was not just for the sake of it, the underlying drive was to move society forward:

It's all about making things easier for people's lives...whether it's a product that you're making simpler to use, or making something quicker to use… its improving people's lives. ***(Respondent 4:42)***

Creative problem-solving provoked strong reactions. There were those who thought that it was the most important EHOM:

Creative problem solving is the real standout there. That's my number one. ***(Respondent 10:78)***

This was predominantly the perspective expressed by those engaged in primary education, while those involved in post-compulsory engineering education expressed doubts, not about the importance of problem solving itself as an EHoM, but about preceding it with the adjective 'creative'. These respondents were in no doubt about the importance of creativity in engineering, because:

*You often have to bring ideas from different disciplines and different divisions to solve the problem. (****Respondent 1:50)***

However, other thought that being creative might be in conflict with the requirements to consider previous solutions to problems and to adhere to recognised standards:

It is common in engineering to use concepts that are not original. Engineers would not normally think that they were being creative unless at least one of the options involved a new concept. Therefore the qualification of problem solving by the adjective creative excludes a lot of engineering work. ***(Respondent 11:87)***

This idea is not supported elsewhere, where the need for creativity to be given greater prominence in the education of engineers is stressed in order to secure new and innovative solutions to challenging world problems [12]. In trying to find a path through this debate, another respondent referred us to the distinction between BIG creativity and small creativity outlined in the Robinson Report [13]. So, while we have included 'creative' with problem solving for now, we recognise that further discussion around this EHoM is required, since it clearly raised an important point about engineers' perceptions about engineering:

*I believe engineering to be much more of an "art" than we commonly recognise. Experience and intuition complement scientific knowledge and underpinning. There is quite a contrast to the approach to a problem taken by a competent engineering professional, to that taken by one a "scientist" (****Survey respondent 40)***

Adapting is an EHoM about which respondents had mixed views. Primary level educators thought that it was too sophisticated a concept for entry level engineers and could only be cultivated after they had some experience to draw on to make judgements. However, experienced engineers and those within higher education thought that it was an important EHoM:

*[Adapting] is very important; a lot of engineering is doing the same things only slightly differently. (****Respondent 5:107)***

Several respondents suggested that it was unlikely that all our EHoM would be found in one engineer and stressed the overall importance of the team in successful engineering projects. Nevertheless, they argued that engineers should be sufficiently self-aware to know when it was appropriate to draw on the skills of others in the team:

I think good engineers, certainly in a team, can do that. They can do what they have to do but they can also sort of observe themselves doing it and ask, "Am I using the appropriate skills at the appropriate points in all of this? ***(Respondent 8:71*****)**

Engineers, as MacLeod puts it, rarely operate in one mode only, but are able to move between 'two modes of thinking' [14] and as a consequence of these discussions we realised that much of the engineer's world is necessarily about holding a series of tensions in balance, for example, between using creativity to invent new ways of doing things and using logic to make things work:

I think any very good engineer can do both, to look at something quite creatively and then put it into some sort of logic to actually get to an end solution. ***(Respondent 4:24)***

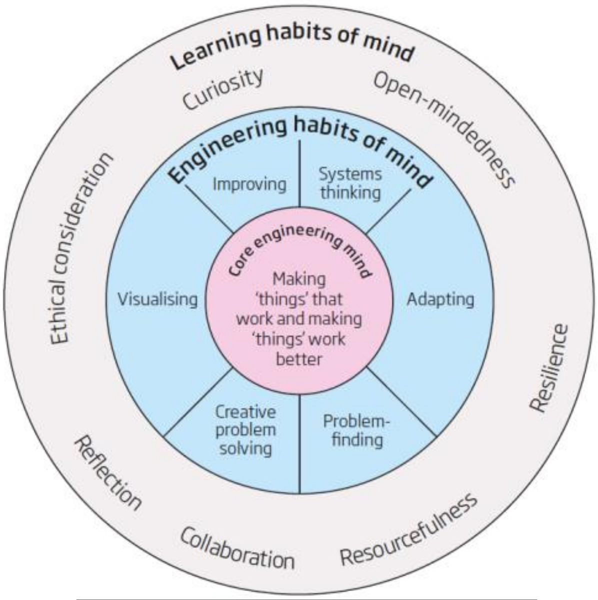

Fig.2. CRL's Engineering Habits of Mind

Having found agreement on our six EHoM, we chose to represent our model in *Fig.2* as series of concentric circles because it allowed us to:
a) articulate at the core of the model the driving force of engineering – 'making stuff';
b) distinguish between two sets of habits of mind important to engineers, placing the more specific EHoM closer to the core, but recognising the relevance of a broader set of learning habits.

We recognise that the term 'making' refers principally to traditional engineering disciplines and also that engineers engage in all sorts of activity which may not involve making things [15]. However, even engineers such as chemical or software engineers who do not 'make' physical products as such, are involved in the sub-elements of making such as designing and implementing. It is this extended definition of 'making' to which we attach central importance.

5 THE IMPLICATIONS OF EHOM FOR ENGINEERING EDUCATION

In our full report [16] we provide examples where innovative pedagogies likely to develop EHoM have been used in schools, colleges and, in particular, in universities [17] where methodologies such as CDIO and PBL offer great potential for developing EHoM. However, good examples, especially at school level, are limited, so we explored the extent to which it might be possible to build on these existing trends by focusing more precisely on the kinds of pedagogical approaches which seem most likely to cultivate learners who might really think and act like engineers.

5.1 Three approaches to engineering pedagogy

By pedagogy we mean two things: *'Pedagogy… is the science, art and craft of teaching. Pedagogy also fundamentally includes the decisions which are taken in the creation of the broader learning culture in which the teaching takes place and the values which inform all interactions* [18].

We suggest that there are three approaches through which engineering educators might make more effective decisions about teaching and learning methods to cultivate learners who really think and act like engineers:

- consider the overall sense of what engineers do and adopt an holistic, or signature' pedagogy which seems, on balance, likely to 'make' engineers;
- look at the six EHoM individually and see what educators have found to be most helpful in cultivating each of these;
- approach the challenge from a different perspective by looking at teaching methods which, in other subjects or vocational pathways, seem likely to be transferable.

5.2 Signature pedagogies for engineering

The concept 'signature pedagogy' refers to *'the types of teaching that organize the fundamental ways in which future practitioners are educated for their new professions'* [19]. The first candidate 'signature pedagogy' for engineering would be to use the engineering design process as the organising principle for teaching. While there are many variations and degrees of complexity inherent in this process, it can nevertheless be easily grasped at all phases of education. It can also be used to contextualise student work in science and maths and foreground engineering practices rather than maths and science practices [20]. Another potential 'signature pedagogy' may be computational thinking, particularly as it is a key feature of the new Computer Science GCSE curriculum in England.

5.3 Methods likely to cultivate specific EHoM

A second way of making choices about pedagogy would be to think specifically about which methods might best cultivate our target EHoM and in our full report we explore these in detail. To give just one example, to develop the EHoM **'**Improving' a powerful method is a process of continuous improvement known as the PDSA (Plan-Do-Study-Act) Cycle developed by Deming and Shewhart [21].

5.4 Vocational learning methods that work

Our third suggestion is to consider learning methods that work in other vocational areas. In our earlier research for City & Guilds [22] we identified a list of vocational methods which work in a number of different contexts and which are part of an engineering repertoire: *Learning by…watching and imitating, by practising, through feedback, by being coached, through conversation, by teaching and helping, by real-world problem-solving and enquiry, by thinking critically, by listening, transcribing and remembering, by drafting and sketching, by reflecting, on the fly, by competing, through virtual environments, through simulation and role play, and through games*. We encountered five additional methods widely used in engineering education. While these can also be used in other vocational areas we found them to have a specific engineering 'spin' on them which makes them noteworthy. The methods, which we describe in more detail in our full report, are: modelling and virtual modelling, using case studies, industry mentoring, capstones and flipped classroom. Of course, any kind of vocational teaching, especially that which aims to cultivate our proposed EHoM, is likely to involve a complex blend of approaches suited to student needs and available resources. Of all the approaches to pedagogy we have encountered, the one created by David Perkins seems both thoroughly grounded in the literature and accessible. In a metaphor which could have been chosen with engineers in mind Perkins explores the ways in which educators can 'make learning whole' [23]. He offers seven principles which seem well suited to both learners and teachers in the real world of engineering education. These include ideas such as 'using extended projects and authentic contexts', working on the hard parts' and 'uncovering the hidden game to make the processes of learning to become an engineer as visible as possible. In our full report we explore all seven of Perkins' ideas in more detail.

6 SUMMARY

Our research found a high degree of consensus in answer to our first question '*How do engineers think and act*?' This enabled us to articulate six engineering habits of mind which are: systems thinking, problem-finding, visualising, improving, creative problem-solving and adapting. The endorsement of these six EHoM by engineers provided the evidence for us to suggest, in answer to our second research question, that the problem with the current education system at all levels is that it does not do enough to cultivate the habits of mind required by today's global engineers. Although there is considerable innovation at higher education, opportunities for young people to encounter engineering in school are far too few. Furthermore, there is little or no explicit acknowledgement that pedagogical methods might be chosen which would cultivate the EHoM that engineers told us they valued. We suggest the engineering teaching and learning community needs to consider re-designing engineering curricula at all levels which *start* from the premise that they are trying to cultivate learners who think like engineers, and we have suggested three starting points for considering these pedagogical methodologies.

REFERENCES

[1] Department for Business, Innovation & Skills, (2013), Professor John Perkins' Review of Engineering Skills, Department for Business, Innovation & Skills, London.

[2] Resnick, L., (1999), Making America Smarter, *Education Week Century Series*, Vol.18, No.40, pp.38-40.

[3] Costa, A. and Kallick, B., (2002), Discovering and Exploring Habits of Mind, Association for Supervision and Curriculum Development, Alexandria, Virginia.

[4] Claxton, G., (2002), Building Learning Power, TLO Ltd, Bristol.

[5] Claxton, G., Lucas, B., and Webster, R., (2010), Bodies of Knowledge; how the learning sciences could transform practical and vocational education, Edge Foundation, London.

[6] Lucas, B., Claxton, G. and E. Spencer, (2013), Progression in Student Creativity in School: First Steps Towards New Forms of Formative Assessments, *OECD Education.* Working Papers, No. 86, OECD Publishing. Available: http://dx.doi.org/10.1787/5k4dp59msdwk-en

[7] Katehi, L., Pearson, G. and Feder, M., (2009), Engineering in K12 Education: Understanding the status and improving the prospects, Committee on K-12 Engineering Education, National Academy of Engineering and NRC, National Academies Press, Washington, DC.

[8] Beder, S., (1999), Beyond technicalities: expanding engineering thinking, *Journal of Professional Issues in Engineering Education and Practice*, Vol. 125, No. 1, pp.12–18.

[9] Cuoco, A., Goldenberg, E.P. and Mark, J., (1996), Habits of mind: an organizing principle for mathematics curricula. *Journal of Mathematical Behaviour* No. 15, pp. 375-402.

[10] Çalik, M. & Coll, R., (2012), Investigating socioscientific issues via scientific habits of mind: Development and validation of the Scientific Habits of Mind Survey. *International Journal of Science Education,* Vol. 34, No. 12, pp. 1909-1930.

[11] Leager, C., (2005), Fostering scientific habits of mind. *Iowa Science Teachers Journal*, Vol.32, No.3, pp. 8-12.

[12] Orhun, E. and Orhun, D., (2013), Creativity and Engineering Education. Proceedings of 41st SEFI Conference, 16-20 September 2013, Leuven, Belgium.

[13] Robinson, K., (1999), All our futures: Creativity, culture and education - The Robinson Report, Department for Education and Skills, London.

[14] MacLeod, I., (2010), The education of innovative engineers. *Engineering, Construction and Architectural Management*, Vol. 17, No. 1, pp. 21-34.

[15] Royal Academy of Engineering and Engineering Council, (2000), The Universe of Engineering - A UK Perspective, Royal Academy of Engineering, London.

[16] Lucas, B., Hanson, J. and Claxton, G., (2014), Thinking like an engineer: implications for the education system, Royal Academy of Engineering, London.

[17] Royal Academy of Engineering, (2012), Enhancing Engineering Higher Education: Outputs of the National HE STEM Programme, Royal Academy of Engineering, London.

[18] Lucas, B., Spencer, E. and Claxton, G., (2012), How to teach vocational education: a theory of vocational pedagogy, City & Guilds, London, p.14.

[19] Shulman, L., (2005), Signature pedagogies in the professions. *Daedelus,* No. 134, pp. 52-59.

[20] Berland, L. K., (2013), Designing for STEM integration. Journal of Pre-College Engineering Education Research, Vol. 3, No.1, pp.22–31. [Online] http://docs.lib.purdue.edu/jpeer

[21] The W. Edwards Deming Institute (2014) https://www.deming.org/theman/theories/pdsacycle

[22] Lucas, B. Spencer, E. and Claxton, G., (2012), Op. Cit., p.61.

[23] Perkins, D., (2009), Making Learning Whole: How seven principles of teaching can transform education, Jossey-Bass, San Francisco.