
AC 2011-2354: NEW PERSPECTIVES ON TEACHING INNOVATION TO ENGINEERS AN EXPLORATION OF MENTAL MODELS OF INNOVATION EXPERTS

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New perspectives on teaching innovation to engineers –

An exploration of mental models of innovation experts

In the 21st century, society and policy makers are looking to technological innovation not only to solve specific challenges, but as a primary element of overall economic growth and success¹. As a result, educating for innovation has become an imperative for engineering. While some elements of innovation education have been in practice for some time, the increased focus on this non-traditional topic raises questions, including: Can innovation truly be taught in an intentional and systematic way? What content is important, and what approaches are helpful? What can we learn from innovation experts that would contribute to innovation education?

We have started this inquiry by using a “mental models” approach. In the first stage, we are eliciting expert mental models about innovation and innovation education, based on a set of open-ended interviews with a diverse set of innovation experts. This paper reports the features of the preliminary composite model emerging from these interviews that could provide a framework for designing instruction for innovation education.

Background and Methodology

In the last decade there have been many articles and books seeking to describe successful innovation. Many of these books have sought to frame the elements of successful innovation for managers^{2,3}. A few have taken the perspective of educators, bridging to practice⁴. Several engineering courses have focused on asking students explicitly to find “innovative solutions” to design problems.^{5,6,7}

Our work does not start from the existing educational approach. We are explicitly concerned with exploring how the perspectives of experts in the practice of innovation can help shape what pedagogies could help enable students to be innovators or contribute to innovation and, building upon these perspectives, what specific skills and knowledge base it may be useful to include in engineering education.

As a pilot to a larger mental model study, we conducted ten semi-structured interviews with experts to arrive at their mental models of what constitutes technological innovation, and what does not; what characterizes innovative organizations and what personal attributes of innovative individuals are. We also asked them what features of education may foster students’ innovation skills and behaviors. We have previously used a mental models approach to understand the conceptual framework of students and to design curricula^{8,9}.

As was observed more than twenty years ago, true expertise is “a mixture of analysis and intuition” that is “a sophisticated form of reasoning...that an expert hones over years of job-specific experience.” Expertise is built on seeing patterns, after analyzing tens of thousands of

relevant “chunks” of information¹⁰. More recently, a study has reported how the most successful innovators practice and develop specific “discovery skills” that distinguish them from others¹¹.

The experts interviewed for this study included recognized innovators and effective innovation managers from a variety of disciplines and industries, including materials, biomedical products, computers, and banking. Their innovation expertise was gained and demonstrated in multiple environments ranging from academic laboratories to start-up companies and large corporations. Experts also included knowledgeable educators and scholars of innovation from academia. All interview subjects expressed interest in innovation education as well as practicing innovation, and half (five) of the interviews were with experts who had career experience as educators as well as innovators.

Mental Models

‘Mental models’ is a psychological term that refers to people’s construction of a “model” in their mind of real or imaginary situations. A mental model captures a connected set of observations, assumptions and beliefs about a domain-specific situation that people draw upon when they think of the situation. Peter Senge writes, “Mental models are deeply held internal images of how the world works, images that limit us to familiar ways of thinking and acting. Very often, we are not consciously aware of our mental models or the effects they have on our behavior”¹². The family of methods called “mental model approaches” attempts to characterize people's intuitive theories of complex domains, in a manner approaching their natural formulation^{13,14,15}. Rouse and Morris have suggested that “The search for mental models is most likely to be successful if a more pragmatic perspective is adopted that emphasizes the utility of the mental model construct for understanding and improving instruction, system design, and other applied ends”¹⁵.

Mental model protocol

For this study, subjects with considerable expertise in innovation were explicitly sought for these initial interviews. We asked a few general questions as prompts, rather than a direct question and answer format to elicit the mental models of our experts and recorded their answers. The prompts focused first on defining innovation and then describing what fosters innovation: the environments, motivations, skills and experiences that are part of each expert’s mental model. Finally, the interviews elicited the elements and approaches to innovation education that are most aligned with each expert’s mental model. The result is a scheme of how each expert thinks about innovation and the implications for innovation education.

Elements of Expert Mental Models of Innovation

We used a fishbone diagram as the initial framework for organizing information from the expert interviews, The key elements from the mental models interviews are integrated into a composite diagram (Figure 1), which references both promoters and inhibitors of innovation success (Figure 2 and Table 1). Elaboration of the “bones” of the fishbone structure is below.

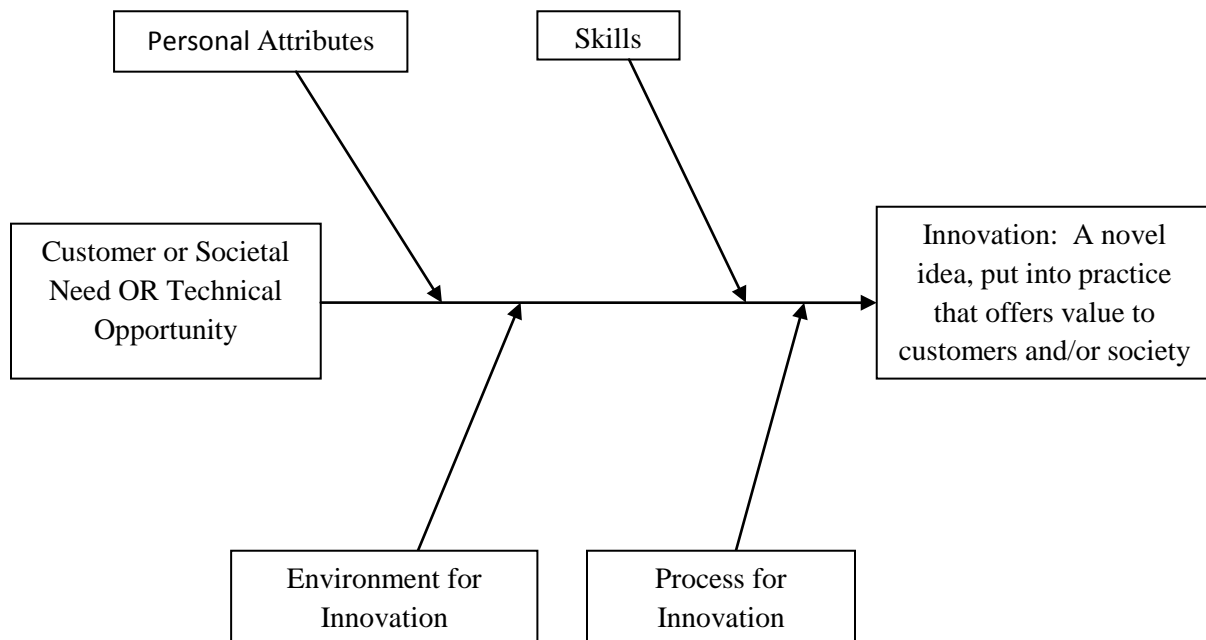


Figure 1: Framework for Organizing Mental Models of Contributors to Innovation

What is Innovation?

Each interview started with the question: “How do you define innovation?” Although there was some variation in specific words, the experts consistently named the same set of key concepts: something new, something that is implemented, and something that provides value. In Figure 1, this composite definition is expressed as: “Innovation: A novel idea, put into practice that offers value to customers and/or society.” Graphically, this is the “end-point” of a composite mental model that summarizes elements that contribute to or advance innovation.

Although “value” is an essential element of innovation, among this set of innovation experts the description of “value” was quite broad. Innovation value was described as “meeting a need that fulfills ... what a market requires”, but also as “a difference that makes a difference”, “positively impacting a lot of people” and even “helping the world”.

Most of the experts clarified their definition of innovation by emphasizing that innovation requires more than “just creativity”, more than “just ideas”, and “invention is not the same as innovation.” One noted that “an academic idea does not lead to innovation because it’s not affiliated with any end game.” The implementation and value creation are essential. Summarizing our experts’ statements, “It is far more than creativity or an invention in a field because it integrates understanding and responding to a need by making an actual product that adds value to people’s lives.”

This is an important point to keep in mind in teaching. While there is a significant literature on teaching or fostering creativity, the carry-through to a value-creating end product under realistic

constraints and how one teaches it is a particular issue to address in teaching students to be innovators or to manage innovation. In the words of one expert, “creativity doesn’t need to have a market.” Innovation does. Teaching for innovation is also different from teaching entrepreneurship. An experienced innovator and professor noted, “You can teach entrepreneurship – with enough case studies and core examples of what’s been done in the right way and what’s made it work, including a kind of team to form around you. ... But you can’t make them think of a new invention or find a new innovation; but (for entrepreneurship) you do not have to, very often there is a new idea out there that they just need to be able to nurture and foster. Innovation is a lot harder than entrepreneurship”

The Starting Point: Customer or Societal Need OR Technical Opportunity

If the common “end-point” is an innovation, the experts offered some different perspectives on the motivating goal. Both the “pull” of a need and the “push” of technical opportunity were cited – often the same expert cited both. On balance, however, the motivating emphasis for successful innovation appears to be “pull” of a need. “In some cases, innovation comes about because the need is very, very clear.” One expert cited the classic work by Eric von Hippel on the sources of innovation¹⁶, as showing that “(most) of the time the innovator was the one who had the actual need.” Of course, need is not enough, an innovation requires both “seeing a problem or opportunity that others do not necessarily see and finding a solution for it.”

Personal Attributes

Whether the starting point is a need or a technical opportunity, however, innovators are motivated by a goal. To quote one of our experts: “if there is no goal, I cannot function.”

Different perspectives are valuable to innovators. “People who are innovative are usually people who are in between two areas.” “I don’t feel satisfied unless I am thinking something which is completely different.” “To be a successful innovator, I am a skeptical optimist.”

They are willing to experiment, and take risks: “Have that personality that you are okay with risks.” “Getting to fail fast and the willingness to move on.” “The willingness to destroy existing concepts or well established practices.”

Innovation is not easy, and personal commitment makes the difference: “You do whatever it takes”; “don’t hold anything back”; “if there is a problem and you are not ready to throw all you have, then don’t be a leader.”

Skills

Technical knowledge and confidence are important for technological innovation: “You have to have enough knowledge of your field to know that an invention has not been previously invented and is actually a new contribution.” But, technical knowledge is not enough. “It’s really a

combination of being a technologist and having market knowledge and understanding because you need to know what will be the application of the technology that you are thinking about.”

Even real needs that are met with good technical solutions do not represent all the elements of innovation. Some of the required marketing skills for value creation are outside the expertise of typical engineers: “it’s about creating want and desire in a population that this new device or entity would make life better.”

There is also a need to sell within organizations. “After the idea, there’s the implementation and deployment, so you have to convince your boss.” “How to tell a story, iteratively prototype, and being able to bring your concepts to life.”

Innovation is a team sport, and requires working well with others: “You have to bring a team together and you learn so much when you hear these different perspectives about the problem.” “Being able to step back and say ‘we are more similar than different, what can we learn from each other?’.” “You have to be okay that other people come up with the same idea, other people can promote through the organization.”

It is also important to be able to “think forward.” “What most innovators are doing is thinking of something today that may have major impact years from now. It’s that long to get there but the impact is going to be transformational.”

Processes

There is a mixed sense of the role of “process” in innovation. Some argue that a prescribed “process” limits creativity. Nonetheless, experts at managing innovation recognize that there are clearly different stages of innovation. The starting point may be an idea, but management of the idea in the front-end is critical. Resources are limited, so it is important to know the “one or two decisions to get right”. Key early decisions include “what attributes create value for what customer, and what system of business activities will deliver these attributes to the customer at the lowest total cost.”

The experts recognize that the process for innovation is “not linear”. Multiple experts cited the importance of using feedback loops consistently for learning in successful innovation – whether something is successful, or unsuccessful, how does it inform your hypothesis?

One expert suggested concepts originally developed at Toyota as a model for an innovation “system”, moving beyond a process. The expert suggested that innovation within a system designed for learning is particularly powerful as has been suggested by Spear¹⁷.

Environment for Innovation

“Smart people” are an important part of a good environment for innovation. From a corporate perspective “you should be cataloguing and capturing expertise and ensuring we have adequate

expertise in those fields where we have to make decisions.” Because innovation often occurs at the boundaries between disciplines, an environment that encourages intermingling of disciplinary perspectives is good for innovation.

A negative for innovation is an environment that focused on tearing apart ideas, and leaving them abandoned. Rather, the environment should be one where everyone works to try to find a way to “make it a yes.”

The key aspect of a good environment for innovation is the emphasis on learning by closing the loop on things that are tried, success or failure. One expert mentioned one company’s environment: “If something fails no one ever gets blamed. Instead, senior people roll up their sleeves and say ask 1) Why did it not work? 2) What could have been done differently? And 3) How do we memorialize this so others can learn? And they celebrate the learnings.”

Surprisingly, constraints and stresses received multiple mentions as part of an environment that promotes innovation. “Once you introduce a new stress you will get innovation.” Constraints can be regulatory, or even financial.

Summary of Expert Mental Models of Innovation

Figure 2 and Table 1 represent a summary of the attributes of all these elements contributing to innovation. Figure 2 is an elaboration of Figure 1 to show that each element has associated attributes that may promote (+) or inhibit (-) innovative behavior and outcomes. Table 1 lists examples of promoters and inhibitors for each element.

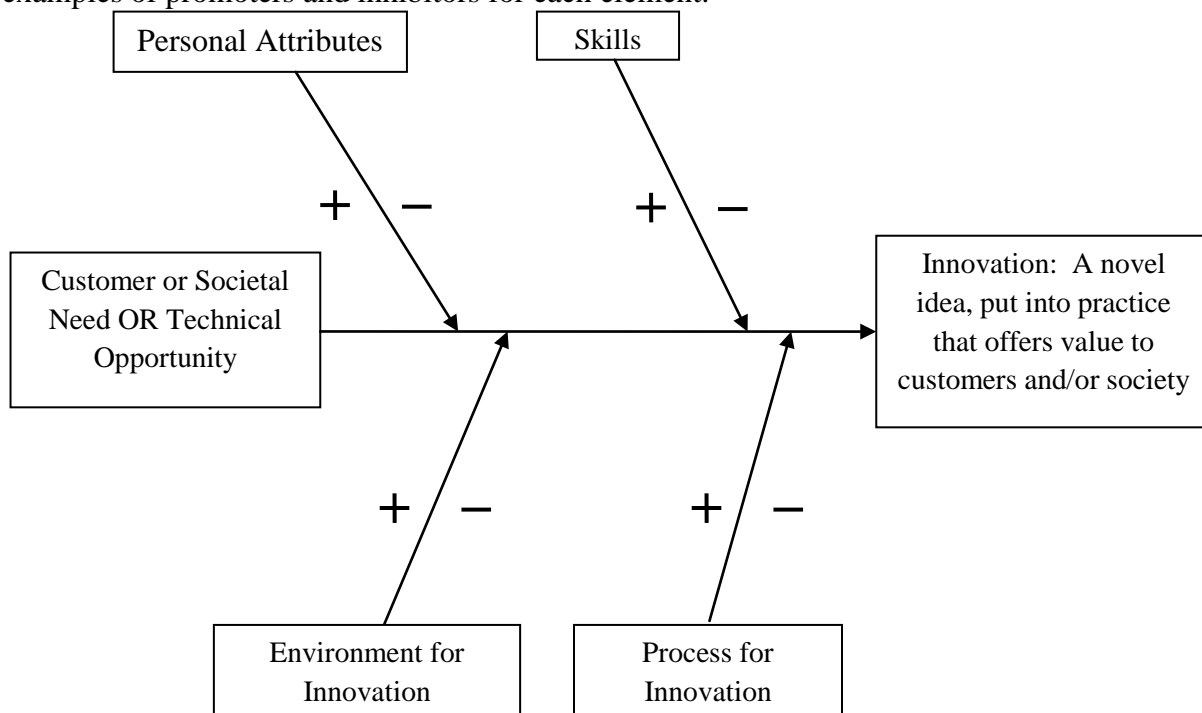


Figure 2: Overview Composite Mental Model Including Promoters and Inhibitors of Innovation (see Table 1)

PROMOTERS (+)	INHIBITORS (-)
Personal Attributes	
<ul style="list-style-type: none"> • Original, positive outlook: “skeptical optimist” • Accumulated expertise but also attitude • Comfortable with multiple perspectives • General interest in and curiosity about the world; interest in multiple fields • Confidence: “trust your gut” • Informed risk-taking, “OK with failure” • Commitment, energy and excitement: “embrace who you are” 	<ul style="list-style-type: none"> • Lack of confidence • Overcritical of oneself and others • Risk aversion
Skills	
<ul style="list-style-type: none"> • Technical depth in a field and breadth in others • Interdisciplinary thinking • Thinking beyond defined problem boundaries; recognizing and challenging assumptions • Team skills: <ul style="list-style-type: none"> ○ respect for diverse perspectives ○ Associating team responsibilities with project needs and individual strengths • Communication, “telling the story” • Market knowledge and understanding to “look forward” 	<ul style="list-style-type: none"> • Lack of deep understanding in at least one field • Narrow disciplinary problem solving: focusing on technical depth without attention to real-world constraints and opportunities • Over- reliance on existing technical literature and experts during brainstorming phase
Process for Innovation	
<ul style="list-style-type: none"> • Management of initial idea • Systems understanding of organization and related spheres • Decision making with understanding of system 	<ul style="list-style-type: none"> • Linear process thinking • Over-specified project details • Trying to do something original at the cost of usefulness
Environment for Innovation	
<ul style="list-style-type: none"> • Common goal: “Unified in the vision of finding a solution” • Understanding that expertise takes time • Smart, confident, committed people • Acknowledging diverse strengths of the team: “receptive, rewarding system where value is placed on innovative ideas” and “mixing and moving people around” • Encouraging environment, ability to float ideas • Learning from success and failure: “look for surprises and explain them” • Celebrate learning 	<ul style="list-style-type: none"> • Underestimating the drain of energy when people are not the best • Tearing apart initial ideas that sound risky • “inventing in a vacuum”

Table 1: Example Attributes of Elements that Act as Promoters or Inhibitors of Innovation

Implications for Innovation Education

If the elements that contribute to successful innovation include a motivating goal (customer or societal need to meet OR technical opportunity to exploit), personal attributes, skills, a process or system for innovation, and an environment for education, we propose that educators should look to these same elements in developing innovation education for engineers. Thus, as shown in Figure 3, to enhance the ability of engineers to contribute to valuable innovation, innovation education should be designed to reinforce the key elements that contribute to innovation. Note that Figure 3 proceeds in a direction exactly reverse of Figure 1 – preparation to innovate is enhanced by an education informed by the factors described by the experts. Thus, the objectives for engineering education for innovation should include:

- To learn to identify needs, predict trends, and recognize novel technical opportunities; “spot surprises”
- To experience exploring possibilities and delivering specific innovations : “immersing them, giving them a real life experience”; “maintaining a high level of interest and excitement”; “we need more ‘do whatever it takes’”
- To learn and practice hard and soft skills and understand underlying principles: “in my lab, first you are going to be learning technique. You have to be able to generate data in a reproducible way, then you need to understand and be able to interpret data and only then can you think of being innovative”; “one of the capabilities that really benefits students tremendously is breadth of communication skills”; “understanding the psychology of change is important”
- To understand the nature and roles of processes and a system in innovation, and
- To understand and learn to contribute to, enhance and establish environments that promote innovation.

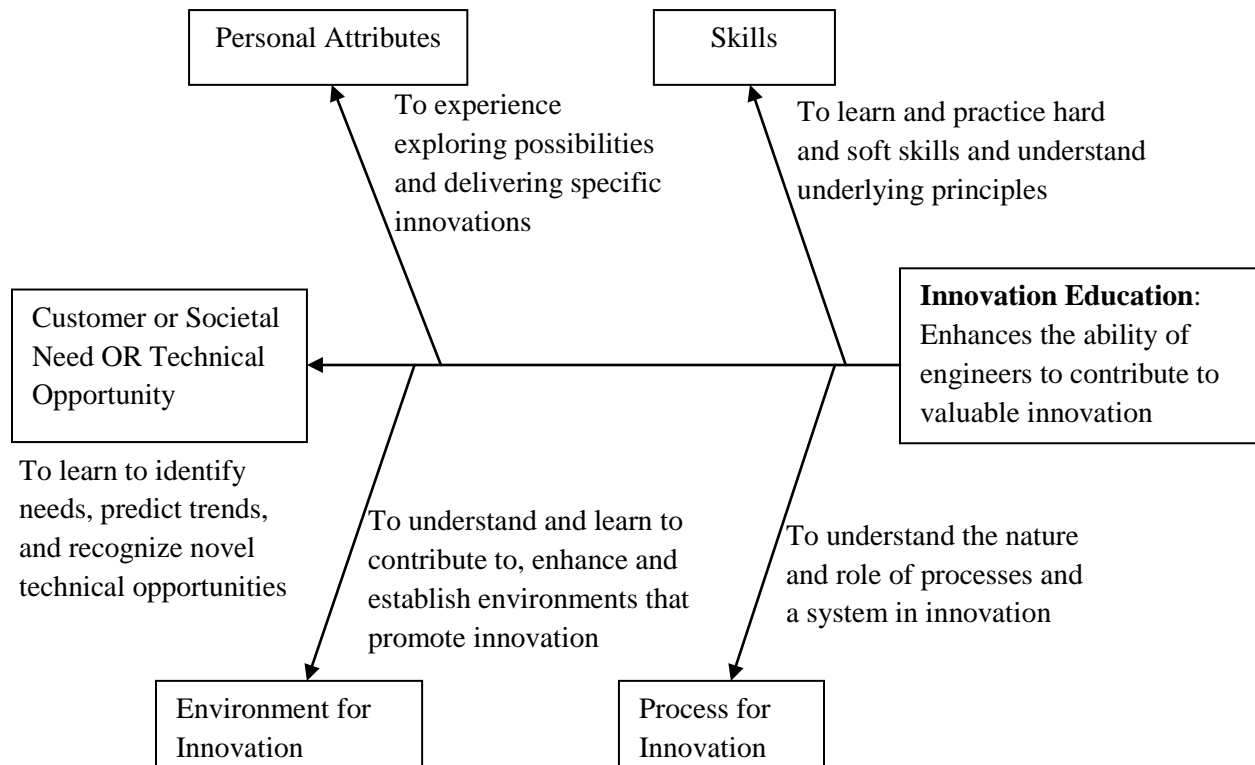


Figure 3: Implications for Innovation Education for Engineers

Conclusions and Future Work

This paper presents preliminary results based on 10 interviews with experts in the practice of innovation. Our results point to several factors that are central to successful innovation, including the role of deep expertise coupled with an urge to share and learn in allied fields; ability to work in an open-ended environment, an understanding of societal needs and behaviors, and a willingness to accommodate risk-taking and individuality. We believe that the resulting lessons about innovation have implications for the design of educational objectives and approaches.

Innovation experts depend upon expertise developed over a long period of time. They draw upon a combination of depth of knowledge and breadth of knowledge, which may require ten or more years of study and experience to acquire. Similarly, years of experience with multiple projects appears key to developing the pattern recognition ability for decision making that is associated with successful innovation management. From an educator’s perspective, the nature of expertise in innovation is an interesting challenge for curriculum design and development.

In a keynote address to the Frontiers in Education Conference in 1997, Herbert Simon talked about how engineering education in the second half of the 20th century had been significantly enhanced by understanding the goals and characteristics of engineering practice, and paying

explicit attention to learning and teaching processes¹⁸. There may be opportunities today to have equivalent impact on engineering education for innovation.

For example, while today's engineering curricula often have design projects with external clients that include team-work, explicitly familiarizing students with innovation-promoting behavior and alerting them to practices that may inhibit innovation success may be underutilized elements of these courses. To what extent do educational experiences include discussions of risk-taking – on the personal and organizational level? Do students recognize the value that different perspectives bring to teams, and the value that depth as well as breadth brings to an individual's education?

Facets of traditional engineering education in general may provide misconceptions of an innovative environment if we do not make students cognizant of these aspects and develop ways to simulate these in the academic setting. For example, in academic settings, sometimes the emphasis on critique does not recognize the opportunity to find ways to take an early stage idea and “make it a yes.” Also, the focus on individual academic disciplines may understate the opportunities for significant innovation at the interfaces between disciplines.

By understanding expert mental models of innovation, engineering students can be prepared with both specific skills for early career contributions to innovation, as well as insights into key levers for the overall innovation system. By teaching these insights, educators may influence ongoing, self-directed education throughout an engineer's career, enhancing the value creation from innovation education.

We are continuing the analysis to build a composite mental model that fully represents the ten expert interviews, and are also planning more interviews. Moving forward, we plan to complement the insights from innovation experts with those from educators as well as students.

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