Creativity and eureka in science and engineering

by Dr Hannes Steyn and Prof André Buys

Creativity lies at the core of all invention, innovation, entrepreneurship and leadership. At the heart of the creative process, in turn, lies the eureka experience: that precious and joyful event of inspired breakthrough insight.

An axiomatic principle of science and engineering is that one can only solve a problem once one understands its context and content really well, and one can only complete a design successfully once one knows and understands the requirements and the underlying technologies. The same is, of course, true for creativity and for eureka.

The roots of creativity

The root of the creativity of scientists and engineers is found in the human evolutionary past: in the creative struggle for survival and growth. In this sense, creativity has become the capacity to understand and employ the laws of nature in the struggle for survival and ascendancy. Today, one might as well speak of the survival of the most creative, as well as the fittest.

The Darwinian creative urge has evolved. As humans evolved from hunter-gatherers to farmers, due to the first disruptive technological revolution (the agricultural revolution), social structures changed perforce as people banded together to protect crops and herds against marauders. The agricultural revolution, therefore, not only introduced new technology, but also introduced a new level of competition and conflict, namely, the clan.

Different techno-historians describe the structure of technology revolutions and their attendant societal developments in different ways. The common theme is, however, the wave-like structure, and revolutionary and compressed nature. The evolution of human creativity in response to technology, struggle, competition and conflict is illustrated in Table 1.

Table 1: The evolutionary frame of creativity

Epoch	Revolution	Society	Competition
		Hunter-gatherer	Individuals
10kBC – 10kCE	Agriculture		
		Agrarian	Clans
± 1800	Industrial		
		Industrial	Nations
± 2000	Information		
		Information	Ideologies
± 2020	Biotechnology		
		Frantic?	Classes?

Human creativity does not only evolve because of the increasing complexity of technology. It also arises from the increasing complexity and intensity of competition and conflict. What is more, the succession of disruptive technological revolutions is compressed. An improvement in creativity should show a corresponding rapid exponential rise in the development of technology.

Rapid demand growth

Lest the crescendo-like technology development, as illustrated in Table 1, convey the idea that progress will carry on without limits, it must be said that the unfettered growth in global human numbers has become unsustainable. A sustainable society is a society that satisfies its resource requirements without endangering the sustainability of

→ *The human creative urge rises during adversity and conflict.*

Source: Wikimedia commons

future generations. Life on earth has become non-sustainable – the extinction rate of life forms increases, non-renewable resources decrease, natural habitat shrinks, humans no longer live in ecological harmony with their natural environment, the terror threat of weapons of mass destruction increases and the digital divide widens. In evolutionary terms, humans have, indeed, become the earth's ultimate infesting weed.

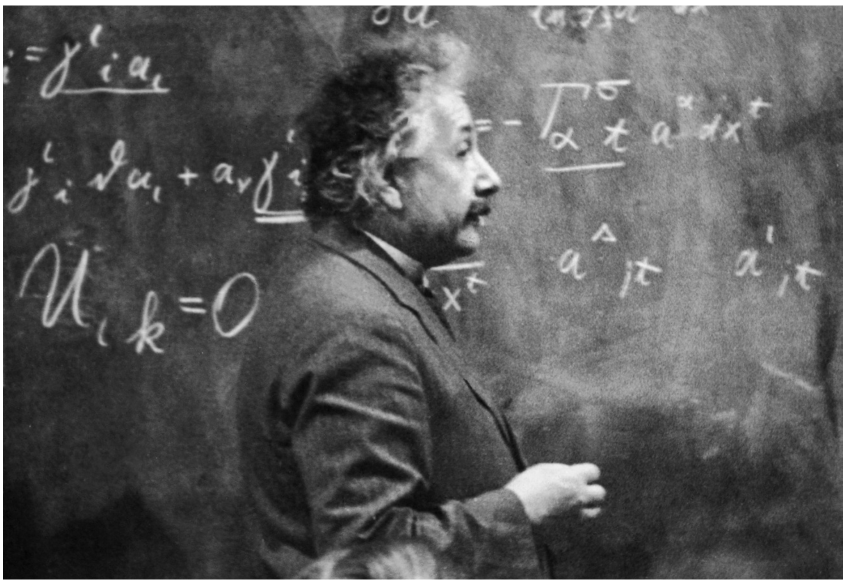
This is, of course, bad news for humanity, but is not necessarily bad news for life on earth. The earth has already experienced at least two mass extinctions (the first 245 million years ago and the second 65 million years ago) and life on earth has recovered stridently from both. The last mass extinction was caused by an asteroid impact on the Yucatán, creating an extraordinary climatic change. Millions of life forms disappeared, including the dinosaurs. The globe itself is, in fact, quite robust, and it actually belongs to the insects, which constitute the majority (72%) of all current earthly life forms. Today, signs of a third possible mass extinction are multiplying. After the third mass extinction, life will probably simply carry on, just like it did before.

Human life on the planet is converging on a crisis. This crisis may precipitate in the next decade or in the next century. Up to now, human creativity has always (at least over the last 10 000 centuries) risen to ensure the survival and growth of the human species. This time the crisis will probably not come from either space or the tectonic crust. It will be man-made and may very well trigger or accelerate another mass extinction. This time it is up to the human race to prevent or ameliorate and defer it; provided, of course, that human creativity, and hence the capacity for problem-solving, increases commensurately.

A shift in theory development

At the start of the 20th century, people interested in technology started to concern themselves with the nature of creativity. One of the first was Hermann von Helmholtz (in 1896), who identified three stages in creative technical work. He was a contemporary of that tireless innovator, Edison. Later came Karl Bühlinger (in 1907) with the isolation of the "a-ha! moment" and Henri Poincaré (in 1908) with his four-stage model of creative scientific work. These early insights were integrated by Graham Wallas (in 1926).

Jacques Hadamard used introspection to describe mathematical thought. His own thinking was largely wordless, often accompanied by images that represent the entire solution to a problem. He analysed the work of many of his peers and found the



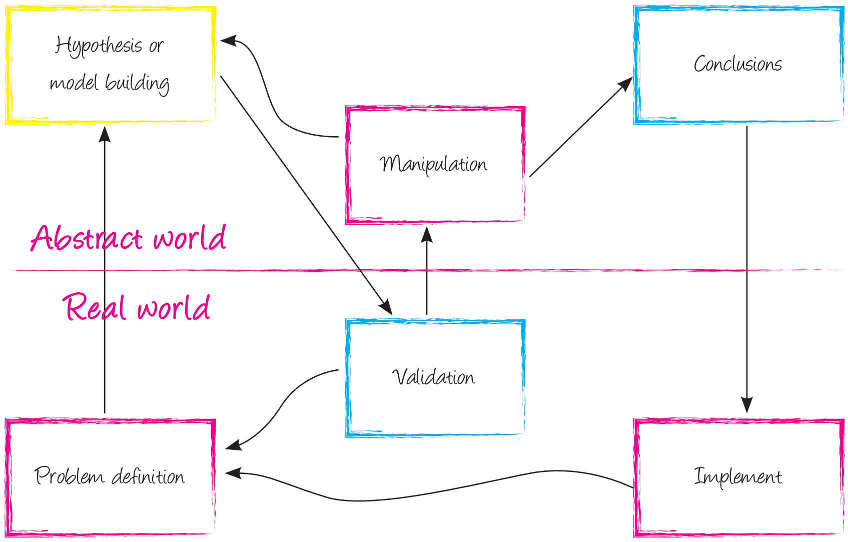
→ *Einstein was daydreaming in a chair in his patent office in Zürich when the holistic idea of the general theory of relativity suddenly dawned on him.*

Source: Wikimedia commons

same phenomenon. Einstein, for example, after years of fruitless calculations, suddenly had the solution to the general theory of relativity revealed to him in a dream, "like a giant die making an indelible impress, a huge map of the universe outlined itself in one clear vision".

The first formal analysis of the creative process from the point of view of psychology can be found in Joy Paul Guilford's 1950 address to the American Psychological Association. Guilford introduced the distinction between convergent and divergent thinking. However, others took a more pragmatic approach. Alex Osborne taught the technique of brainstorming. Genrikh Altshüller introduced his theory of inventive problem-solving and Edward De Bono has had some success since the 1960s with the ideas of lateral thinking, the "six thinking hats", etc.

Some theories suggest that creativity may be particularly susceptible to affective influence. Affective disorders, or disorders of the mood, include depression and bipolar illness. The elation (positive affect) following on breakthrough creative output is well known. Similarly well known (after the comparative work of Arnold Ludwig at the University of Kentucky) is the significant correlation between affective psychosis and creative achievement. Ellis Paul Torrance found a correlation between creativity and intelligence, beyond a threshold, in only a sample of highly intelligent people. Since 2000, authors such as Alice Flaherty and LR VanderVert have mapped the creative process on brain structure. This brief overview of inquiry into creativity displays a distinct transition over the last century from a focus on scientific creativity (Helmholtz, Poincaré, Edison, Einstein and Hadamard) during the first half of the 1900s to more



1. *Schematic representation of the scientific method.*

general creativity during the second half of the 20th century.

The creative work of scientists and engineers

The work of scientists and engineers invariably follows the scientific method, which obeys an iterative hypothetic-deductive process and is based on the philosophical ideas of logical positivism that are best expressed by the philosophers Immanuel Kant and Ludwig Wittgenstein. The scientific method is broadly outlined in Figure 1, which can be readily understood by starting at the problem definition and following the arrows.

The curved arrows show some of the iterative review paths. Scientific knowledge propagates incrementally in concentric waves from the core of existing knowledge. The scientific method focuses on formal problem statements, as well as on measurement and experimentation. Peer review, traceability and transparency are important and so is the statistical significance of findings. Good science depends on a curious and open mind, but also on a healthy measure of scepticism.

When it comes to creativity, the procedural formats of problem-solving and design are vital, because they are based on the scientific method. And the scientific method is fundamental for technological progress. The philosopher René Descartes declared: "*Cogito ergo sum*" ("I think, therefore, I am" or "I think, therefore, I exist"). In short, without thinking, human existence is meaningless. It is creativity – that ultimate expression of intelligence – that distinguishes the human being from a cabbage or a rabbit.

In the practical sense, the scientific method culminates in the rigorous procedural formats for problem-solving, design and systems engineering. But the products, processes, services and businesses that are the usual subjects of science and engineering display life cycles. And it is this life cycle dimension that usually invokes the discipline of project management in the practical work of scientists and engineers.
In project management, the design method is used over and over again in stage after life cycle stage, much like in a spiral; thus progressively creating models and specifications with

→ *The ideas of systems engineering and project management is used intensively in the defence environment, but is now also popular throughout science and engineering.*
Source: Cool toys, great pictures, USAF

increasing maturity. That is, with slow cost increase and rapid risk reduction. In this way, a mature design emerges and a cost-effective product comes to market.

A systems approach to creativity

In *The web of life*, Fritjof Capra (1996) introduces the holistic world view: a view of the world based on a new perception of reality. He calls it deep ecology. Capra stresses that the major problems of our time (pollution, climate change, runaway population growth, digital divide, decreasing biodiversity, global terrorism) cannot be understood in isolation. They are systemic and interconnected. From the systemic point of view, the only viable solutions are those that are sustainable. A sustainable society is one that satisfies its needs without diminishing the prospects of future generations.

Deep ecology and self-organisation shift the current cognition model based on informatics from cognition by symbols to cognition by connectivity; from information processing to the emergent (heuristic) properties of adaptive neural networks. The mind, thus, becomes a highly cooperative, interconnected system and the entire system acquires coherence in intricate patterns. Perception shifts from data processing to instant and ongoing neural pattern recognition. There is no doubt that the deep ecology ideas of Capra and his peers will be essential for new understanding in neuroscience and thus for creativity too. In a book by Richard Dawkings, published in 2008, Nicholas Humphrey (psychologist and evolutionist) describes the development of a model of consciousness.

He stands, observing and reflecting, at a rail. The first rail is that of the crib of a baby boy. He observes the baby thrashing around with arms flailing, hands grasping randomly and an occasional grimace flashing on his little face. He wonders what kind of an experience the boy is having. He then stands at a second rail, observing and reflecting again. This time it is the rail of the gallery in a concert hall. He looks down at the congregating orchestra. As they arrive, each player makes himself comfortable on the chair, arranges the scores on the music stand, starts to tune his instrument and plays a few sequences, softly, experimentally. For the moment each musician is playing for himself, oblivious to the cacophony arising from the rest of the orchestra, all the other musicians also tuning and experimenting with their instruments. Then, some sections try a few fleeting bars together.

But, they are all waiting for the conductor to appear, rap his baton on the podium and so bring the orchestra to order. Of course the conductor is an important figure in deciding on the repertoire, in setting the style, arranging, in leading rehearsals, in beginning and timing things. But once the orchestra plays, the conductor's role becomes mainly ceremonial, save for an encouragement here and a synchronisation there. Well, in a way, the boy is in that stage: the stage before the conductor arrives; the stage before the dawning of self-awareness. In much the same way, he finds himself surrounded by an interconnected web of sections: let's say one section of woodwinds, which we shall equate for the moment with the faculty of the senses. He has another section: let's say the strings, which we shall equate for the moment with memory. He has yet another section: let's say percussion, which we shall equate for the moment with logic or emotion, and so on. There is indeed a whole federation, as it were, of separate, independently growing mental faculties or subjectivities.

This foregoing federative model of awareness, verbalised by one of the most erudite modern exponents of neuroscience and promoted by the world's number one science writer, is probably as good as it gets, for now. Moreover, Humphrey's idea of awareness and its consequences for creativity fit neatly with the selforganising system ideas of Capra and his peers. The Humphrey model of awareness provides a powerful holistic metaphor for creativity too. We have been searching for enhanced creativity in every nook and cranny – in IQ, in lateral thinking, in brainstorming, in thinking stereotypes, in dreaming, in doodling, in stimulation and even in madness, but our efforts have tended to specialisation and to exclusive (belief-like) recipes; to pot-luck, as it were. As so often happens in exploration, the rash analytical scalpel that we have applied to human creativity to date probably cut through tissue, nerve, vein and sinew alike, thus uncovering stump after bloody truncated stump, and missing – time after time – that beautiful systemic, grander and more pervasive whole.

Incremental theory expansion

In science and engineering, the eureka moment is usually embedded in a creative process that comprises three stages. The first stage is the incubation stage in which the problem is defined and both the quantitative and the qualitative aspects of the problem are thoroughly explored. Focused attention is often deliberately suspended to allow the subconscious access to the problem. The second stage is the eureka stage, in which the sudden breakthrough insight usually occurs under circumstances that are often unique and particular to the individual concerned. The final stage is the elaboration stage, in which the output of the eureka event is prepared for implementation. Elaboration usually entails the description of the eureka result in terms accessible to a wider circle of peers, ready for dissemination.

Without a common language and extensive use of written language, man is doomed to mediocrity. It is amazing that humans, those late-comers in the 4.6 billion-year-old evolutionary history of planet earth, were so tardy in their early development. After the discovery of writing some 5 000 years ago, things really happened at an accelerating rush. A mere 3 000 years after the advent of writing, the Roman Empire was in sway, the Christian Era had started and some prominent Egyptian, Chinese, Greek and Roman leaders recorded their philosophies, which are still taught and studied today. The importance of urbanisation and of the consequent development – 2 000 years later – of coded language (writing) led Hans Eysenck, the IQ guru, to state that "Einstein would not have prospered in an igloo, or Mozart in a kraal, or Shakespeare in a wigwam."

Young Einstein was troubled by his Bavarian high school's discipline. He later wrote that the spirit of learning and creative thought were lost in strict rote learning. Einstein was not only a keen violinist, but an avid sailor too. As a student in Bern, he often sailed on the lake. A companion of that time, Fräulein Markwalder (his landlady's daughter), noted that every time the wind died down, Einstein's notebook came out and he started writing, practically oblivious to the rest of the crew. But the moment the wind rose again, Einstein was immediately ready to sail and promptly put way his notebook.

> This habit of making notes, designs, drawings and formulae, as well as keeping a journal and other manuscripts, is typical of highly creative technical people. They write, all the time. This habit is one of the reasons why we have so much on record from scientists such as Da Vinci, Newton, Poincaré, Darwin, Einstein and others. They probably did not write in anticipation of fame. They did it because it was an essential part of their trade.

> That ever-present and stereotypical engineer's affectation, the Designer's Journal, which is usually a black hard-covered notebook (or electronic equivalent), is much, much more than a status symbol!

About his concurrent love for physics and music, Einstein said: "Both are born from the same source and complement each other." His oldest son remembered: "Whenever he felt that he had come to the end of the road or into some difficult situation in his work, he would take refuge in music, and that would, usually, resolve his difficulties." Einstein's sister remarked that playing music seemed to "put him in a peaceful state of mind, which facilitated his reflection." While puzzling over a physics problem, Einstein would play his violin until, suddenly, he would stand up and declare: "There, now I've got it!" A solution had suddenly appeared to him, his sister observed.

Writing (using coded speech) and playing the violin (using coded music) clearly had a major influence on the creativity of the world's most famous scientist, Albert Einstein. In this respect, it is noteworthy that Werner Heisenberg, of the uncertainty principle fame, was an accomplished pianist. But probably the most famous example of the science-and-art blend is Leonardo Da Vinci (1452–1519). Da Vinci was not only the creator of the *Mona Lisa* and *The Last Supper*. He was also a musician, a scientist, and a designer par excellence.

As you exercise your brain in logical and holistic thinking, it becomes second nature – you become mentally fit for that way of thinking. The saying (about neural hard-wiring) goes that neurons that fire together, grow together, so by simply thinking hard and often enough about a specific desirable reality, you start

The irascible Beethoven was renowned for his moroseness and disregard for authority; his handicap (deafness) was central in his creativity.

Source: Wikimedia commons

creating that reality. And, as success breeds more success, objective reality itself responds to your projection. This mechanism or control system was first called the power of positive thinking by the famous pastor, Dr Norman Vincent Peale. However, a lightweight, bubbling optimist does not convince with his or her positive, yet capricious projections. On the other hand, an optimistic visionary on the solid ground of a proud track record gets the attention every time. Such optimism and enthusiasm are infectious. This contagion is an important environmental feedback and reinforcing mechanism in the power of positive projection. By means of the positive projection of vision, the leader starts to create the reality of that vision.

Creating one's own reality by using the power of positive thinking is important for everyone, but for the leader, or inventor, innovator or entrepreneur, it is crucial. Good leaders envision a desired outcome with such clarity and such persuasive power that they rally and muster others to share it enthusiastically. In this way they mobilise and inspire the resources of a talented team, and the snow-balling momentum becomes unstoppable. They create a new reality. They are driven towards their goal by the compulsive rush of their creative energy, as if under a compelling force similar to gravity.

Edison said that genius (innovation, invention, entrepreneurship or leadership) is 1% inspiration and 99% perspiration. This remark is accurate enough and it points to the importance of the preparatory or incubation phase – the build-up of potential energy before its release. Holistically speaking, therefore, the build-up is more important (and certainly much more time-consuming) than the release.

In the theory development of this article, the various components have been verified either by anchoring them in literature or in industrial experience. In the examples of eureka moments investigated so far, the circumstances of the eureka occurrence remained similar. In some cases, they occurred under conditions of stimulation, in others without stimulation. But the circumstances always occurred at that borderline when the tug-of-war between the conscious and unconscious mind wavered in favour of the subconscious. This condition, in which inhibitions are suspended, thus allowed the (regular) space of convergent (left-brain) thinking to be invaded by divergent (right-brain) thinking.

In almost every case investigated, the onset of the eureka moment was sudden, holistic and brief. It was followed by joy and satisfaction.

In every case the eureka moment followed on a period of dedicated and persistent hard work or incubation. In most cases, there was some intentional suspension of focused attention, just as Henri Poincaré suggested. Every eureka moment was followed by verification and consolidation. This elaboration stage requires that the brilliant new insight, and perhaps even its outline implementation, be thought out logically and captured in a peer language, in a common and succinct vocabulary.

Creative productivity, particularly during the eureka event, is highly dependant on the individual's state of mind. Of course, moods can swing from melancholy to elation. In a really bad (morose and despondent) mood, a depressive patient will sometimes experience a debilitating lack of creativity and productivity. In a good (euphoric) mood, he or she will, however, be as sharp, energetic and enthusiastic as his or her genetic endowment allows. However, moderate human mood cycles are experienced by almost everyone. Some swings are diurnal, while others have a monthly or even seasonal nature. Clearly, for enhanced creativity, one needs those really positive moments.

Scientists and engineers employ an optimum blend of convergent and divergent thinking in their quest for creativity. The framework in Table 2 is useful in the preparation of eureka moments.

Table 2: Creativity paradigm

Creative output		Logic and reason	
		Beginner	Advanced
Envisioning centre	Beginner	The amateur	Unimaginative, plodding progress
	Advanced	Fantastic but impractical ideas	Invention, innovation, entrepreneurship and leadership

Adapted from Geyer (1987).

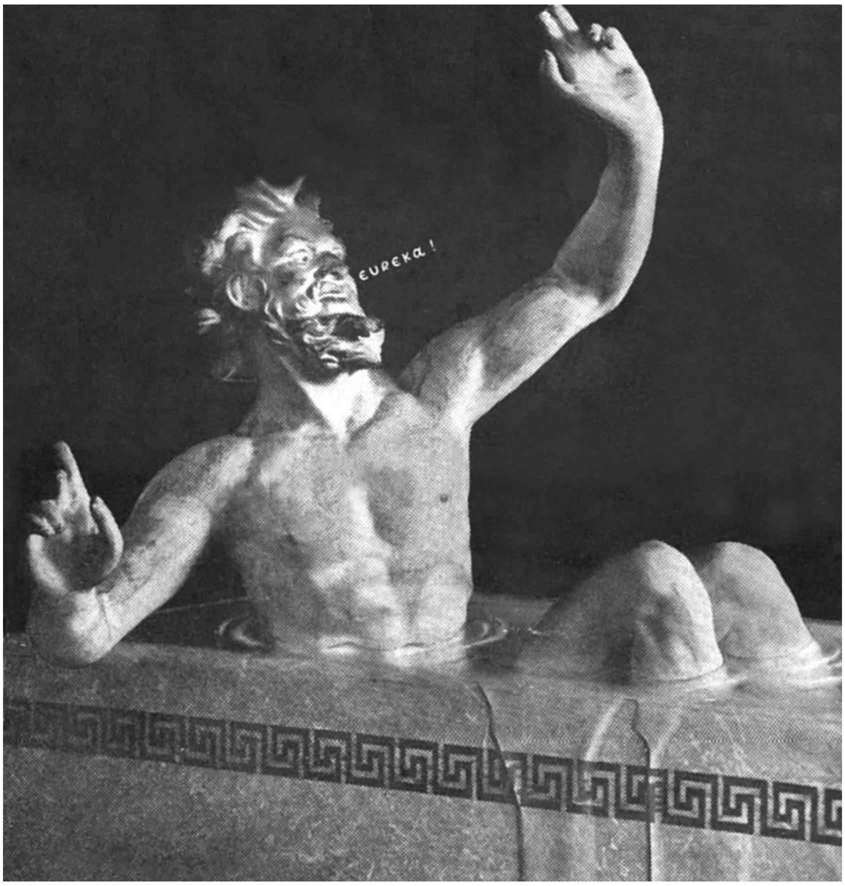
This fine balance between logic (serial processing) and vision (parallel processing) is akin to the best blend of science and art (or logic and holism). For optimum creativity, scientists and engineers need the wonder, imagination and flair of the artist, combined with the grim reason and perseverance of their own discipline.

Joy Paul Guilford and Erich Geyer were not the only ones to identify these two unique and important thinking styles. Friedrich Nietzche introduced the distinctions between the Apollonians and the Dionysians. On the one hand, the Apollonians favour logic, the analytical approach and a dispassionate weighing of evidence, and on the other hand, the Dionysians lean more towards intuition, synthesis and passion.

It has now become clear that, for optimum creativity, a careful blend of the two thinking styles is essential. Some critics say that scientists and engineers should develop the finer part of their lives, such as art, theatre, history, music and philosophy, to make of them more civilised human beings. However, the very blend of science and "the finer things in life" (the best synthesis of Nietzsche's Apollo and Dionysus) is also essential for optimum creativity. This supplement is not a "nice-to-have" cosmetic augmentation, but a vital ingredient in success in science and engineering.

Scientists, engineers, entrepreneurs and leaders often experience eureka-like breakthrough moments of exceptional insight in their work. Naturally, the explorer, detective and artist do too. In science and technology, the moments of brilliant new insight are so profound and delightful that scientists over the ages have given them a name: They are called "eureka moments". In the Greek language, "eureka" means "I have found it." The exclamation, "eureka!" was, reportedly first used by the mathematician Archimedes, some 2 200 years ago, when he stepped into a bath and noticed the attendant rise in the water level. This fluid displacement and buoyancy phenomenon became known as the Law of Archimedes.

Successor scientists followed by using the same exclamation during similar ecstatic moments of discovery. The exclamation "Eureka!" was initially used for "aha!" moments of invention or discovery, but since then, science and technology have progressed dramatically. Today, we know that not only invention, but also innovation, entrepreneurship and leadership all rely on moments of breakthrough visionary thinking. These climactic moments of brilliant thought have revolutionary technological and business consequences, much like the revolutionary consequences of the first discoveries.



Archimedes discovered buoyancy in his bath. He also said "give me a place to stand and I shall move the earth."

Source: Wikimedia commons

Eureka moments require a discontinuous (or transient) cognitive response and they deliver peaks of inspired, brilliant insight.

The experience of these precious moments is so climactic, exquisite and intoxicating that it can lead to addiction. It is as if the energy of all the foregoing toil is suddenly bunched up into a single ecstatic spurt of creative productivity. These moments are even more precious because of what they represent: the triggers of revolutionary progress. They represent the onset of exponential growth: growth in science, technology and business. Let's face it. If you have an intractable bent for addiction, you could become addicted to substances that are far worse than your creative juices.

Up to this point, it has been necessary to narrow the somewhat general definition of creativity down to its specific meaning in science and engineering, and to anchor this definition in its evolutionary roots. There is no evidence of a silver bullet solution. As always, creativity will demand total dedication, persistence and hard work.

Hopefully, some young scientists and engineers, who come to understand the complexity and urgency of the creativity crunch, will join the quest for improved creativity. Of course, whether or not the consequent growth in creative productivity will be up to the task of staving off the inclement global crisis remains to be seen.

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*In a curious (but pleasant) reversal of fortune, **Dr Hannes Steyn** studies for a PhD under the leadership of **Prof André Buys**. Prof Buys, in turn, worked under the leadership of Dr Steyn in Defence. This was after a successful career in the nuclear industry. In sharing the experience of industrial immersion, the authors have had the privilege of leading gifted technical people for most of their lives.*