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Way of the Solar Impulse Project

Revisiting an Inspiring Design Thinking Process at the Light of a DKCP Process in the C-K Framework

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Abstract

«Solar Impulse is a plane that is no longer a plane.» Making a successful flight with solar energy only was only possible by breaking – for the first time ever in aviation history - a series of dominant thinking axes, all prevalent since the tip of that industry cycle. And it was only by raising the whole partners' team to the awareness of "conceptual moments" that critically missing knowledge could be captured from surprising industrial domains. Which in turn shifted a plane-making process upside down.

By accounting for major steps in the design thinking process (since the initial "crazy" ideas in 1999 down to the preparation of the coming 2015 round-the-world flight), this paper elucidates the underpinning methodology at the light of a DKCP process. How was the Solar Impulse fossil energy-free plane conceived? Which foundational rupture concepts were at stake at its inception? What can be its true and long-lasting identities as an object? What new management principles were adopted across an ad-hoc multi-national partnership?

A number of dominant designs backing the traditional aviation industry are revealed along with the accompanying ruptures signing off entire original innovation paths. The learning encompasses the methodological, flight physics, materials, architectural, manufacturing processes, quality, decision-making, and team management dimensions.

The Solar Impulse project may soon spur a radical departure from more than a century of dependency on non-renewable energy sources. It also potentially sets off the motive for different consciously planned and purpose-oriented mega projects in society. Those projects in which the role of an underpinning design innovation methodology gets paramount for warranting success and gradually becomes a critical and most sustainable asset for worldwide industrial leadership.

I - A Swiss-born dream gets wild

How long more a dependency on fossil energy may last? What would be an object that is a plane and that flies with not a single drop of fuel or emission? These daunting questions were asked in 1999 by visionary scientist Bertrand Piccard at EPFL in Lausanne. It was only after deep investigation that genius Swiss engineer André Borschberg came with a conceptual idea:

> *«Should it fly, it's got to be a glider equipped with photovoltaic cells on the wings, to be equipped with batteries to fly at night, and to feature an extremely light avionic structure so to fly day and night.»*

This initial definition came of age as the one historical disjunction from the then available sum of knowledge, such as flight physics, flight maths, and traditional materials. Every professional heartedly realized that current knowledge was wholly insufficient. A march for systematically querying new knowledge was launched: in chemistry, plasturgy, light structures, composite materials such as those found in automobile industry, carbon fibers, foams, films, also micro-technical assembly. Yet, a plane made of plastic wasn't a too easy thing to take seriously by then…

This paper advocates that the Solar Impulse design process can be understood far deeper at the light of a C-K Theory implementation (e.g. Le Masson & al, 2010) and DKCP process (Hatchuel & al., 2009[1]), which is based on C-K Theory. The thoroughgoing interaction between managers, engineers, architects, marketers, designers, pilots, testers, manufacturers and researchers tenaciously mixed a considerable amount of knowledge arguments pertaining to a vast number of domains of expertise along with advanced conceptual considerations (most often looking quite original, if not weird), and concurrently.

The downstream innovations and side outcomes that result today are innumerable (in products and components, but also at manufacturing process level). All in all, it becomes clear that a now world famous Solar Impulse undertaking makes a case in point whereby innovation design is raised to new levels of requirements that may signal the coming exigencies of tomorrow's industry and economy. Times are undeniably gone when classical innovation schemes were advocating the sequencing of phases and, quite arbitrarily it now seems, were splitting process from product innovation (e.g. Utterback & Abernathy, 1975). If only one thing, the next sections testimony of the arduous conceptual phase, in search for making the foundational blueprint concept workable.

Which comes first from product or process?

An enlightening mental shift happened when engineers realized they had to adopt process expertise concurrently to working on the product and began to ask how to design a process innovation that induced a product innovation. Which in turn lighted a quest for new knowledge: plastic assembly (requesting e.g. welding, gluing, brazing, injection, molding), manufacturing parts by machining, films and foam blocks making. Actually,

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[1] Or D(esign)-K(nowledge)-C(oncepts)-P(ropositions) process. A previous sub-model was coined KCP. Op. cit: *«(…) performance comes from the fact that this method contrasts with classical creativity techniques, insofar as 1) it insists strongly on knowledge sharing, 2) the design reasoning is strongly oriented by the organizers when they propose the C-projectors ['blueprints'], and 3) it ends with a design strategy and not with a set of selected ideas.»*

most of these were also plain research topics by then. And simulating the parts behavior under extreme conditions and testing was yet another research domain.

Two years would pass before any result could be shown. By then, SOLVAY's core business focused on advanced materials and new solutions and came to be extensively challenged. Further partners gradually entered the game in Switzerland, Germany, France, as did several SOLVAY's laboratories in Germany, Belgium, France, Italy, and the USA.

Which then triggered another daunting challenge: how to manage a team-like collaboration in the face of cultural differences, delays, and with no hierarchical structure? Plus an utter requirement of extreme competence in every single field and, needless to say, an indefectible adherence to the end goal -this possibly meaning exploding single partner's budgets. Innovation in management practice was needed and went mostly resolved through selecting best-of-breed individuals and companies at the same time, plus freedom in finding solutions.

A first conundrum requiring a rupture: energetic autonomy

A solar-powered plane could surely fly under daylight. But operating it at night is the bottleneck. By storing energy, kinetic energy could become available when needed, but the problem was then the too heavy embedded weight. Engineers envisaged using potential energy instead. During the day, the plane gets one favorable condition: it can go up in elevation. Which becomes a potential to use at night. Which founded the advent of the *parabolic flight* concept algorithm:

(1) getting up to 9000m elevation during days and by fully charging batteries before sunset,
(2) effectuating night segments as a mere glider down from 9000m to 2000m,
(3) when slowly approaching the 2000m elevation before dawn, only then using the still fully available charge before next sunrise,
(4) and back up again to (1) [exit: except for the pilot's fatigue or atmospheric conditions, which require closeby landing].

Which procedure amounted to divide the flight process into two parts, each with its own rule: a) the night flight with no energy consumption first, then batteries for keeping constant elevation around 1500-2000m elevation; b) the day flight based on the sun's cycle of availability (Fig. 1).

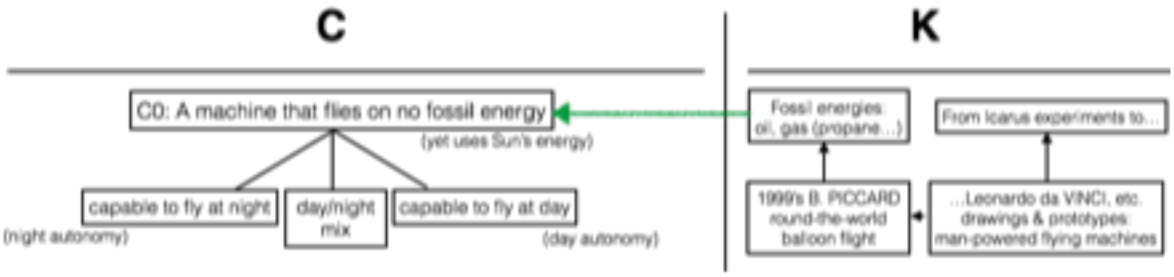

Figure 1 - *An initial C-K diagram expands according to the two alternating regimes (day and night) of a solar-powered machine.*

Another conundrum requiring innovation: the critical temperature-pressure versus oxygen trade-off

Temperature being hotter at low elevation and very low -minus 40°C or less- at high elevation, how about protecting the pilot, apparatus weight, and all volume factors included? And batteries too? With the minimum weight and no use of any single energy Watt. For making things even tougher, the cabin issue quickly came to the fore: it could only be ultra light and not pressurized. Hence, a pilot would need oxygen or suffer loss of consciousness after just 30s. And an oxygen tank and a mask would be too heavy to carry.

Engineers came up with the molecular sieve net piece, which enriches and generates enough oxygen when higher than 4000m. In this way, the *parabolic flight* concept pushes towards the potential energy solution: a solution to capture storage. The initial $\mathbf{C_0}$ *«a solar plane flying without a drop of fuel»* brief concept got transformed into concepts about flight processes and was split into two: *«a potential energy-based flight with an oxygen mask»* and *«a potential energy-based flight with a molecular sieve.»* Two new formulations were then defined:

$\mathbf{C_1}$. A solar energy-based flight with an O2 tank (therefore heavier, hence requesting more power).

$\mathbf{C_2}$. A solar energy-based flight with a molecular sieve (therefore placing less power demand).

Which in turn triggered an astounding cabin innovation: the pilot's armchair would be suspended to the careening, offering an alternative horizontal position for 10mn sleeping sessions, featuring a shell to protect the pilot and cockpit instruments from elevation hazards. It would be made of polyurethane mousse for good mechanical resistance and thermal isolation and be a lightest component. A whole cabin weighting 7kg! (**Fig. 2**).

As strange as it can be, this is no longer a plane... Or a plane that may indeed retain a plane-like shape, but boasts the weight of a medium size sedan car and the power of a Piaggio Vespa™. The development team eventually selected the CO2 tank technology for practical reasons (**Fig. 3**).

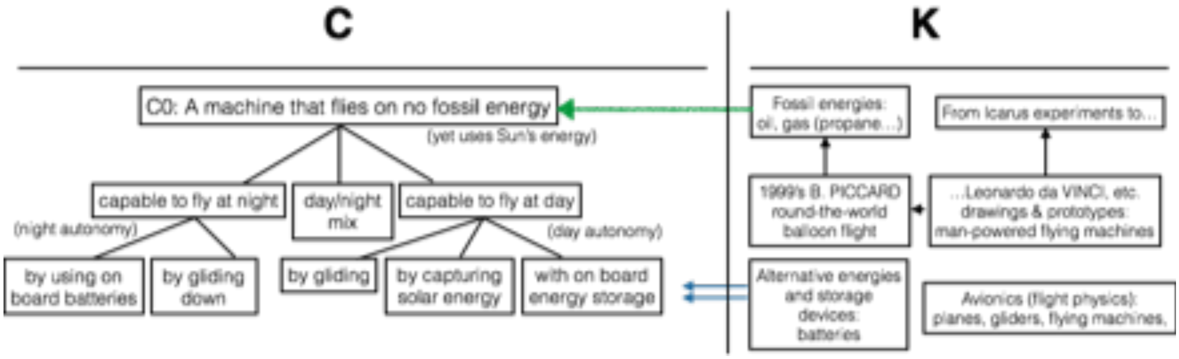

Figure 3 - *The original «glider-plane» becomes a versatile machine, accommodating solar energy storage and the pilot's constraints concurrently.*

When the dominant designs of an entire industry splinter

One differentiating merit in managing multi-partners teams well resides in the capacity to unlock the traditional, possibly obsolete, views of a particular organization. Fact is that older structures eventually get to the point of inhibiting nonetheless mandatory evolutions. Such dominant thinking (DT) threads were found nesting in at least six areas. **Table 1** provides a rational background for breaking no less than six implicit rule(s) which were forged across time.

DT 1 - **A PLANE IS A HEAVY BODY, AS IT SHOULD CARRY ITS OWN ENERGY**

☞ *When energy is available all around, the only issue is to be able to capture it. Plus store the minimum vitally necessary only.*

DT 2 - **PLANE STRUCTURE AND INTERIOR PROTECTION ARE TWO DISTINCT ISSUES**

☞ *Biomimicry can help: some nature's and structural shells protect an organism living inside.*

DT 3 - **AN ENERGY TANK COMES IN 3D VOLUMES**

☞ *Solar cells are essentially two-dimensional devices, hence could «stick» on the plane's envelope by means of special assembling.*

DT 4 - **PLANE PROPULSION IS SINGLE SOURCE (KEROSENE OR ELSE, BUT CHOOSE)**

☞ *Day flight and night flight reveal two disparate energetic issues under incident solar rays.*

DT 5 - **WHILE FLYING, I'S ONLY POSSIBLE TO CONSUME ENERGY**

☞ *Getting day solar energy can enable delayed elevation loss by storing potential energy for next night.*

DT 6 - **OXYGEN AVAILABILITY AND HIGH ELEVATION: TWO MUTUALLY EXCLUSIVE ISSUES**

☞ *Molecular sieve nets enrich the little air available with O2 so to breathe normally.*

Tables 1 - *Over a century of a self-structuring aviation industry, a dominant thinking matured rules that were designed mostly around fossil energy. Here are a few such cases with the proposed crackling for each.*

By isolating each dominant rule and breaking it through conceptual expansion reasoning, radically innovative ways could be opened. However, an even more intricate relation between dreamy concepts and acceptable knowledge had soon to be faced with.

II - When maturing the dream calls for an array of wild paths

Cracking the energy yield conundrum

One m^2 typically receives 1KW of energy under a 45° latitude. By averaging this over 24h, it means ¼ effective sunlight over 6h, thus a 250W energy supply only. Given that energy attacks the plane extrados, the profile generates a further loss: say 200W input the solar cells only. One would typically expect a maximum of 20% energy efficiency factor for non domestic cells use, which leaves just a mere 40W available for flying… at best!

A solution was found with a $200m^2$ photovoltaic surface, a body geometry with a 63m wingspan and 3m cord, accommodating 12000 solar cells units and embedding 400kg of top performance Lithium-based batteries. The entire plane then weighted no more than 1600kg. This is equivalent to designing and building a wide body long-haul carrier, as large as an AIRBUS or a BOEING, weighting less than a medium size car and featuring the power of a street moped, i.e. cruising at about 70km/h -power being cube to speed.

Reversing process vs product dominance

If, as it does, welding plastic implies irreparability, it would imply a different manufacturing process. Any additional feature for disassembly would also increase weight, while becoming an additional source of manufacturing problems. By simplifying the general architecture, the parts number can be decreased. This is why engineers put into place a process (**Fig. 3**: e.g. the wingspan**)** which suppressed both spare parts and the maintenance logistical chain. The causal chain:

simplified architecture ⇨ lowering weight ⇨ product reliability

revokes a process or product dominance and enables redefining the initial $\mathbf{C_0}$ concept with the following attributes:

«A solar mechanics that flies
which has
a *simplified structure*
and is
e*asy to manufacture and mount in small series*
with
a low weight and a large wingspan
and which
improves both flight performance & reliability.»

This conceptual definition embeds a new hidden capacity to trigger a market, given that it meshes:

known properties: *has got a plane, wings and a cabin...*

with:

yet unsought properties: *made of plastic, cells, paper...*

for which would-be customers could quickly sense a new feasible adoption path.

A product-process co-design is henceforth endorsed that intertwines process and product: *«process makes product that makes process, etc.»* Welding plastic as a unibody case invites the pilot protection property yet also reinforces the overall mechanical resistance property. As the whole product gets rigid by having its inside organs protected, the status of the cabin cover becomes more than a mere protection: it has a structural mechanical function. The plastic casing becomes resistant and offers a great surface for capturing sun's energy too. Plus, the plane uses its own envelope as the supporting case for the moving parts.

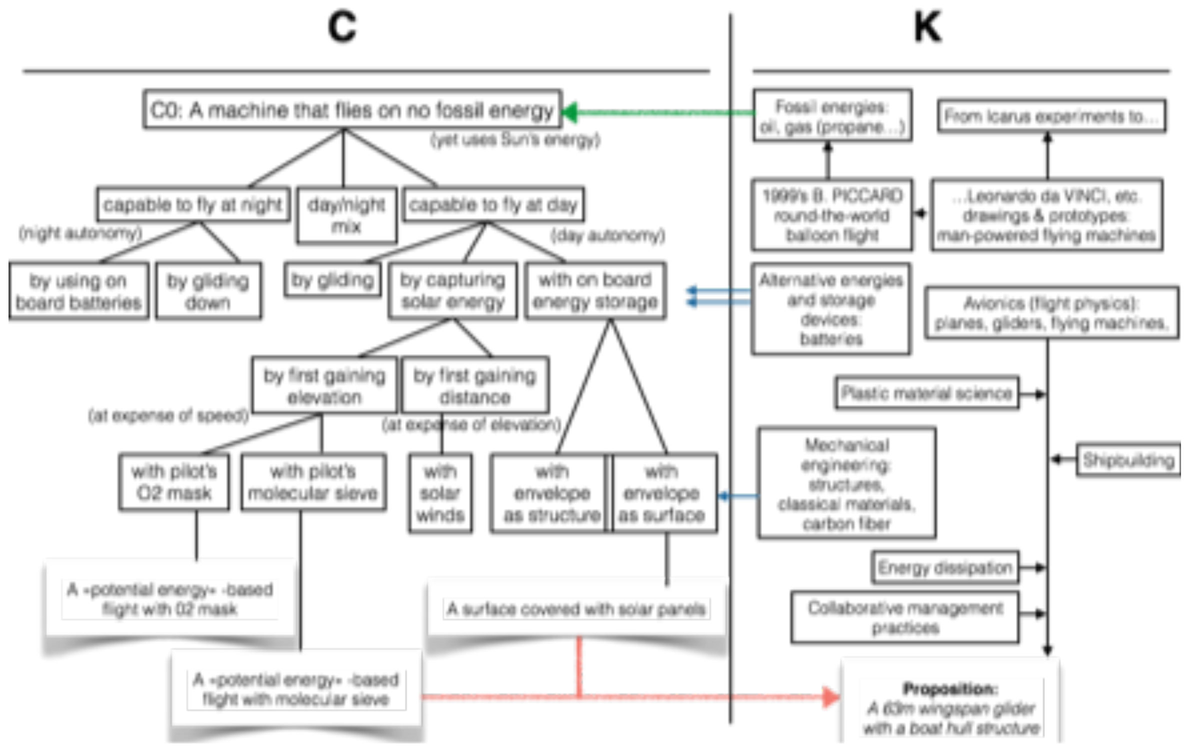

Figure 4 - *A developed C-K diagram taking advantage of new product-process related properties enables a joint occurrence of concepts with knowledge.*

Where an *«it won't work!»* outlook triggered yet another partnership

As the Solar Impulse team went on in search for light gliders manufacturers, a German leader in the field who was called for help explained why the machine wouldn't fly: far too big and far too light. In plain words, a good recipe for failure. The team went further on by probing a hulls manufacturer on the banks of the Leman lake -a shipyard company who became famous for building racing boats, even one winning an America Cup once. Indisputably, they were making boats and had not the faintest knowledge about planes.

Yet, they were building racing boats with carbon fiber, hence were mastering a science of lightness. And after sharing some views, the small boat manufacturer accepted to come on board Solar Impulse.

A full-fledged Solar Impulse consortium came then to light, from banks to automobile, aerospace, shipbuilding, insurance and engineering. Plus computer scientists, chemists, physicists, mathematicians, not forgetting meteorologists. The multi-skills team gathered 70 expert staff, and still does, each individual and partner member having a key, wholly irreplaceable role within the integral venture.

One lesson is that only such a knowledge-covering team could achieve the required robustness for fittingly flying the initial concept. After more than a dozen years of trials, only the sizable spread of the conceptual explorations both in breadth and depth could answer for a soaring variety criterion. Only the sheer spread of competencies and know-how could cope with the demand for a well-built prototype. Overall, all four key dimensions of a collective creativity undertaking (Hatchuel & al., 2009[2]) have been made apparent through the DKCP integrated framework (Agogué & al., 2014; Bellec & al., 2014) based on the C-K design innovation theory.

III - When both impact and side results rocket sky high

Solar Impulse acted as a flying laboratory that already originated numerous side results. The societal and market value of Solar Impulse can be perceived as impacting many earth-bound activities in the freshest way: thermal isolation (buildings isolation market), ways of capturing solar energy, domestic solar, encapsulation, lighter structures by replacing metal by other materials having similar performances, etc. Even lubricants (noting that lubricated systems consume less energy) or the design support through modeling and simulation (as a «plastic-structured» plane becomes a flexible object), or structural computations and flexible structural resistance (which is quite different an issue from rigid structures). Plus new technologies and new flight algorithms. The whole problematic of *lightness* certainly holds truest for civil aviation today, even for automobile and other, terrestrial or not, moving vehicles. Most of Solar Impulse by-products are already industrialized: it's clearly become new business bringing new solutions to the planet's challenges.

Partners' yield count is impressive: 12 qualified on board products, 25 different applications, 6000 components, which are not solely technical or technological. On the issue of batteries, acknowledging that chemists still work hard on storage means today, what's still

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[2] Op. cit: «(The) four main dimensions of a collective creativity method (are): 1) To explore the whole conceptual potential of the initial concept; 2) To involve and support people in a rule-breaking process; 3) To enable the relevant knowledge activation, acquisition and production; 4) To manage the collective acceptance and legitimacy of rules (re-)building.»

hindering is the 400kg batteries for flying during night. Should the flight be limited to a day cruise, a tourism version could be obtained by removing them and replacing them with say 2 or 3 seats. Solar-powered drones exist today that boast up to several days range for surveillance, military, cartography, etc. applications.

A chemical industry brought to the scene solutions that nobody could ever imagine before. The paradox is that the chemical business has long been perceived to belong to the industry's energy greedy category, yet it is most logically preparing the energetic transition and has obtained solutions for each energetic situation. In the present energetic evolution period, different systems will co-exist. Here, a Solar Impulse machine acts as the messenger: *a product that carries a message.* Which carries a second momentous impact of the project by contributing to the Group's reputation and to the chemical industry standing at large, by demonstrating that chemistry is in a leading position when it comes to bringing solutions to the huge challenges the world is now facing.

And a third impact, possibly the most revealing one, is the unfaltering engagement of SOLVAY's staff in this project, which enhanced their motivation and the pride of belonging to a company who made the right decision to become a leading Solar impulse partner. At the right moment, right at the very project onset time (SOLVAY Group, 2003).

Yet, due to its large wingspan and its lightness (**Fig. 5**: the historical flight over Paris, landing at Le Bourget Air Show on 15 June 2011), the Solar Impulse plane can only sail under favorable weather conditions, such as neither adverse nor side wind; absolutely no turbulence; no humidity; and, in particular, no rain.

It has nevertheless broken the rules of a whole avionic industry by not merely improving what already existed. It has breached a brand new strategic market space by being not a clothed mechanism but a cloth-as-envelope system with an energy function. Thanks to the insight provided by using C-K Theory, this paper has uncovered how a complex design reasoning can be shaped and coordinated (for a more immersive presentation of the Solar Impulse case at the light of a deeper DKCP process, see the accompanying eBook (Blanchard & Corsi, 2014). As for next step, what remains to be performed is the building of relevant and vibrant ecosystems which can warrant lasting success in accordance with our global planetary challenges (SOLVAY Group, 2014).

References

Agogué, M., Hooge, S., Arnoux, F., Brown, I., An introduction to Innovative Design - Elements and Applications of C-K Theory, Presses des Mines - Transvalor, Paris, 2014.

Bellec Y., Corsi P. and Lafon D., *Introducing a Critical Maturation Phase Within Industrial DKCP Processes*, 7th SIG Design Theory Paris Workshop, SIG on Design Theory of the Int. Design Society, 27-28 Jan. 2014.

Blanchard, Ph. & Corsi, P., First Steps in Driving C-K Ateliers, eBook Series, Vol.2, Apple Store, Apr. 2014.

Hatchuel, A. & Weil, B., *A New Approach of Innovative Design: An Introduction to C-K Design Theory,* ICED 03, Stockholm, The Design Society, Aug. 2003.

Hatchuel A. & Weil B., *C-K Design Theory: An Advanced Formulation,* Research in Engineering Design, 2008.

Hatchuel, A., Le Masson, P., et Weil, B., *Design Theory and Collective Creativity: A Theoretical Framework to Evaluate KCP Process,* 17th Int. Conf. on Engineering Design, Stanford University, 2009.

Le Masson, P., Hatchuel, A. & Weil, B., Les processus d'innovation – Conception innovante et croissance des entreprises, Paris: Hermes, 2006.

Le Masson, P., Hatchuel, A. & Weil, B., Strategic Management of Innovation and Design, Cambridge: Cambridge University Press, 2010.

SOLVAY Group, *Solvay Partners the Solar Impulse Project,* Press release, 2003. See also: http://www.solvay.com/fr/about-solvay/solar-impulse/index.html.

SOLVAY Group, *Solvay Ready to Join Solar Impulse 2 on Its Trip Around the World,* Press release, Brussels, 9 April 2014.

Utterback J. L. & Abernathy W. J., *A Dynamic Model of Process and Product Innovation,* Omega, The International Journal of Management Science, Vol. 3, No. 6, 639–656, 1975.

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