Sanjay Kumar

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A Thought Experiment

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Email: skumarsdr@gmail.com

About the Author

Sanjay Kumar, Ph.D. (KUL, Belgium), did post-Ph.D. research at the following places: Utah State University (USA), National Laser Centre (South Africa), Shanghai Jiao Tong University (China), and York University (Canada). He has been active in research for the last twenty-five years (H-index 20).

He is the author of the following books:

- Additive Manufacturing Processes, 2020, Springer
- Additive Manufacturing Solutions, 2021, Springer
- Additive Manufacturing Classification, 2022, Springer
- Additive Manufacturing Advantage, 2023, Springer
- A new theory of additive manufacturing, 2024, Springer
- A concise encyclopedia of additive manufacturing, 2025, Springer
- A New H-index, 2025, Scholarly Dialogues Press, ISBN: 978-93-5592-389-9

Preface

The short book is presented in the form of dialogues between two researchers. They and their dialogues are invented. Their dialogues try to draw attention towards various aspects of additive manufacturing (AM), i.e., its organization, its shortcomings, and its various nuances as understood differently by laymen and different experts.

The use of imaginary dialogues, a form of thought experiments, is an established method for truth-seeking in science communication and pedagogy. This is the first time it is applied in AM. This is written for those involved in AM. The use of metaphors and narratives can also make it useful for those engaged in education. It can be especially useful for those who are experts in other fields but are interested in AM.

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Sanjay Kumar

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Additive Manufacturing Debate

Abstract

Two imaginary researchers, R1 and R2, start talking about hybrid additive manufacturing (AM). Their talk turns into a debate. None of them is less knowledgeable. One cannot teach the other. They are not interested in being part of a Socratic dialogue, where one assumes the role of a teacher, while the other becomes a student. They wonder whether both AM and hybrid AM are the same. Soon they discover that what they understand about the definition is far different than what it is. One says the definition has an inner contradiction; another defends it. One says the name of AM is not right; another shows a brighter picture. One argues that this name can have a negative implication on the education; the other questions the logic. Their discussion includes directed energy deposition, sheet lamination, powder bed fusion, other manufacturing techniques, pre-processing, and post-processing. One says sheet lamination is not AM; another shows how to make a product using sheet lamination. One says selective laser sintering should not be considered AM; another questions the way AM is getting compared with an established subject. At the end, there is no attempt to draw a conclusion; there are only viewpoints, logics, and arguments.

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Conversations

R1: What are you working on these days?

R2: I am working on hybrid additive manufacturing (AM).

R1: What is this?

R2: This is the combination of one AM technique with other techniques, such as machining (1) (2), forming (3), injection molding, forging (4), or other AM techniques (5).

R1: Why do you not do only AM?

R2: It is not enough. For technical reasons, when AM is combined with some other techniques, fabrication is more efficient. Or for economical reasons, when AM alone is expensive. I work on directed energy deposition (DED) (6) to create a special feature. The feature is created on a block that I machined before. Thus, I combine two techniques, DED and machining, to make a part. Since the part is not made by AM alone but by the application of AM and machining, I call the resulting technique a hybrid AM technique.

R1: You are mixing two techniques. Why do you not call it a compound or mixed technique?

R2: What is the difference between mixed and hybrid?

R1: A hybrid technique means you are creating a new technique out of two techniques, where two

techniques have lost their identity or past behaviour to make a new technique. If your technique is not such a hybrid technique, better call it a mixture of two techniques.

R2: You are saying that two techniques lose their identity. Can you give an example?

R1: When you use cutting and electrochemical machining simultaneously, the impact of cutting force in the presence of electrochemical accelerates the machining. This acceleration makes the combination of two techniques a hybrid one (7). When they are combined, they do not behave in the same way as when they are used one after the other. This is the loss of their past behavior or identity. When you sequentially combine machining and DED, whether you get the same acceleration in the action?

R2: Where did you get this knowledge about hybrid manufacturing from?

R1: It is a concept that says the combination of two manufacturing techniques can be called hybrid only when the combination gives a drastic improvement in the result. It means when you add one and one, you should not expect that it will be two, but it should be more than two (8) (9) (10).

R2: But this is about machining. Why should I follow it when I am engaged in AM? Besides, it is not followable.

R1: Why?

R2: It says, as you already said, there should be a drastic improvement in the result. That is not always possible. That is not for all combinations of techniques. When two techniques are combined, the primary motivation is to get a product made or to remove the inefficiency of one technique with the help of another technique. The moment you bring a condition that the combination of two techniques will be called hybrid only when the combination brings a drastic improvement in the result, you are ignoring a number of techniques that are not combined for that purpose. Then, you are excluding many combinations from being termed as a hybrid technique. Do not mistake me. I am not against it if a combined technique gives a drastic result. But I am against making a hybrid technique a lofty goal that will be achieved only by a few.

R1: When you are already aware of what a hybrid technique should be, why do you call your combined technique a hybrid technique?

R2: If mixing of two techniques is accepted as a hybrid technique, then why should it be called a mixing technique? When I use 'hybrid AM' for the combined technique I use, it is because everyone uses the same name for the same type of combinations (11).

R1: Do you mean since everyone is using it wrongly, you are also using it wrongly?

R2: Please give me an example that will fit in an ideal hybrid AM.

R1: Should I create a hybrid AM out of two existing AM techniques?

R2: Please go ahead.

R1: Let us take the lower portion of a powder bed fusion (PBF) (12) machine. I mean the platform in which powder moves from one side to another side. Now, we have created half of a future machine. This is the lower portion of the future machine. We need an upper portion of this machine so it will be complete. We go and search for another AM technique so we will find the upper portion. Let us take another material jetting (MJ) (13) machine. Let us take its upper portion. I mean, let us take only its jetting system. Let us not take its platform where the jetting happens. Now, we have the jetting system of MJ as an upper portion of our future machine. Our future machine is complete, with its lower portion taken from PBF and its upper portion taken from MJ. This is a hybrid AM because it has been made from PBF and MJ, where PBF and MJ have lost their separate identities. You cannot take PBF out of this hybrid AM. If you try to snatch PBF from this hybrid AM, you will only have the lower portion of PBF, which will tell a story that once upon a time it was PBF. It will remind you that you have created the hybrid AM, not out of nothing. To create it, the contribution of PBF was taken, and the contribution of MJ was equally taken. But when the hybrid AM was created, there was no more PBF or MJ.

R2: Yes, a hybrid AM machine is created, but how will we use it?

R1: Do you not use it every day? Is it not the technique that you call binder jetting (BJ)? (14)

R2: Do you mean the upper portion of hybrid AM will jet binders instead of general materials, and the lower portion of hybrid AM will become a powder conveying platform?

R1: Yes.

R2: Do you want to say BJ is both AM and hybrid AM?

R1: Yes.

R2: I can also make another hybrid AM, like this. Let us take the lower portion of a BJ machine. It will be the lower portion of our future hybrid AM machine. We need the upper portion of our hybrid AM machine to make it complete. Let us search and find the upper portion. Let us take the upper portion of a DED machine. This upper portion consists of two parts: one part is for transferring energy, and another part is for transferring material. Let us choose only one part that transfers energy. Now, we have taken half of the upper portion of DED. This half part transfers energy; let us say it transfers laser energy. This one part becomes the upper portion of our future hybrid AM machine. Now, our hybrid AM machine is ready, which has an upper portion that transfers a laser beam. And its lower portion is present for conveying the powder. Do you agree that this is a hybrid AM machine?

R1: Yes.

R2: Is this not an AM machine that we call laser PBF? Just tell me whether PBF is an AM or hybrid AM. Do you remember where our discussion started? I mean, you remember which one is the first technique,

so another technique can be derived from it. Can you inform me which technique was first born? If you consider PBF as a first technique and derive BJ as a hybrid technique, I can consider BJ as a first technique and derive PBF as a hybrid technique as well.

R1: At least, you agree that hybridity should be reserved for something special and should not be belittled for using it for a combination of sequential techniques that you use.

R2: I shall always call a combination of two techniques a hybrid technique. What you say about a hybrid AM is just a beautiful concept.

R1: So you are saying that you will continue saying the same thing and there is no need for any change in the subject or nomenclature.

R2: No, there is no need. Because techniques are added for fulfilling a need. They are not added for fun. AM is like open software. Anyone is welcome to do whatever they want as long as industrial problems are solved and AM is advanced.

R1: Is this open software or indiscipline?

R2: What is indiscipline here? What is in the name? It is the solution that is more important than how the solution is named. The way you are proving an AM is a hybrid AM, the way you are saying that a technique can be both AM and hybrid AM at the same time, brings to me a point that you do not have any respect for the organizational structure of the subject.

R1: When I say a technique is both AM and hybrid AM, I want to say that a technique can have multiple identities. An identity is given to a technique from a given perspective. The moment we change the perspective, the identity changes. A technique can be known differently in different circumstances. Did I say anything wrong?

R2: Can you give an example?

R1: PBF is an AM technique. It is a hybrid AM technique, as you have already said. PBF is a laser materials processing technique when it uses a laser beam. It is a powder metallurgy technique when it deals with metallic powders. It is an advanced sintering technique when it sinters polymer powders layerwise. It is a welding technique because it is an extension of welding when welding is used to weld metal powders. It is a digital technique because it helps convert a digital model into a part. It is an advanced casting technique where casting first happens line by line and then happens layer by layer. It is a rapid manufacturing technique when it makes an end part fast. It is a rapid prototyping technique when it makes a prototype fast. It is a rapid tooling technique when it makes a tool fast. It is a mass production technique when it makes many products. It is a customized production technique when it is used to make a single customized product. It is a mass customization technique when it makes many customized products. It is a recent technique when it is compared with old machining. It is an old technique when it is compared with four-dimensional printing. It is an expensive technique when it makes an expensive product. It is a cost-effective technique when it makes an expensive part inexpensively. It is an unsafe technique when it is

unable to make a magnesium part. It is the best technique when it can make a complex part. It is an illegal technique when it makes an illegal part. It is a molding technique when it makes a mold. It is a rapid molding technique when it makes a mold fast. It is…

R2: Please stop. I do not disagree with the various names you provide and claim to be their identity. If you want, I can also add some more names so that your list will become bigger. You are not understanding my problem. I am a teacher. I go to a class to teach. When I start teaching, after giving the definition of AM, I tell them that there are seven AM techniques. Should I not say there are seven AM techniques? Should I tell the students, "AM is so much more advanced that whatever you want, you can assume, and I will be there to prove that whatever you assume will not be wrong"?

R1: Why do you make the education so strict? Why do you not have the humility to first say that there are seven AM techniques and then, when the class advances, to prove that whatever you said can be interpreted differently as well? I believe that whenever you go to class, you engage in a monologue as if students have no right to interrupt you. Whatever you have reserved to teach on the 10^{th} day, you never like to mention it, even if a student asks a question about that.

R2: I am trying to point out the confusion that will be created by arbitrarily shuffling AM with hybrid AM, and you are giving me a sermon on how an education should happen. Why do you not address the issue directly?

R1: Which issue? Why do you not tell students that there are other ways to classify AM? Classifying differently, interpreting differently, etc. allow the subject to evolve. Do you not want the subject to evolve further?

R2: Are you helping the subject to evolve? Hybrid AM is used when AM is not sufficient to make a part. Our direction is from AM to hybrid AM. This is a forward direction. If you make a hybrid AM machine from two AM machines, and that hybrid AM machine is nothing but an existing AM machine, then you are not going forward. Your movement is circular. You are not making a new part. You are making the same part.

R1: I have shown you a concept in which a hybrid machine will not be the sequential addition of two machines. The concept will help develop new machines, which will help the subject to evolve. If the concept of a hybrid machine has led to the existing machine, this is not something to be considered a backward movement. But this will help understand an existing AM machine from the perspective of hybridity.

R2: Hybrid AM is a broader concept that not only includes hybrid machines but also hybrid process development and multi-material product development (15). I wonder whether you are aware that a hybrid AM can occur even in the absence of a hybrid AM machine.

R1: So you mean you are saying that by sequentially using machining and DED, your fabrication was part of a hybrid AM process? I mean, you have developed

a hybrid AM process without a need to develop a hybrid machine.

R2: Yes, of course.

R1: At least, now, you are not blaming other people for the reason you call your technique a hybrid AM. Can you tell me why you call it a hybrid AM process?

R2: You see, a process is a set of steps (16) (17).

R1: How do you know that?

R2: Is not the process a set of steps?

R1: It is. But what the steps are is interpreted differently by different people.

R2: Can you explain?

R1: If some people change the material, they say they have changed the material, not the process. If some other people change the material, they say they have changed the process because the 'type of material' is one step of their set of steps. If some people change the parameter, they say they have changed the parameter, not the process. If some other people change the parameter, they say they have changed the process, because the 'value of a parameter' is one step of their set of steps.

R2: For me, both are right. What is wrong with it?

R1: If a person changes the material one day and says that one has changed the material, not the process, then it is fine. But if the same person changes the

material another day and says that one has changed the process, not the material, then it is arbitrariness.

R2: But how does this arbitrariness affect the subject?

R1: For example, AM is called hybrid AM, and hybrid AM is called AM.

R2: I do not say so.

R1: Can you say how you develop a hybrid AM process?

R2: I use machining as a first step. Let us call it A. I use DED after that. Let us call it B. My hybrid process is AB, where B always comes after A. As long as the sequence is maintained, the process is the same, irrespective of the different parameters and materials I use to execute my process. When I make different products, I still say that I am using the same hybrid AM process because for me, a process is synonymous with a technique.

R1: But you said you are developing a hybrid AM process. If you always use the same technique in the same sequence, where is the development? What you do is not development, it is the repetition of the same thing.

R2: When I make different products, I check whether my techniques, my sequence of techniques, or my combined technique works for these products. I discard many products that I cannot make. Going through the rigorous optimization to select some out of many products that I can make is what I call the development. It is this optimization that teaches me which products I have to accept in the future to make.

The ability to select some product designs out of many designs is a continuing process, which I call the development.

R1: Can you elaborate further on how you employ DED on a machined block?

R2: DED is used to make various features of different sizes and shapes on various types of machined blocks. Sometimes, I use DED to apply a metallic coating on the block.

R1: If you use DED to apply a coating, how do you claim that you are engaged in AM? Is AM not a shaping technique? The moment you apply a coating, you are not creating a shape.

R2: Sometimes, I use an aluminum block for making a mold. Aluminum has a high machinability. That is why I use it. But aluminum does not have good wear resistance. That is why I need to apply a coating to make its surface stronger. I use DED to make a coating on it. When I apply coating, I apply more coating on the internal cavity of the mold, because this is the internal cavity that goes through more wear. I apply less coating on the outer surface of the mold. I use a DED machine because it allows me to apply the differential coating on different surfaces. The moment I apply a thicker coating on the internal cavity, I change the size of the internal cavity. This non-uniform size change with respect to the outer surface gives rise to a shape change. This shape change would not have occurred if I had applied a uniform coating everywhere. Though I apply coating, the end result is a shape change with the help of coating. Therefore, it is AM.

R1: Do you mean you never apply a uniform coating using DED?

R2: I apply. It happens when some customers want their parts to be uniformly coated. But this is not what comes under the development of a hybrid AM process. This comes under customer service, which is the post-processing of a part. When we apply a non-uniform coating, as happened in an aluminum block, we do not call it post-processing.

R1: Do you mean when you apply a non-uniform coating on the aluminum block using DED, it is not post-processing?

R2: It is a post-processing in the sense that it comes after machining. Since machining is a process, a process that is coating that comes after machining automatically gets the right to become post-processing. But still it is not post-processing, because in AM, a process denotes a zone only where a shaping takes place. Post-processing is reserved for those techniques that come after the shaping is finished. Post-processing in AM is not supposed to interfere in the shaping. In a hybrid AM process, shaping happens due to the contribution of both machining and DED. When the first process, i.e., machining, is done to contribute to its share of shaping, the shaping is still not finished. The shaping is waiting for the second process, i.e., DED, to come and give its share of contribution. Unless shaping by DED is done, our combined process is not finished. Unless our combined process is finished, how can a post-process start? If we call the shaping by DED post-processing, we reduce the shaping by DED to that type of post-processing that is reserved for a technique that is not capable of shaping.

R1: You say AM is meant for shaping, and post-processing is not meant for shaping. But this is accepted when it is only AM that is meant for shaping. But you are not using only AM for shaping; you are using machining plus AM for shaping. Why will this understanding of post-processing be applied in this case?

R2: I am using AM for shaping. But since AM is not sufficient for shaping, I take help of machining. Since I take help of machining, I cannot call that my process is only AM. Therefore, I call it hybrid AM. But whatever I call it, I am still under a broader AM. Since it comes under the broader AM, the understanding of post-processing that is applied in AM is still applied.

R1: Is it not the other way round? I can argue the other way. Since I am working in machining and machining is not sufficient to make the product I require, I take help of AM. But I am still working in a broader machining that I call hybrid manufacturing. Since I am working in the broader machining, I can call the application of AM on a machined product post-processing. Am I wrong?

R2: You are not wrong. You call it hybrid manufacturing, I call it hybrid AM. You can interpret it differently by saying the application of AM is a post-processing. I can interpret differently by not using the term post-processing, because I do not want to confuse my audience by arbitrarily using the term post-processing. If you interpret differently without confusing to whom you are addressing, how will you be wrong?

R1: Do you mean hybrid manufacturing and hybrid AM are different? I mean, are their audiences different?

R2: Hybrid manufacturing is a broader term that includes everything, e.g., two different machining processes. Therefore, even if the same audience is addressed differently, the audience will not attend with the strict sense of post-processing that he is accustomed to in AM. I mean audiences and readers are not different. But when a reader reads AM papers, he should be prepared that he will not find any post-processing in any paper that tries to change the shape. Hybrid AM is the same as hybrid manufacturing as long as the latter includes at least one AM technique. If it does not include, hybrid AM is its subset.

R1: You said that the understanding of post-processing is different in AM than in general manufacturing. Is it logical?

R2: AM is a shaping technique. Besides, it is a developing technique; therefore, post-processing is widely used in AM. Since AM is not capable of making all shapes, post-processing is used to help it. If post-processing is not strictly separated from an AM technique, it will not help understand what AM can do alone. General manufacturing is more understood than AM. Besides, post-processing in general manufacturing is more understood than that in AM. Therefore, post-processing in AM needs to be strictly defined irrespective of whether it is defined such strictly in general manufacturing.

R1: In your hybrid AM case, you use both machining and DED for shaping. Why do you not consider DED

as a main process and machining as a pre-process, so you will still work in AM instead of hybrid AM?

R2: In AM, when we say post-processing (18) is not meant for shaping, i.e., when we repeatedly say the same thing, we give the impression that it is only during the post-processing stage that we need to be careful not to have any shaping attempt to be free from any potential mistake that we can commit. We forget that besides post-processing, pre-processing is also not meant for any shaping. Therefore, the pre-processing stage also cannot include shaping by machining. There is only one way I can describe my process, and that is by considering it hybrid AM. I cannot describe my process by saying, 'I am working on AM, where the pre-process step consists of machining to make a shape.' If I dare to say so, I have not understood what AM is.

R1: I work in powder bed fusion (PBF) as well. We pre-process our powders. The pre-processing brings a change in the shape of a powder. Thus, there is a change in the shape. Now, you are saying that the pre-processing stage is not meant for a shape change. Can you clarify where the anomaly is?

R2: In PBF, when powders of various shapes are made during the pre-process stage, these shapes do not affect the shape of a part. Because they are not meant to affect. Because whatever the shape of the powders is, these shapes are meant only to create the shape of a layer. Thus, a layer always has the same rectangular shape irrespective of the shape of its constituents. This brings up the question of why powders of different shapes are made. These are made so the layer can be spread smoothly. If powders are not of the right shape and size, it can affect the

smoothness of the layer, or it can bring difficulty in spreading a layer (19) (20), but it will have no influence on the shape of a cross-section that can be carved out. If the layer is not smooth and the reason for the lack of smoothness is the powder shape, even then it will have no influence but to make the part dimensionally inaccurate and have a rough surface. The shape of this part will still be decided by making a cross-section during the process stage (21). Thus, whatever the shape of the feedstock that is made during the pre-process stage is not carried forward to the process stage.

R1: What if I create sheet metals of various shapes by machining and join them layer upon layer? Will it come under AM?

R2: No, it will not come under AM. Because in AM, shaping needs to happen only during the process stage. If you create sheet metals of various shapes, this creation comes under the pre-process stage. If you join them, then you carry forward the shape from the pre-process stage to the process stage, which means you are no longer working in AM. You are supposed to create a shape during the process stage. If you say that since you are joining layer by layer, therefore it is AM. Then you are again wrong, because the way you join, you do not create a shape. You do not intend to create shape during joining as well. I mean, your joining is unaccompanied by a shape creation.

R1: Do you want to say that sheet lamination (22) (23) is a hybrid AM?

R2: No, it is not hybrid AM as well. Because for being a hybrid AM, one of the processes must be AM.

When you create a shape by machining, one of the processes is machining. When you join them layer by layer, let us say by welding, then it is not AM. Because joining in AM is meant to create shape. Therefore, another process besides machining that you are using is not AM but joining. Therefore, sheet lamination is neither AM nor hybrid AM, but it can be a combined technique consisting of machining and joining. If you define this combined technique as hybrid manufacturing, it is hybrid manufacturing.

R1: Why are you saying, 'If you define…'? Do you want me to create a shape and define it as well?

R2: What I want to say is that it is a combined technique. I want to insist that it is a combined technique. A combined technique can be defined in many ways. Someone can say it is hybrid manufacturing, while others can say it does not fulfill the criteria of hybrid manufacturing. Some people can say it is special machining, while others can say it is special joining. When I say as far as defining is concerned, you are free to define it however you want, because your way of defining must not dilute the fact that sheet lamination is neither AM nor hybrid AM.

R1: What if I do not take pre-machined sheet metals, but I create shape layer upon layer by machining during the process stage? Is it AM?

R2: Then again, sheet lamination is neither AM nor hybrid AM. Because when you do layer upon layer machining and create shapes, you are creating shapes without applying the method of joining. Though you are engaged in layer upon layer joining, this joining does not create shapes but sustains the shape created

by machining. Just holding the shape created by some other method is not equal to creating the shape by joining. Since shaping is not done by joining, sheet lamination is not AM. The absence of AM and the presence of two techniques, i.e., machining and joining, make it a hybrid manufacturing technique.

R1: Can you suggest which type of sheet metal processing we should do so that we can have AM?

R2: The relation between sheet metal and AM is similar to the relation between the North Pole and the South Pole; they are not meant to meet. As long as there will be sheet metal, there will be no AM, and vice versa. Sheet metal is incompatible with AM. A sheet metal has only one use in AM: to become a substrate.

R1: Should I explain how to create AM products from sheet metals?

R2: Please go ahead.

R1: I take a number of rectangular-shaped metallic sheets. I keep them on a platform, one layer upon another layer, and join them by welding. At the end, I do not have thin sheets any more; they all have been joined to make a thick rectangular part. It is an AM product. This follows the principle of layer upon layer joining. Do you agree?

R2: No, it is not an AM product. AM is for the creation of a shape. You are not creating any shape. Though, you are making a thick rectangular part. But it is not because your method of joining has an ability to make this, but because your method of joining relies on someone else's ability to make it. Someone

else has made a thin rectangular sheet and provided it to you. The shape you create relies on what shape someone else has provided you. Since that person has given you sheets of rectangular shape, you can only create a part of a rectangular shape. If you want to create a part of a cylindrical shape, you will again look for that person to provide sheets of disk shape. When you create a cylindrical-shaped part, you relies on a disk-shaped sheet. The creation of a cylindrical-shaped part from disk-shaped sheets is not an original creation but a natural outcome of the stacking of disk-shaped sheets. This is not an original creation because your method of joining has no ability to change a rectangular-shaped sheet to a disk-shaped sheet. Since your method of joining can never change the shape of a sheet, you will never make an AM part.

R1: It seems to me that you have not understood well the definition of AM. Can we revisit it?

R2: Yes, sure.

R1: The definition says, 'It is a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.' (24) Since the definition says that it is a process of joining materials to make parts, when I join sheet metals to make parts, I fulfill the definition because the sheet metal is a material.

R2: I do not deny that the sheet metal is a material, but you are supposed to make a part from a 3D model. How will you make parts from different 3D models using sheets of only rectangular shape?

R1: What if my 3D model is of a rectangular part?

R2: Then, of course, you can make a part using your rectangular sheets. But since you have chosen that your base material will be sheets of rectangular shape, you will always make only rectangular parts. Since you always make parts of only one shape, you hide the inability of your joining methods by not trying to make different parts. You still do not fulfill the definition, because the definition is not for a methodology to make only one shape.

R1: Revisiting the definition has given new insight. Should we revisit again?

R2: Yes, sure.

R1: What is the definition of a layer?

R2: A material that is laid out or spread to create a surface. (24)

R1: I just wonder what the use of this definition of a layer is when this definition cannot be applied for the layer that is in the definition of AM.

R2: How do you say so?

R1: In material extrusion (MEX) (25), a layer is neither laid out nor spread to create a surface.

R2: Do you want to say that MEX is not a layer upon layer technique?

R1: As per the definition of a layer, MEX is not a layer upon layer technique.

R2: Can you explain?

R1: In MEX, a material is deposited at certain points or areas on a surface; this deposition is not the laying out or spreading to create a surface. In MEX, there is no business of laying out or spreading the material. If you define a layer that is made by the spreading, then MEX does not contain this layer when it executes layer upon layer joining.

R2: If it is not layer upon layer technique, how can it be defined?

R1: It can be defined as a cross-section upon cross-section technique.

R2: Is a cross-section not the same as a layer?

R1: No. A layer is that is spread on the whole platform. A cross-section is that is spread on part of the platform; that part corresponds to the horizontal cross-section of a CAD model.

R2: Do you want to say that when it is said that AM is a layer upon layer technique, it is wrong?

R1: This definition is partially wrong. This definition does not apply to MEX, but it applies to powder bed fusion (PBF). In PBF, material is spread on the whole platform to create a layer. Therefore, when you say AM is a layer upon layer technique, you mean you follow a technique that will always cover material on the whole platform to make a layer. It is PBF, not MEX, where material is needed to cover the whole platform in order to execute the technique.

R2: If the definition is partially wrong, how has it survived for so long?

R1: The definition has survived because it creates ambiguity. In MEX, when it is said it is a layer upon layer technique, it means it is referring to a cross-section of a layer. In PBF, when it is said it is layer upon layer technique, it means it is implied that a cross-section will be carved out of a layer. In MEX, the definition survives because it conveys that a cross-section is in the form of a horizontal layer. In PBF, the definition survives because it conveys the methodology by which the technique will be executed. In PBF, the definition does not mean that a layer is a cross-section. But the absence of this meaning of a layer in the definition does not make the definition wrong, because the definition hinges on another meaning of the layer (that conveys the methodology) to become right.

R2: It means you want to say the definition is wrong in MEX for one reason and is wrong in PBF for another reason.

R1: It means I want to say the definition is right in MEX for one reason and is right in PBF for another reason.

R2: There are many AM techniques. Can the definition be wrong for many other reasons in the remaining techniques?

R1: There can be many techniques in AM. But they boil down to only two techniques (26): MEX represents one technique, and PBF represents another technique. If these two techniques are covered, then please be assured that the whole AM is covered. Please don't worry about any other techniques.

R2: But, these techniques are not "layer upon layer" but "usually layer upon layer." What is the difference between "layer upon layer" and "usually layer upon layer"? Does "usually" mean there was less confidence in AM when the definition was made?

R1: "Usually" means AM is a layer upon layer technique. But if a technique does not follow layer upon layer methodology and claims to be AM, its claim cannot be denied. For example, two-photon polymerization is not a layer upon layer technique but is AM.

R2: Does not "usually" dilute the definition?

R1: It dilutes. But what if it is strict? Creating a definition is easy, checking who uses it in which way is difficult.

R2: You want to say that since there is no benefit in having a strict definition, therefore a definition must not be questioned or updated.

R1: This thing I am not saying. I am saying that creating a definition without having an ability to control its use is not effective.

R2: Do you think the name of AM should be changed? (27)

R1: Why?

R2: The name misleads.

R1: How?

R2: One gets the impression from the name that the subject is about a type of manufacturing that adds. While in actuality, this is not what it is. It has a definition that prohibits a type of manufacturing that does not add layer upon layer. It means a type of manufacturing that adds arbitrarily is excluded.

R1: Why do you want to include the manufacturing that adds arbitrarily? Do you like arbitrariness?

R2: I do not like arbitrariness. But I do not like if the name gives the impression that it includes an arbitrary addition, and then I later find that it excludes the arbitrary addition. The mismatch between the name and the action disappoints me. I wonder why a correction in name is not required.

R1: I question the impression you got. Why did you get the impression that the name is for general addition? What is the source of your impression? If you say you got the impression, then I wonder whether you have a history of using AM for general addition. Do you remember anyone who manufactured by general addition without layer upon layer technique and called the manufacturing AM?

R2: I do not understand why you mean that "I got the impression" means it is the only I that got the impression. Do you deny that AM is not a general term? Do you deny that manufacturing by addition never happened in history? Will you not allow me to call manufacturing by addition "additive manufacturing" because the definition is applied to additive manufacturing and is not applied to its synonym, i.e., manufacturing by addition?

R1: I want evidence. Do you have any evidence that the term AM was used for the general addition some forty or fifty years back? If there is no evidence or weak evidence, it is not improper to use the term AM. The term AM became famous when it was associated with layer upon layer technique. When it became famous, it was getting questioned. In the beginning, this name became a unifying force, which brought various techniques using different names to come under one umbrella. This name is no longer a common noun but has become a proper noun. This name needs to be patented or registered as a trademark so the advancement of the subject will not be hindered by unnecessary issues.

R2: You are talking about technicality, you are not talking about morality. Do you agree that a general term should be snatched from the general public only to be used to represent a particular subject? Do you agree that particularization of general terms is the right thing to do? What will happen if some entity will trademark or patent the general terms, such as Sun, Moon, etc. and will not allow these terms to be used by the general public? Are you setting a good precedent for others to follow?

R1: You are blaming for something that has never happened or will never happen. No one has stopped anyone from using AM for the general addition. It is the people who are not using it for the general addition, because AM is well-recognized and accepted for layer upon layer technique. If it were not accepted by people, even patenting or registering the term would not have helped. If it is possible, get the term AM patented for the general addition, and see how you control the people when they do not use it for the general addition.

R2: Do you not see the harm that is happening because of the use of the general term AM for a particular technique?

R1: Which harm is happening? Can you give an example?

R2: Yesterday, I went to teach AM to 2nd year students of mechanical engineering. This was my first day. I wanted to know what students know. I asked them to define manufacturing. Happily, everyone answered well. I knew that they might not have any exposure to AM because they are just 2nd year students. I asked them whether they know AM. They replied in the negative. Then, I asked them to guess what it is. They took time to guess and said AM should be a type of manufacturing in which materials should be added to make a product.

R1: What is the problem?

R2: The problem is that what they guessed is not what AM is. If they fail to guess, then their past teachers need to be blamed. In this case, their past teachers need not be blamed, because when they guessed, they reached a conclusion that is more logical and intuitive. Is it not the aim of education that students be taught to navigate the field without external help because they have been taught how to inculcate logical thinking? But still they are failing to guess rightly, then it is the subject that should be blamed. When the name of the subject was selected, it was not selected with the aim that it should not disturb the logical flow of thinking.

R1: This is a minor thing. Not everything can be expected to fit in a logical narrative. Students learn many things for which there are no past connections. It is the meaning of education: how to teach new subjects and how to introduce them. That is why students go to new classes and take higher education. Do you mean that students should be taught up to high school and they should be left to learn new things based on the logic they have been taught up to their high school level?

R2: Do not minor things add up and become a major problem?

R1: I am afraid I shall never be able to explain you.

R2: Let us talk about your work on PBF. You told that you pre-process your powders. Can you just tell a little bit more about your work?

R1: I actually work on selective laser sintering (SLS) of polymers and ceramics.

R2: SLS is not AM.

R1: Are you joking? All papers say SLS is AM. And you are saying SLS is not AM.

R2: Can you tell what sintering is in selective laser sintering?

R1: In sintering, we want to join particles by applying heat. We bring all particles together, so we keep two particles adjacent to each other. When we apply heat, these atoms move. Though when the particles are kept adjacent, there remain gaps between these particles. The moving of these atoms

is called diffusion. When they cross the boundary, they start filling the gap, and a neck is getting formed between two particles (28). When the gap does not exist, we say our job is over. If we increase the temperature, there is a chance that melting can occur. That is why we need to be cautious that by whatever means we want to achieve sintering, we should not inadvertently cause melting.

R2: It is the principle that you are talking about. Please tell me how many times you have made sure that there should not be any melting when you work on an SLS machine. Do you have the means to make sure? Do you have enough experimental parameters to make sure? Do you have a machine that gives a guarantee that every particle that you will use will not undergo any sort of melting?

R1: It is the product that matters. Is it necessary to control each particle, when without controlling every single particle, we can fulfill the product requirement?

R2: Are you sure you never melt particles? Why do you use the word sintering when some particles melt?

R1: Sintering includes partial melting (29).

R2: But when you explained sintering, you did not include partial melting. Why do you not call selective laser partial melting instead of selective laser sintering?

R1: What if I call it selective laser sintering?

R2: Then, you should not call it AM.

R1: I work according to the definition of AM. I fulfill all the criteria that the definition expects me to fulfill. Since I fulfill the definition, it is AM.

R2: Fulfilling the definition is not a sufficient criterion to be AM. Your technique, i.e., SLS, needs to come under some AM category. Please tell in which AM category your technique comes.

R1: It comes under PBF.

R2: How can SLS come under PBF? PBF implies fusion, as it consists of fusion. Fusion means melting. You have just said SLS does not involve melting. Therefore, SLS has no category to be part of, which makes SLS a non-AM technique.

R1: Where it is written that it needs to come under some category?

R2: Is it possible to accept a chemical element as a chemical element unless it is part of the periodic table?

R1: Do you want to say that the periodic table of chemistry is equivalent to the classification of AM and chemical element of chemistry is equivalent to a technique of AM? Is it logical to compare a developing subject, like AM, to be compared with an established subject, i.e., chemistry? It is too early to compare and make an opinion.

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