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Integrating 4D Printing Processes into STEM Education

Yeshaswini Baddam, Md. Nizam Uddin,
Thisath Nisitha Dasal Attampola Arachchi Attampola Arachchige Don, and Eylem Asmatulu*
Department of Mechanical Engineering
Wichita State University, 1845 Fairmount Street,
Wichita, Kansas 67260-0133
*Email: e.asmatulu@wichita.edu

Abstract

The combination of three-dimensional (3D) printing and smart materials into printable material has led to the development of new outstanding technology, referred to as four-dimensional (4D) printing. In the last decade, 3D printing technology has made significant progress with respect to materials, printers, and processes. However, considerably more research could be done to handle various challenges. The additive manufacturing (AM) industry is discovering new applications, new materials, and new 3D printers. Meanwhile, smart materials can alter printable properties or shapes when external stimuli is applied. 3D printing of these materials also changes their shape or properties over time. Here the fourth dimension, which is time, can be combined with conventional 3D printing. 4D printing is the procedure through which a 3D printed object changes itself into another structure as the result of the impact of environmental stimuli such as temperature, light, or other environmental influences. 4D printing will open new possibilities that are useful in larger-scale applications, will work in extreme conditions, and create a transformable structure. This paper will introduce the background and development of the 4D printing technology, 4D printing process, materials, potential applications, and integration into science, technology, engineering and Math (STEM) education.

Keywords: 3D printing, 4D printing, additive manufacturing, environmental stimuli, STEM education

1. Introduction

Additive manufacturing (AM) has become the new industrial revolution, marking a major turning point in the field of advanced manufacturing processes by providing innovative solutions to traditional manufacturing suppliers in various industry sectors such as aerospace [1], automotive [2], medical [3-5], and energy [6-9]. AM, which is well known as three-dimensional (3D) printing, manufactures 3D geometries by joining material layer-by-layer [10]. The additive manufacturing system was introduced in the late 1980s, and since that time, there have been tremendous AM advancements. In 1984, Chuck Hull of the 3D Systems Corporation filed a patent for a stereolithographic process [11], which attracted the world's interest and created a booming time for 3D printing.

At present, 3D printing is used generally by consumer communities and the media to represent a wide variety of printing technologies including fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM), inkjet 3D printing (3DP), and direct ink writing (DIW). [15-16]. A considerable amount of progress has been made in this field by complementing conventional manufacturing to produce new products with high accuracy and speed, and increased complexity and functions. While researchers are still extensively working to overcome various challenges due to the limitations of high-performance printable materials, build size, surface finish, quality of final products, and cost to replace most conventional manufacturing methods [17], a novel research that led to unexpected enlightenment in the field of AM of smart materials and structures has emerged as four-dimensional (4D) printing technology.

The concept of 4D printing emerged during a 2012 TED conference [18] when Tibbits demonstrated how a static printed object changed over time (Figure 1), which marked a kick-start to the 4D printing technology where the fourth dimension is time. Since then, 4D printing has become a new and exciting branch of 3D printing, gaining considerable attention from researchers and engineers in various disciplines. 4D printing involves carefully designed geometries with exact measured deposition of various smart materials or active fibers that can change shape under external stimuli. For example, consider a bi-metallic strip that is familiar with elementary books. When heat is applied, two different metals will expand at various rates. One side will bend in one direction once the heat is applied, and the other side will bend in the opposite direction when cold is applied. Now consider a bi-metallic strip that is 3D printed and reacts to a heat environment. This could be applied to create practical products such as a 3D printed window blind that opens during sunlight, or vice-versa, that bends and closes to shade the home. Therefore, three aspects must be fulfilled in order for 4D printing to occur [19]: (a) use of stimuli-responsive composite materials arranged layer by layer; (b) an external stimulus to which the material reacts—for example, water, pH, heat, cooling, gravity, moisture, ultraviolet light, magnetic energy, solar energy, temperature, wind, or even humidity—however, the source of energy can be natural or man-made like tensional or compression forces, such as stretching and bending; and (c) an amount of time required for the simulation to be completed, which results in a change in the geometry of the object. An example of the biomolecular self-assembly concept [20] by Tibbits (2012) is show in Figure 1, where separate parts are shaken in a flask and then self-assembled when the independent pieces find each other.

Figure 1**.** Self-assembly of independent pieces [20].

1.1 Difference between 3D Printing and 4D Printing Technology

4D printing is a term utilized for self-assembling materials, which implies that a smart material can change its shape beyond its manufactured shape. By including the idea of "time" to the 3D printing procedure, 4D printing strategies can make structures equipped for acting and responding in pre-modified approaches to various stimuli-flexing or changing size when a specific temperature is applied. In this way, 4D printed items utilizing new materials can possibly change numerous parts of our day-to-day lives. In conclusion, 4D printed objects can transform themselves over time, while 3D printed objects preserve their shape, like plastics or metal parts. Table 1 summarizes the main differences between 3D and 4D printing technology [21].

Table 1. Difference between 3D and 4D printing technology.

3D Printing	4D Printing
Creates objects by printing layer by layer from a CAD model (computer 3D model).	Transforms a 3D-printed object into another structure under the influence of external energy such as light, temperature, heat, water, chemicals, the pressure to self-assemble or change.
Uses the principle of additive manufacturing as the object is made by adding material in layers rather than removing the material or shaping material by cold, and hot techniques.	Uses stereolithography, for example, a technique that uses photo-polymeric liquid to build A 3D object layer upon layer.
Uses many different raw materials such as PLA, ABS, Polycarbonate, Nylon, Carbon, and so.	Is limited to using smart materials with expandable elements, depending on the material properties and application, for example, hydrogel, elements with shape memory, carbon fibers, smart textile materials, and liquid crystal elastomer.
Creates objects that can be rigid or flexible, depending on the printing material; however, it does not change the original shape, even after removing the load.	Produces objects that are also rigid and flexible, transforming the shape over time under the influence of external environmental stimuli such as light, temperature, heat, water, chemical, pressure, etc.
Determines the size of the object based on the size of the printer.	Produces a structure that is much larger than the printer's dimensional limitations.
Involves three variables: length, width, and height.	Uses time as the additional variable besides length, width, and height in 4D representation.
Creates printed objects consisting of geometric bodies such as cubes, cylinders, pyramids, spheres, prisms, etc.	Produces a geometry that is much more complex, including four-dimensional polytopes, for example, a tesseract (analog of a cube).
Presents as a real-life factual concept.	Presents as an abstract idea.

2. Materials and Processing Methods

4D-printed components/structures are classified based on the printing mechanism, either with a combination of multiple materials or with a single material that exhibits physical changes. The main difference between the 4D printing of single and multiple materials stays between their limiting factor of changes. In the 4D printing of a single material, the limiting factor is the smartness of the single smart material that shows how readily the printed components react to the stimuli. For the 4D printing of multiple materials, the extent of the changes, especially changes in the overall shape (stretching, compression, bending, twisting, etc.), depends on the complexity of the basic design of these necessary components.

For example, a 3D-printed shape memory polymer (SMP) structure using the PolyJet printer is presented in Figure 2. It has three connected letters “NTU” in the printed form. This structure was heated to above its glass transition temperature (Tg), straightened at high temperature, and then cooled to room temperature while maintaining the pulling force. Upon reaching room temperature, the pulling force was removed, and the sample took the shape as shown in Figure 2(a). When heated to above the Tg temperature, the sample returned to the printed form shown in Figure 2(b), demonstrating a full shape recovery [13].

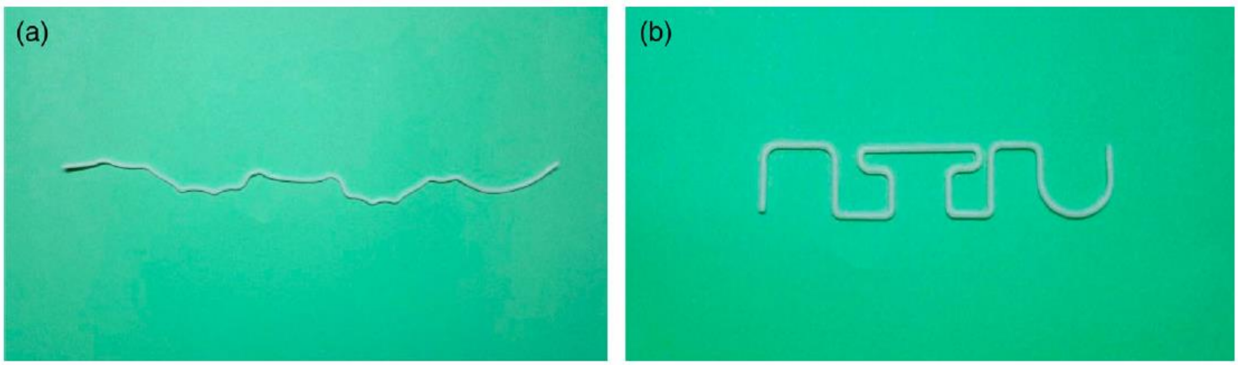

Figure 2. Printed sample of “NTU”: (a) before heating and (b) after heating [13].

The idea of 4D printing depends on five factors; AM procedure, kinds of stimulus-responsive material, stimuli, interaction system, and mathematical demonstration. The majority of AM procedures can assist 4D printing if the chosen stimulus responsive material is compatible with the printer. For a single multi-material print, a 3D printer equipped for printing various materials is required to consolidate at least two materials to create a heterogeneous combination. AM techniques are equipped for multi-material printing, such as the PolyJet printer, fused deposition modeling, and Prusa i3 multi-material [22]. Table 2 shows the development of 4D printing smart materials, beginning with the starting form of the material, printing process, and respective external stimuli used over the years.

Table 2. Material and processing methods for 4D printing technology.

Starting Form of Material	Smart Materials/ Composites Used	Printing Process	External Stimuli	Future Research	Reference
	Barium Titante $BaTiO_3$, BTO) nanoparticles polyethylene glycol diacrylate matrix	Digital Projection printing (DPP)	Produces electrical charge when stress is applied and vice versa	Investigate Piezoelectric coefficient upper limits & their relationship with other parameters.	[23]

Starting Form of Material	Smart Materials/ Composites Used	Printing Process	External Stimuli	Future Research	Reference
Single material/ form	Nickel-titanium (NiTi) shape memory alloy (SMA)	Selective laser melting (SLM)	The shape change is activated by temperature	More understanding of the relation among other processing parameters, shape memory properties of the SLM printed NiTi part.	[24]
	Shape memory polymers (SMPs) – polyurethanes (PEEK, PET, PEO)	PolyJet	The shape change is activated by temperature, magnetic fields, light, and moisture	To understand the science behind the physical mixing and the resultant material properties.	[25]
	Soybean oil epoxidized acrylate	SLA - 3D laser printing technique	The shape change is activated by temperature over time	Soybean oil consists of fatty acid residues: stearic, oleic and linoleic acids (alkane groups) may freeze benefitting the shape fixity	[26]
Multiple Materials	Composite of dielectric elastomers (electroactive polymers), and rigid material	PolyJet	Produces large strains upon activation by electricity	Manufacturing of multi-layered membranes, producing soft structures that do not require prestaining	[26]
	Composite of (hydrophilic polymer), and rigid material	PolyJet	Volume of hydrophilic polymer increases when exposed to water	Exploring new materials and other activating mechanisms for fabrication	[27]
	Composite of quantum dot (QD) suspension (an optical Physical Unclonable Functions with QDs) and rigid material	PolyJet	QDs absorb UV light and emit visible lights	More research on how the QDs affect the parameters of the photopolymerization process	[28]
	Composite of SMP fibers and elastomeric matrix (glassy SMP fibers that reinforce the elastomeric matrix)	PolyJet	Shape change activated by temperature	Fabrication of a component with continuous and spatially varying material properties	[29]
	Multilateral shape memory polymer (SMP) Tango Black Plus and Vero White Plus	PolyJet	Shape change activated by temperature	More reliable design of meta-material lattice and tubular grippers and stents with both self-expanding and self-shrinking features	[30]

4D printing has become popular because it offers many functions in a single piece with one-time manufacturing. Functions of the many shapes have been investigated by researchers. Figure 3 shows a collection of 4D-printed components/structures and changes under the influence of external stimuli [19].

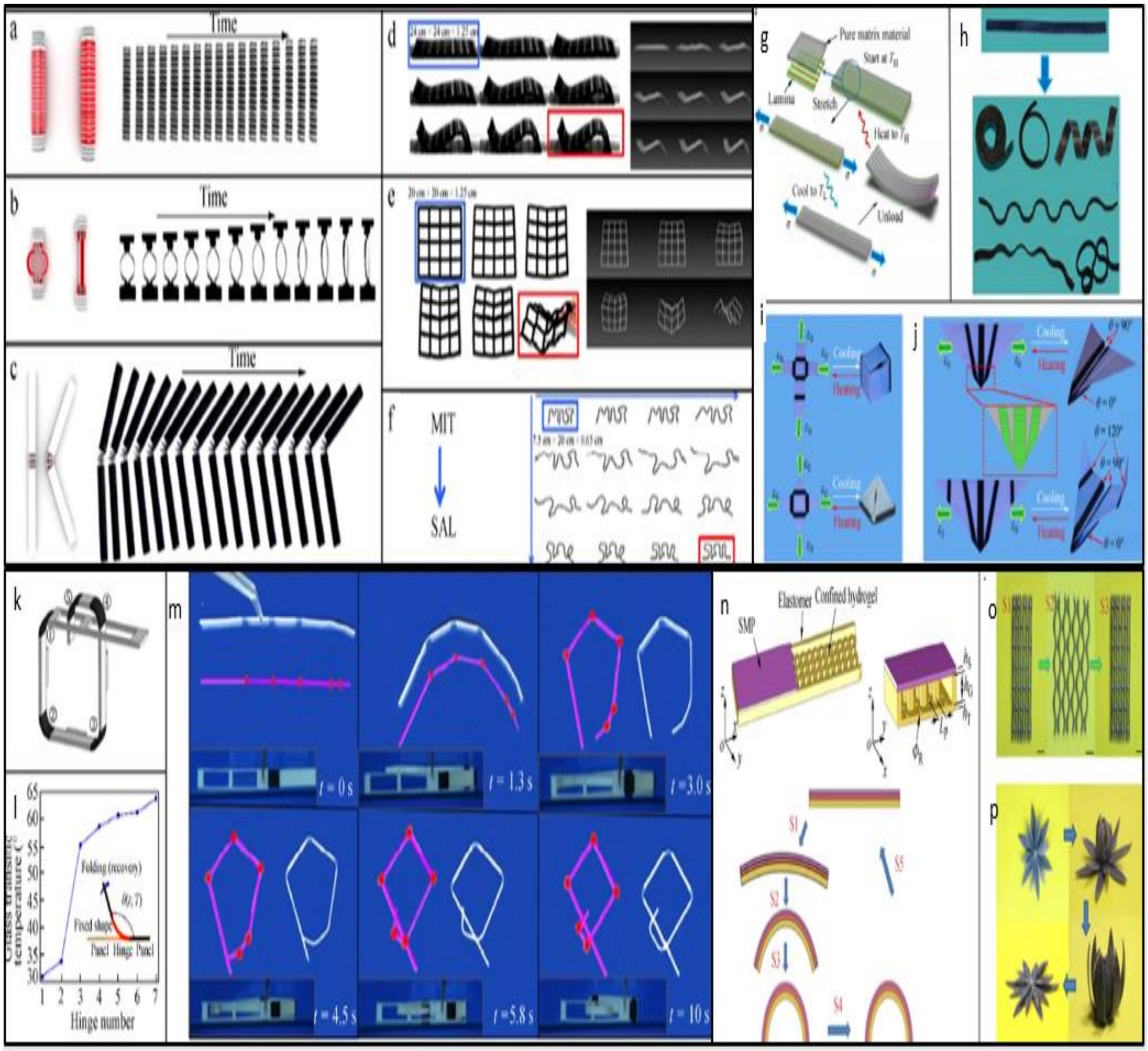

Figure 3. Collection of 4D printed samples and changes under the influence of external stimuli [19]: (a–c) Left: rendered illustration of linear stretching, ring stretching and folding primitive; Right: video frames of fabricated primitive evolving in water over time; (d) morphing of grid into sinusoidal wave; (e) morphing of grid into hyperbolic surface; (f) shape evolution with time from the letters "MIT" into "SAL" [31]; (g) schematic demonstration of laminate architecture and programming process; (h) representative images for folding with different fiber architectures [31]; (i, j) active origami structures of box, pyramid and airplane [32]; (k) schematic diagram of interlocking SMP component; (l) Tgs of digital SMPs used for hinge materials (inset shows schematic view of folding of SMP hinge.); (m) comparison of experiments (plane and side views) and simulations (red lines) for time-dependent folding [33]; (n) schematic demonstration of reversible actuation device in which SMP and elastomer layers confine a hydrogel; (o, p) self-folding/unfolding periodic macro-structure and lotus flower (scale bars are 15 mm.) [34].

Unlike 3D printing, 4D printing depends on building stress into a printed 2D structure. For example, upon heating, the stress is discharged, and the structure further develops with time into 3D. Such procedures conquer the average layer-by-layer printing impediment. Current 4D printing techniques depend on limited control of the anisotropic filler direction in a polymer lattice in order to create pressure. Thus, the pressure must be controlled in a pixel-after-pixel premise through ink writing. Such a successive procedure naturally limits its speed, despite the way that it overlooks the tedious multilayer development in the z measurement. Materials and procedures empower ultrafast printing of multi-dimensional responsive polymers, including hydrogels and shape memory polymers. Figure 4 shows 4D printing via a digitally defined transformation and direct 4D printing with built-in internal stress [35-36]. This method employs digital light exposure on light-curable monomers, necessitating neither the layer-by-layer process in the vertical dimension nor the sequential pixel manipulation in the planar dimensions.

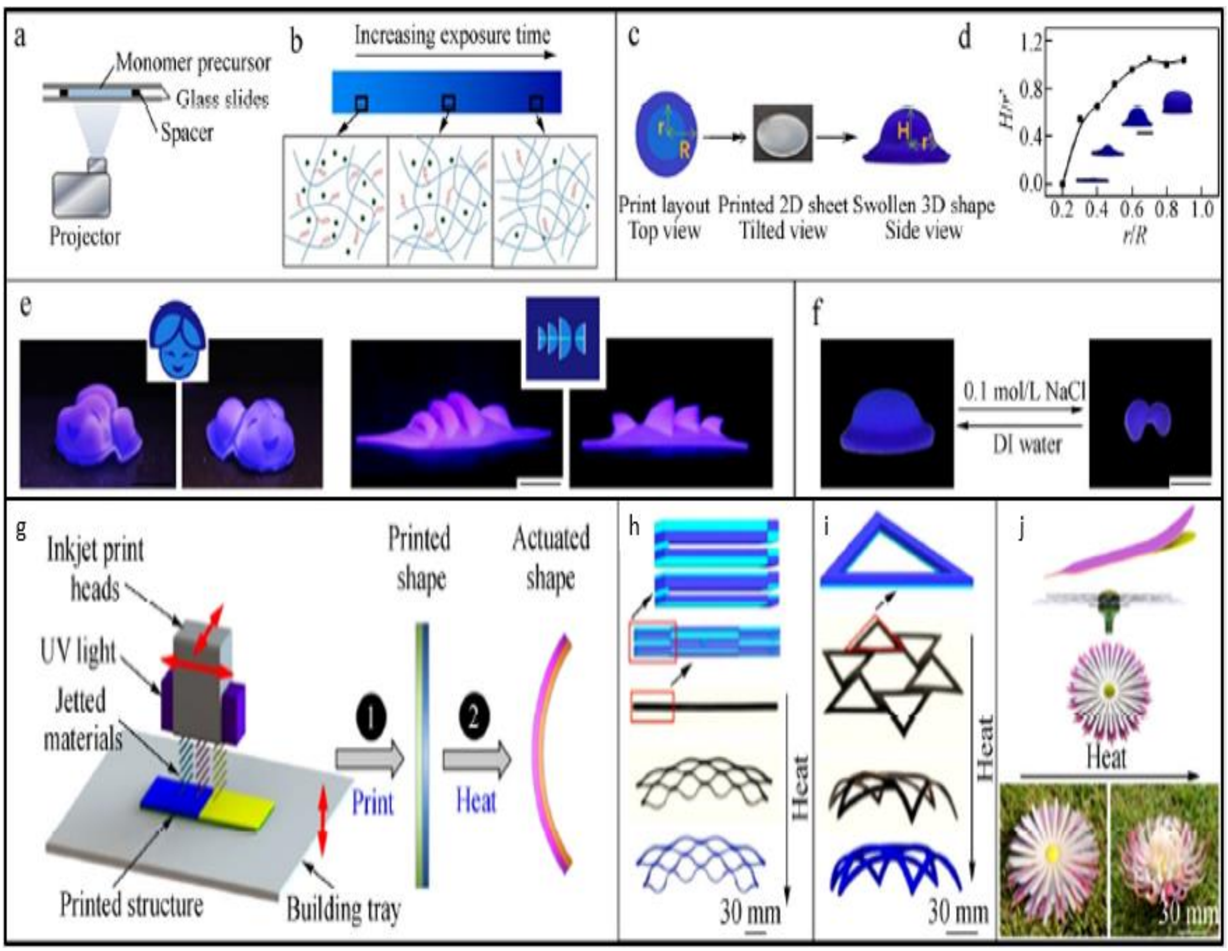

Figure 4. 4D printing by digitally defined transformation and direct 4D printing with built-in internal stress [19, 35-36].

Digitally defined transformation steps include the following: (a) printing setup; (b) spatial-chemical heterogeneity resulting from digitally controlled light exposure; (c) illustration of planar sheet with patterned concentric circles swollen into cap shape 3D structure; (d) control of geometry by printing 2D layout; (e) demonstration of printing versatility: cartoon face, multi-scale buckled structure, and theater; (f) printed 3D object changing its shape under certain stimulation (scale bars are 1 cm) [35]. Direct 4D printing with built-in internal stress is generated by the following steps: (g) printing process; (h−j) diverse structures printed in collapsed configuration and deployed upon heating [36].

3. Integrating 4D Printing Processes into STEM Education

Previous research has been conducted on additive manufacturing, and 3D and 4D printing [37, 38]. 4D printing can make a variety of objects from car parts to human organs. The advantages of 4D printing include the following: expanded capacities of the printed items; new applications from versatile materials; included assembling effectiveness; and decreased assembling cost and carbon footprint. The Department of Mechanical Engineering at Wichita State University (WSU) has more than 480 undergraduate and 100 graduate students, and students have begun to work on additive manufacturing research projects during their studies. Mr. Thisath Nisitha Dasal Attampola Arachchi Attampola Arachchige Don (undergraduate student), Mr. Md. Nizam Uddin (Ph.D. candidate), and Ms. Yeshaswini Baddam (M.S. student) from the Department of Mechanical Engineering were involved in the present study, learned many new techniques, and gained considerable new skills and knowledge about 3D and 4D printing. The undergraduate student used these research activities as his study requirements (Engineer 2020) in the College of Engineering at WSU. These students are also co-authoring this present study and have made many contributions during the experiments. We believe that 4D printing training will enhance the knowledge of many engineering students in order for them to perform more detail studies in the future.

4. Conclusions

4D printing is new and an emerging technology. This paper compares the similarities and differences between 3D and 4D printing technology, different factors such as materials, process and application of this technology. 4D printing uses additive manufacturing techniques to create upgrade responsive parts that can change its shape starting with one then onto the next when subject to proper boosts. The utilization of 4D printing innovation is required to essentially turn out to be increasingly broad with more applications crosswise over biomedical, aviation, as well as defense industries. Here three of the engineering students, also authors of this study reviewed 3D and 4D printing technologies. The undergraduate student has used these research activities for his Engineer of 2020 requirements. Overall, these studies greatly benefit undergraduate engineering students for their future academic studies at different institutions.

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