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RESOURCES FOR SCHOOL TEACHERS

3D PRINTING - THE CONCEPTUAL BLUEPRINT

For over two thousand years, human thought has slowly built up the framework that makes metal 3D printing possible today. Most descriptions of 3D printers focus on how the machines work, but few have asked the deeper question:

What ideas had to exist, in sequence, for a Selective Laser Melting (SLM) metal printer to even be conceivable?

(courtesy: MaterFlow)

This unique document guides us through some of the **crucial concepts of 16 pioneering thinkers** from the *Atlas of Human Imagination*. In the following pages, we trace the conceptual chronology of 3D printing technology – one insight at a time – spanning two millennia.

First, 3D solids had to be understood as **2D slices**: from Democritus' geometry of cones, through Archimedes' method of exhaustion, to Newton's calculus formalising infinitesimals.

Three-dimensional space itself had to be addressable: Descartes' XYZ coordinate system turned spatial geometry into precise numerical locations.

Motion and automation followed: Gutenberg's replication of printed information, Al-Jazari's programmable automata, Da Vinci's mechanical designs and Faraday's motors made controlled action possible.

Matter itself had to be mastered too: Mendeleev's elements, Kelvin's thermodynamics and Gibbs' phase diagrams explain how complex alloys heat up, melt, flow, solidify and cool down.

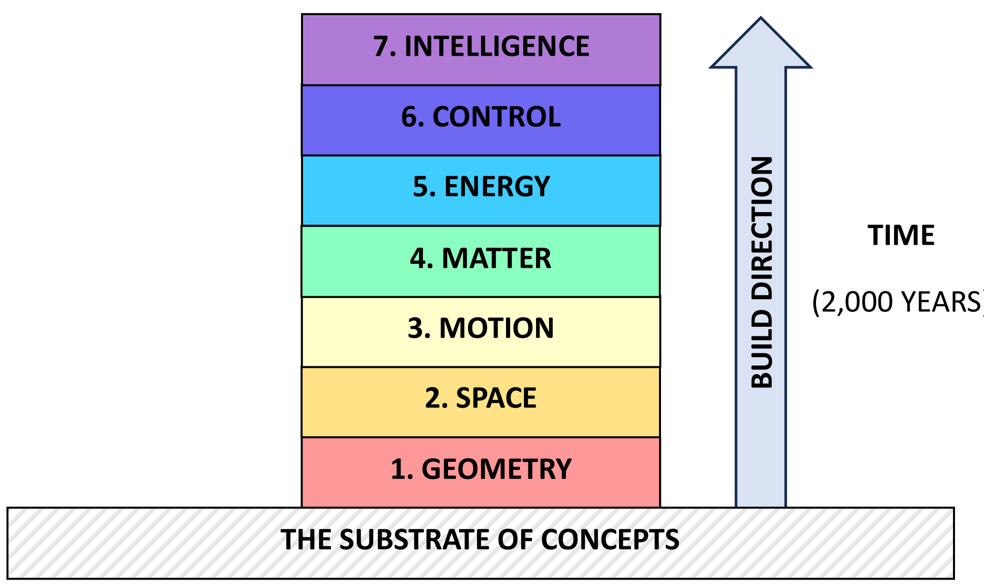
Energy for melting was next: Einstein and Planck gave us the physics behind lasers, focused light capable of melting metal with high precision.

Computation then enabled control: Al-Khwarizmi's algorithms, Lovelace's symbolic reasoning, Turing's universality and Hopper's programming languages transform design into machine action.

Finally, **Intelligence** allows machines to discover optimal forms: Hinton's deep learning creates topologically optimised structures that humans could scarcely imagine.

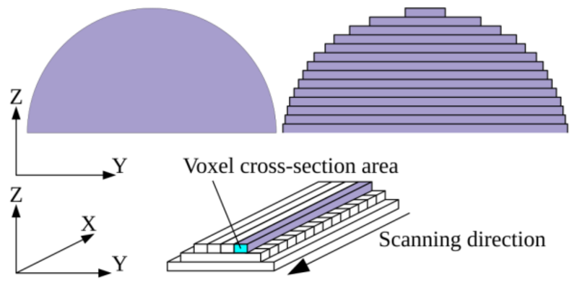
Seen in this new way, an SLM printer is not just a machine; it is **the culmination of centuries of ideas**, an extraordinary convergence of geometry, space, motion, matter, energy, computer control and intelligence, all brought to life in the 21st century.

Almost as if it were 3D-printed itself (see schematic diagram below), the philosophical concepts stack up, **layer by layer,** mirroring the physical process whereby each layer supports the next layer.



1. GEOMETRY – Transforming 3D Objects into 2D Slices

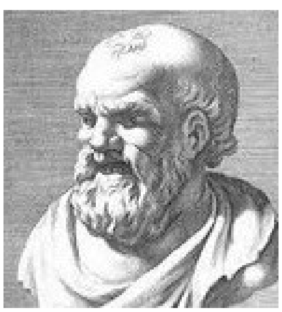
In 3D printing, it is very important to understand how 3D solids can be represented as a vertical stack of thin slices of 2D material (also known as *infinitesimals*). This method of slicing is shown in the schematic below.



The conceptual leaps that allowed this to happen were as follows:

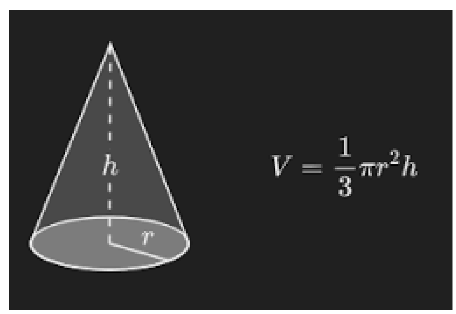
- **Democritus**: conceptual slicing of 3D objects, like cones and pyramids
- **Archimedes**: method of exhaustion
- **Newton** (Leibniz): calculus formalising *infinitesimals*

Democritus (400 BCE)



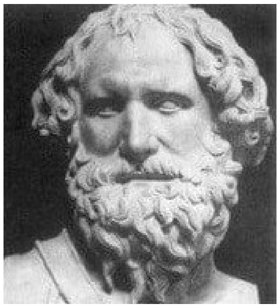
Research Discovery

Volumes of 3D shapes, like cones and pyramids, made up of a stack of 2D slices



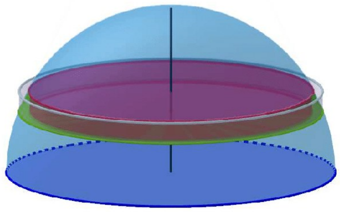
Over two thousand years ago, the Greek philosopher Democritus proposed that a solid could be understood not as a single, indivisible form, but as a composition of infinitely small parts. His work on the geometry and volume of cones (see image, right) imagined a cone as a stack of ever-thinner circular slices, anticipating the modern method of breaking a 3D object into 2D layers. Each slice in a CAD file corresponds to a thin section of the object, just as Democritus' slices corresponded to imagined cross-sections of the cone. In this way, he laid the conceptual groundwork for thinking about solids as **layered structures**, centuries before the mathematics or technology existed to realise them physically.

Archimedes (270 BCE)



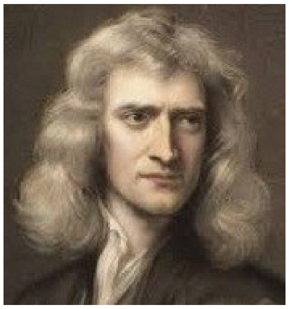
Research Discovery

Method of exhaustion to calculate volumes and areas of shapes – precursor to calculus



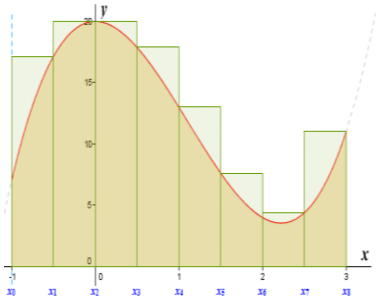
Archimedes took the idea of slicing solids a step further by giving it a rigorous, quantitative form. Using his **method of exhaustion**, he approximated volumes of cones, spheres and other shapes by summing ever-thinner slices (see image, right), taking the limit as their thickness approached zero. This was an early form of integration, allowing him to calculate volumes and areas with precision. In modern terms, it anticipates the numerical slicing of a CAD model for 3D printing. His work transformed intuitive geometry into a methodical approach, laying the mathematical foundation for later developments in calculus and, ultimately, the layer-by-layer thinking that underpins all 3D printing methods.

Sir Isaac Newton (1686)



Research Discovery

Calculus (co-discovered with Leibniz) as a key mathematical tool



Sir Isaac Newton completed the transformation of slicing from a geometric intuition into a universal mathematical method. With the development of **calculus**, he formalised the idea of infinitesimally thin slices, allowing the volume of any solid to be calculated by integrating its cross-sectional areas. What Democritus imagined and Archimedes approximated, Newton made general and systematic (see image, right). Calculus provides the mathematical language that allows 3D objects to be decomposed into layers, ready to be built back up again – one slice at a time. Any deviations or errors in the slicing step later manifest themselves as surface roughness in the physical world.

Bottom line: without geometry, there is nothing to slice.

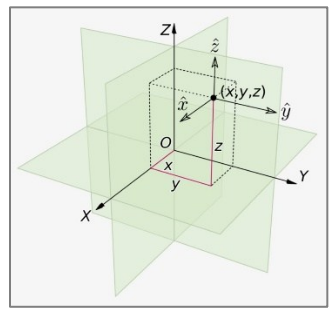
2. SPACE – 3D Coordinate System XYZ

The next thing that becomes necessary for 3D printing is a system that enables precise spatial positioning of objects and machines. This was addressed by René Descartes in the 1600s when he devised the **Cartesian coordinate system** that can give exact numerical position in space using X, Y and Z coordinates. This system was not specific to any particular technology, and applies equally well to a 3D printer, location tracking on a smartphone, or a space satellite in orbit.

René Descartes (1637)

Research Discovery

Cartesian coordinate system in 3D, involving plotting points on X-Y-Z axes



René Descartes was a French philosopher and mathematician who provided the missing link between geometry and action by making space itself measurable. His **Cartesian coordinate system** (see image, right) assigned numerical values to position, allowing points in three-dimensional space to be defined precisely as (*x, y, z*). This transformed geometry from abstract form into a system that could be easily calculated, stored and manipulated.

In modern 3D printing, every point of a digital model, every slice, every tool-path, every movement of a laser beam is defined within such a coordinate framework. Without Cartesian coordinates, a CAD model could not be sliced, nor could a laser or print head be guided accurately through space. Descartes' insight turned geometric ideas into locations, making precise digital fabrication possible.

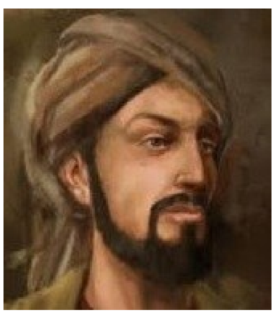
Bottom line: without coordinates, there is nowhere to print.

3. MOTION & AUTOMATION – Mechanical Systems

The next range of concepts and technologies that are needed relate to motion and automation. In this section, thoughts are literally turned into action. For 3D printing, material and energy need to be moved in a precise, controlled, repeatable manner. The key concepts and pioneers who allowed this to happen include:

- **Al-Jazari:** programmable mechanical automata, predating electrical or CNC machines by many centuries
- **Gutenberg:** mass replication and automation of information (printing press as precedent)
- **Da Vinci:** mechanical design, gears, cams and automata concepts
- **Faraday:** electromagnetism, giving motors and actuators

Al-Jazari (1206)

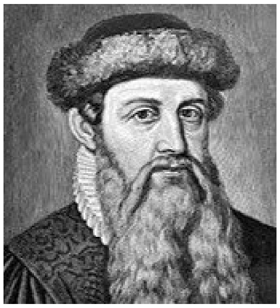


Research Discovery

Programmable mechanical automata; the 'father of robotics'

The Mesopotamian engineer Al-Jazari introduced the idea that machines could follow a predefined sequence of actions. His **programmable automata** and water clocks used cams, cranks, levers and rotating drums with adjustable pegs to control timing and motion, making them programmable in a mechanical sense (see image, right). This was an early form of automation: behaviour encoded in a mechanism rather than directed continuously by a human. The same principle underlies modern automated machines, including 3D printers, where motion is governed by pre-defined instructions and executed repeatedly with high precision.

Johannes Gutenberg (1440)

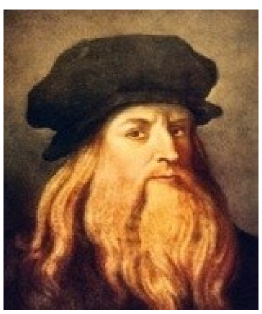


Research Discovery

Replication and mechanical repeatability in 2D paper printing

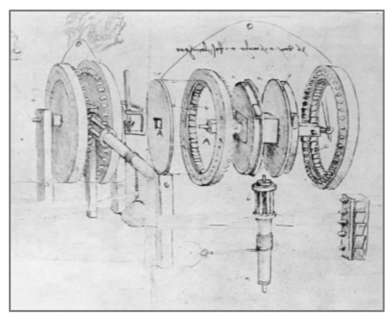
Gutenberg's **printing press** (see image, right) demonstrated that complex outcomes could be produced reliably through mechanical repetition. By mechanising the replication of information (see image, right), he showed that human ideas could be transferred into physical form at scale, with consistency and accuracy. Although not a motion system in the modern sense, the printing press established a crucial precedent: that machines could reproduce structured patterns automatically. This concept of repeatable, standardised, scalable output is fundamental to all digital fabrication technologies, including 3D printing.

Leonardo Da Vinci (1510)



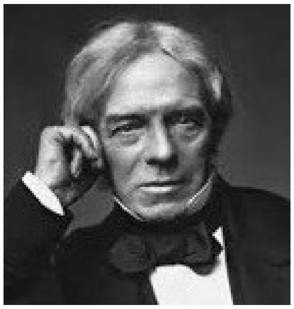
Research Discovery

Mechanical systems for motion, as well as engineering metallurgy



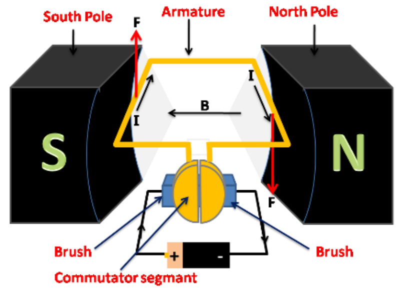
Leonardo Da Vinci was an Italian polymath who explored motion as a design problem in its own right. His detailed studies of gears, cams, linkages, bearings and automata show a deep understanding of how continuous motion could be transformed and controlled (see image, right). While some of his machines were never built, his work established the principles of mechanical design that underpin modern engineering: components with defined functions, assembled into systems capable of precise movement. These ideas remain central to the **mechanical architecture** of today's automated machines, from CNC tools to 3D printers.

Michael Faraday (1831)



Research Discovery

Electromagnetism; and the creation of the first ever electrical motors and actuators



The English scientist Michael Faraday completed the transition from mechanical ingenuity to modern automation by revealing the relationship between electricity, magnetism and motion (see image, right). His discoveries in electromagnetism led directly to the **electric motor**, allowing controlled, repeatable movement to be driven by electrical signals rather than humans or water power. This made precise, programmable actuation possible at scale.

In a metal 3D printer, motors derived from Faraday's work drive the build platform, re-coater and laser scanning systems, translating digital instructions into physical, servo-controlled motion with unprecedented accuracy.

Bottom line: without motion and automation, printing is just theoretical.

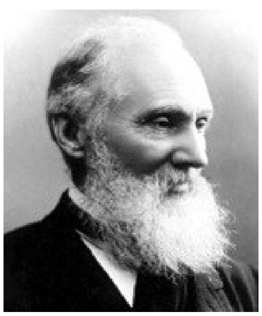
4. MATTER – Phase Changes, Melting and Freezing of Alloys

For metal 3D printing to be possible, matter itself had to become predictable and controllable. This requires a detailed understanding of how metals respond to heat, how different elements combine to form alloys, and how materials change phase as they melt and solidify.

Thermodynamics explains how energy flows through a material; chemistry defines what the material is made of; and phase diagrams describe how structure and phases emerge during cooling. Together, these ideas allow metal powders to be melted, shaped and resolidified with precision, controlling microstructure and mechanical properties at the scale required for 3D printing. Two key pioneers from the *Atlas* include:

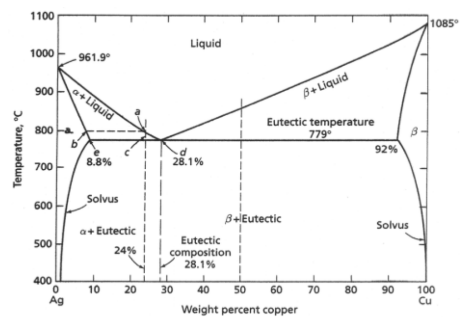
- **Kelvin:** thermodynamics, thermometry, heat, phase control (with some help from Gibbs)
- **Mendeleev:** chemical elements and alloy design with predictability

Lord Kelvin (1848)



Research Discovery

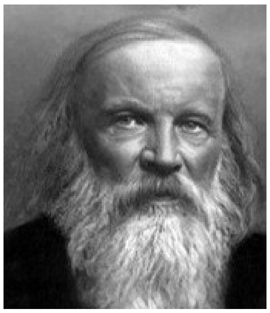
Thermodynamics, thermometry and phase changes (melting and solidification)



The English physicist Lord Kelvin is most famous for his development of the Kelvin temperature scale, starting at 0 K or absolute zero. This helped establish temperature as a precise, measurable quantity and laid the foundations of **thermodynamics**. His work made it possible to understand how energy flows through matter, and how materials respond as they are heated and cooled. These principles were later used by other scientists like Josiah Willard Gibbs to create phase diagrams of metal alloys (see image, right) showing thermal behaviour, like melting points, as a function of temperature and composition.

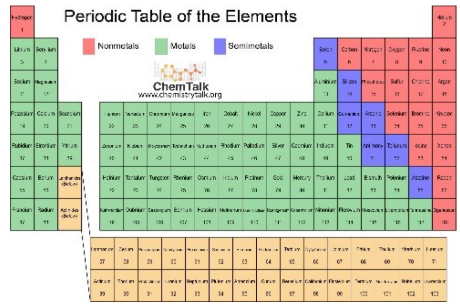
In metal 3D printing, this understanding is essential: alloy powders must be heated above their melting point, held within a narrow thermal window, and then cooled in a controlled way to avoid defects like pores, cracks or residual stress. Concepts such as thermal gradients, heat flow and equilibrium - all formalised by Kelvin in the 1800s - govern how a melt pool behaves and how a printed layer **solidifies from the liquid state**. Without thermodynamics, metal printing would be blind to the behaviour of matter under these rather extreme conditions.

Dmitri Mendeleev (1869)



Research Discovery

Theoretical framework for metals and non-metals by arranging them in the Periodic Table



The Russian chemist Dmitri Mendeleev was the first person to correctly arrange the known elements by their atomic properties and chemical behaviour, thus creating the famous ***Periodic Table* in** 1869 (see image, right). This framework enabled prediction of new metallic elements that were not known at that time and it also led to a deeper understanding of alloy properties when elements are mixed together. Metallurgy would be largely empirical guesswork without it.

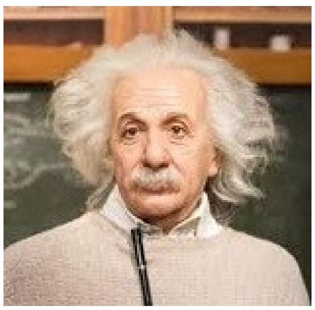
The modern metal powders and alloys used in 3D printing are direct descendants of this insight. By selecting and combining elements deliberately, engineers can tailor alloys for printability, strength, ductility and thermal performance. In this way, Mendeleev's classification of matter underpins the **controlled composition of the metallic alloys** that SLM printers melt and form, layer by layer.

Bottom line: without control of matter, printing becomes defective.

5. ENERGY – Physics of Lasers

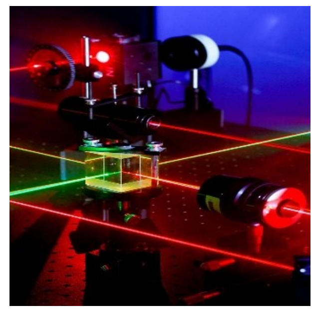
To melt metal with precision, energy must be delivered in a highly controlled and localised form. Laser physics makes this possible by transforming light into an amplified, coherent, intense light beam capable of depositing energy exactly where and when it is needed. This technology has been experimentally perfected over the past 100 years, but the conceptual breakthrough can be traced back to Albert Einstein in 1917 in his paper: *"Zur Quantentheorie der Strahlung"* ("On the Quantum Theory of Radiation"), Physikalische Zeitschrift, (1917), 18, 121–128.

Albert Einstein (1917)

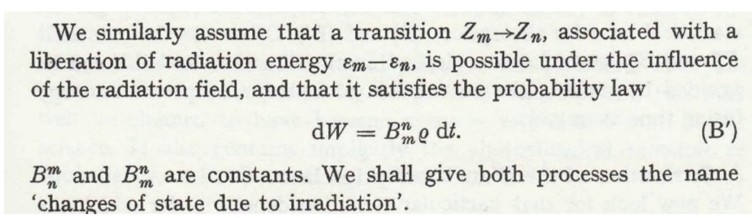


Research Discovery

Stimulated emission of light and the physical foundation of laser technology



In 1917, Einstein published a short but profound paper that made lasers conceptually possible. While studying how atoms interact with radiation, he introduced the idea of **stimulated emission**: the process by which an incoming photon can cause an excited atom to emit a second photon with the same energy, direction and phase (see image, right). This insight showed that light could be amplified coherently rather than emitted randomly. To describe this, Einstein introduced what are now known as the *A* and *B* coefficients, linking spontaneous emission, absorption and stimulated emission within a single theoretical framework (see the original excerpt below, which represents the 'conceptual birth' of lasers).



We similarly assume that a transition $Z_m \rightarrow Z_n$, associated with a liberation of radiation energy $\varepsilon_m - \varepsilon_n$, is possible under the influence of the radiation field, and that it satisfies the probability law

$$dW = B_m^n \varrho \, dt. \quad \text{(B')}$$

B_n^m and B_m^n are constants. We shall give both processes the name 'changes of state due to irradiation'.

Although no lasers existed at the time, Einstein's seminal paper revealed that light could, in principle, be controlled, amplified and directed as a monochromatic beam. Many decades later, this physics became the foundation of **laser technology**, allowing highly focused energy to be delivered precisely enough to melt metal powder in Selective Laser Melting machines.

Bottom line: without an energy source, metal does not even melt.

6. CONTROL – Algorithms & Computer Control Systems

For a 3D printer to transform a digital model into a physical object, human intent must be translated into precise, executable instructions, or in other words, **control**. This requires formal algorithms, symbolic reasoning, universal computation and abstraction layers – concepts that directly underpin slicing, tool-paths, firmware and motion control in modern 3D printing. The key concepts and pioneers from the *Atlas* who enabled this include:

- **Al-Khwarizmi:** formal algorithms
- **Lovelace:** machines manipulate symbols
- **Turing:** universal computation
- **Hopper:** abstraction layers for computer programming

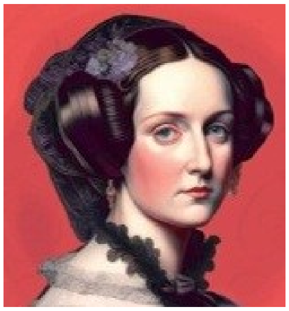
Al-Khwarizmi (820)

Research Discovery

Algebra; and he gave his name to the word *"algorithm"*

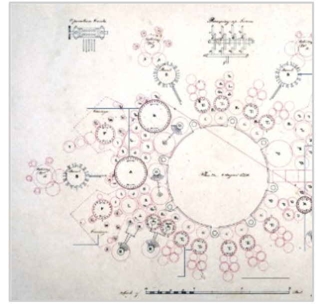
The Persian mathematician Al-Khwarizmi introduced the bold idea that a problem could be solved by a finite, ordered sequence of steps. His work gave us the concept of the **algorithm**: a repeatable procedure that transforms inputs into outputs (see image, right). This notion lies at the heart of all machine control to this day. In 3D printing, slicing software, path planning, motion commands and sensors are all expressed as algorithms, ensuring that complex actions are carried out consistently and precisely.

Ada Lovelace (1843)



Research Discovery

Algorithms in early mechanical computer systems; machines can manipulate symbols



Ada Lovelace was an English mathematician who recognised that machines could operate on symbols, not just numbers. She understood that a **calculating engine** could follow abstract instructions and produce results beyond just arithmetic (see image, right). This insight marks a crucial shift: machines could execute general processes defined by human intent. Modern CAD models, slicing instructions, laser-paths and tool-paths are symbolic representations, made actionable through her conceptual leap.

Alan Turing (1936)

Research Discovery

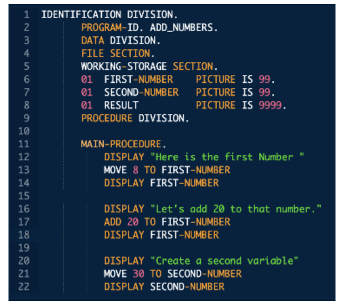
The concept of the *Turing machine* that can calculate anything algorithmically

Alan Turing was a British mathematician, logician and computer scientist who laid the foundations of theoretical computing. He introduced the **Turing machine** and showed that a single machine could, in principle, perform any computation, provided it was given the correct instructions (see image, right). His concept of universal computation unified all algorithmic processes within one framework. This **universality** underpins modern digital control systems, allowing a single computer to handle geometry, plan motion and control lasers and motors inside a 3D printer.

Grace Hopper (1952)

Research Discovery

Programming languages, like COBOL, as well as computer compilers for coding



```
IDENTIFICATION DIVISION.
       PROGRAM-ID. ADD_NUMBERS.
       DATA DIVISION.
       FILE SECTION.
       WORKING-STORAGE SECTION.
       01  FIRST-NUMBER    PICTURE IS 99.
       01  SECOND-NUMBER   PICTURE IS 99.
       01  RESULT          PICTURE IS 9999.
       PROCEDURE DIVISION.

       MAIN-PROCEDURE.
           DISPLAY "Here is the first Number "
           MOVE 8 TO FIRST-NUMBER
           DISPLAY FIRST-NUMBER

           DISPLAY "Let's add 20 to that number."
           ADD 20 TO FIRST-NUMBER
           DISPLAY FIRST-NUMBER

           DISPLAY "Create a second variable"
           MOVE 30 TO SECOND-NUMBER
           DISPLAY SECOND-NUMBER
```

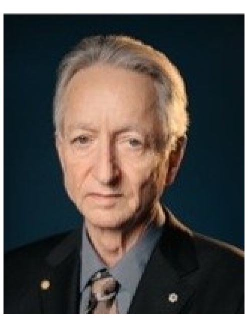
Grace Hopper, the American computer scientist, made computation practical by introducing abstraction layers that separated human thinking from machine execution. By enabling computer instructions to be written in more accessible forms and translated automatically into machine code, she made **language-based programming** a useful engineering tool (see image, right). Her novel methods made coding, debugging and compiling practical and efficient. This approach underlies modern firmware and control software, allowing the complex manufacturing behind 3D printers to be defined, modified and executed reliably.

Bottom line: without computer control, printing can only be manual.

7. INTELLIGENCE – Topology Optimisation via AI

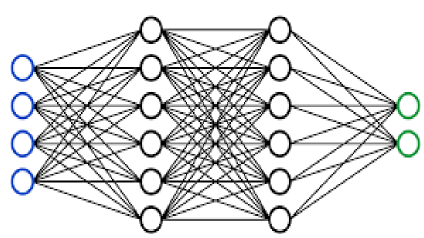
Modern machines can now discover structure, rather than simply follow human instructions. Deep learning and AI enable generative, topologically optimised forms, exploring design possibilities that would be impossible to conceive manually. These optimised structures are often only manufacturable with additive layering, making the machine not just a tool, but an active participant in shaping the object it creates.

Geoffrey Hinton (2004)



Research Discovery

Neural networks, deep learning and AI, which can now also be used in 3D printing



Geoffrey Hinton is a British-Canadian computer scientist and mathematician who has worked for decades on **deep learning**. He helped develop modern neural networks (see image, right), backpropagation and probabilistic models that use high-dimensional optimisation, enabling computers to learn complex patterns from data. Hinton's research transformed artificial intelligence (AI) by developing deep learning methods that allow machines to learn complex patterns.

In engineering design, this enables **topological optimisation**: algorithms exploring vast design spaces to discover shapes that distribute material efficiently in response to loads and constraints. The resulting forms are often organic, non-intuitive and impossible to machine using traditional methods. 3D printing can now make these designs physically real, as material can be placed only where it is needed, layer by layer (see the bracket example, below). In this way, Hinton's contribution to AI completes the conceptual stack: machines do not merely execute instructions, but actively participate in shaping the objects they produce.

(Courtesy: Airbus)

See also: www.bbc.com/news/science-environment-24528306

Bottom line: without AI, exploration of complex design space is severely constrained.

Conclusion:

By tracing the ideas of 16 pioneers from the *Atlas of Human Imagination*, across the diverse fields of geometry, mechanics, physics, thermodynamics, chemistry, computation, programming and artificial intelligence, we see that 3D printing is more than just a machine – it is the product of 2,000 years of interconnected thought and experimentation. The *Atlas of Human Imagination* celebrates this cross-disciplinary lineage, showing how insights from philosophy, mathematics, engineering and science converge to turn human ideas into tangible, layered reality.

And, as we saw earlier, the human imagination itself has been 3D-printed.

David Jarvis
www.davidjarv.is
8/2/2026

Some Honourable Mentions in the World of 3D Printing:

These additional 18 figures have made major contributions, indirectly and directly, to the field:

- **Imhotep** (2600 BCE) – layer-upon-layer construction of monuments and step-pyramids
- **Alhazen** (965–1040) – optical systems, lenses and mirrors, crucial to future laser-based systems
- **Christiaan Huygens** (1629–1695) – wave theory of light, again crucial for laser control
- **Robert Hooke** (1635–1703) – elasticity, material science and microscopic observation
- **Leonhard Euler** (1707–1783) – mechanics and structural calculations, relevant to 3D printing models
- **Joseph Fourier** (1768–1830) – heat transfer and conduction, important for melt pool modelling
- **Carl Friedrich Gauss** (1777–1855) – Gaussian distribution, relevant to laser beam intensity profiles today
- **James Clerk Maxwell** (1831–1879) – electromagnetism, foundational to understanding motors and lasers
- **Josiah Willard Gibbs** (1839–1903) – phase diagrams, chemical thermodynamics and phase rules
- **Max Planck** (1858–1947) – quantum theory and energy quantisation, linked to Einstein's laser physics
- **Norbert Wiener** (1894–1964) – cybernetics, feedback and control systems
- **Richard Feynman** (1918–1988) – ideas on nanotechnology and manipulating matter very precisely
- **Theodore Maiman** (1927–2007) – created the first operational laser; directly enabled laser-based AM
- **Iver Anderson** (1940s–1970s) – gas atomisation techniques for making metal alloy powders
- **Patrick Hanratty** (active 1961–1980s) – often called the 'Father of CAD/CAM'
- **David Bourell** (active 1980s–present) – academic expertise in laser powder-bed fusion
- **Ulf Ackelid** (active 1990s–present) – industrial expertise in 3D printing using electron-beam melting
- **Chris Sutcliffe** (active 1990s–present) – academic and industrial expertise in SLM technologies.

FOR TEACHERS

Using the *Atlas of Human Imagination* in Lessons

Some Classroom Ideas exploring the Blueprint of 3D Printing (14-18 Yrs):

1) Geometry – Transforming 3D Objects into 2D Slices

- **Activity:** Give students a simple 3D object (pyramid, cone or cube) and ask them to **draw or cut it into sequential slices**. Discuss how Democritus, Archimedes and Newton conceptualised solids as layers, and relate this to how 3D printers build objects layer by layer.

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2) Space – 3D Coordinate System XYZ

- **Activity:** Using a grid or small cubes, students **mark X, Y, Z coordinates** of points on a model. Show how Descartes' Cartesian system allows precise positioning, just like a 3D printer's toolpaths.

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3) Motion & Automation – Mechanical Systems

- **Activity:** Build simple **mechanical automata** or paper models with cams and levers that follow a sequence. Link to Al-Jazari, Da Vinci, Gutenberg and Faraday to illustrate how programmable, repeatable motion laid the foundation for modern printers.

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4) Energy – Lasers and Light

- **Activity:** Shine a **laser pointer or focused light** through a convex lens onto a surface to explore intensity distribution. Discuss Gaussian beam profiles, Huygens' wave theory and Maiman's first laser, showing why energy must be very precisely controlled to melt metal.

5) Matter – Phase Changes and Alloy Control

- **Activity:** Use **wax, chocolate or gallium metal** to demonstrate melting, flow and solidification. Discuss Kelvin, Gibbs and Mendeleev: how composition and temperature control the material's behaviour — the principle behind melt pools in SLM.

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6) Control – Algorithms and Computer Instructions

- **Activity:** Give students a **step-by-step design problem** that must follow precise instructions. Highlight Al-Khwarizmi, Lovelace, Turing and Hopper, and show how algorithms and abstraction turn human intent into machine action, like slicing in a printer.

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7) Intelligence – Topology Optimisation and AI

- **Activity:** Provide a **design challenge** (bridge, tower or truss) and let students experiment with removing material while maintaining stability. Discuss Hinton's deep learning and modern generative design, illustrating how machines can discover optimised structures beyond human intuition.

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